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Application of phase change material heat storage device for control of Varroa mites in beehives

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Abstract

Bees are commonly thought to be useful for generating honey. In the natural environment, pollination of flowers, on the other hand, has the greatest ecological impact on bees. Both the importance of bees to humans and the urgent need to take action to prevent their unjustifiable and slow elimination are generally understood. Bees are now subjected to a variety of stresses and problems. They had to face with the natural challenges in their environment, such as temperature, humidity and predators etc. The major goals of this project are to employ sustainable energy technologies to eliminate the most serious threat to bees, Varroa mites, to design a practical prototype that is easy enough for beekeepers to use, and to show that heat treatment is a non-harmful technique for bees and their products.

The current study looks into the possibility of using phase change materials (PCMs), specifically Sodium Acetate Trihydrate (SAT), as a heat source for thermal treatment. Following a study of phase change materials, it was determined that SAT was the best material for thermal treatment applications due to its thermal, physical, and chemical capabilities. When an active PCM pack is placed to the brood box, a simple mathematical model is used to approximate the thermal interaction that happens. The findings showed that, even under ideal operating conditions, the PCM pack is incapable of overheating the interior of the beehive. The major simulations aided in forecasting PCM pack behaviour, identifying temperature distribution, and estimating the time required to reach the thermotherapy temperature. In addition, an observation beehive was employed to monitor many laboratory and outdoor studies. All of the experiments were planned ahead of time. The goal of these tests was to figure out the most efficient way to process heat treatment.

The results of the intended simulations were obtained and analysed. The temperature variation in the brood chamber was found to be quite close to that observed in laboratory testing and comparable to that reported in apiary investigations. Any type of mesh in the brood box's lowest half blocked the free transfer of heat, according to laboratory research. A thermal insulation top cover was also determined to be required to prevent heat from escaping. The outcomes of the on-site tests demonstrated that the external ambient temperature has a considerable impact on the performance of the PCM pack. In conclusion, it was proved that the Varroa mite, the principal pest that threatens bees in the United Kingdom and around the world, can be eradicated using sustainable energy technology such as PCMs. In this study, developing a basic mathematical model that approximates the thermal interaction was achievable. The purpose of these testing was to learn

more about the most efficient approach to undertake heat treatment. The findings of the on-site testing revealed that the surrounding environment's temperature has a significant impact on the PCM pack's performance. The prototype developed will help in the reduction of Varroa mite infestations in UK apiaries, which will improve bee living conditions, will not harm other species with harmful chemical substances, will be reusable and thus environmentally friendly, bee losses will be reduced, Varroa mites will cease developing pesticide resistance and pollination of agricultural products that are critical for human sustenance and corners will be reduced.

This research could lead to a lot of additional work, such as improving the prototype and developing an in-depth assessment approach to confirm that this technology effectively eliminates the Varroa mite from the brood box.

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This project would not have been feasible without the kind contributions of numerous people:

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First, thanks to Janet, whose interest in beekeeping first alerted us to the issues that bees confront in the United Kingdom, laying the groundwork for our project, which ultimately expanded into an inter-disciplinary collaboration.

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Nomenclature

Abbreviations

APS-C Advanced Photo System type-C

CAD Computer-Aided Design

CFD Computational Fluid Dynamics

CMOS Complementary Metal-Oxide-Semiconductor

EG Ethylene Glycol

EVOH Ethylene-vinyl alcohol copolymer

GRP Glass Reinforced Plastic

HDPE High-density Polyethylene

HT Heat Treated

HTC Heat transfer coefficient

MRD Maximum Recovery Diluent

NHT Non Heat Treated

OECD Organisation for Economic Co-operation and Development

PCM Phase change material

PCR Polymerase Chain Reaction

pH potential of hydrogen

PLA Polycactic Acid

PVC Polyvinyl Chloride

RT-qPCR Real-Time Quantitative Reverse Transcription

SAT Sodium Acetate Trihydrate

UK United Kingdom

Mathematical Notation

α	Permeability coefficient of the porous media	[ ]
δH_{pcm}	Change in the PCM enthalpy	[J]
δT	Temperature difference	[K]
δt	Time lapse	[s]
δ_{air}	Thickness of the air layer	[m]
ϵ	Void percent of the porous media	[ ]
ρ_f	Density of air	[kg/m^3]
$A_{beehive}$	Beehive box surface area	[m^2]
A_{floor}	Area of the floor	[m^2]
A_{pcm}	PCM pack surface area	[m^2]
A_{roof}	Area of the roof	[m^2]
C_2	Inertial loss coefficient	[ ]
Cp_f	Heat capacity of air	[J/kgK]
D_p	Diameter of the porous	[mm]
h_{pcm_f}	Convective heat transfer coefficient of PCM	[W/m^2K]
h_{pcm}	Convective heat transfer coefficient of PCM	[W/m^2K]
k_{air}	Thermal Conductivity of air	[W/mK]
L_{pcm}	Specific latent heat	[kJ/kg]
m_{pcm}	Mass of PCM	[kg]
N_{bc}	Number of bees	[ ]
q_{bees}	Heat created by bees	[W]
T_a	Ambient temperature	[K]
$T_{beehive}$	Beehive temperature	[K]
T_{fb}	Temperature of the fluid at the bottom	[K]
T_{fm}	Temperature of the fluid at the middle	[K]
T_{ft}	Temperature of the fluid at the top	[K]
T_{pcm}	PCM temperature	[K]

U_{floor}	Conductive heat transfer coefficient of the floor	[W/m^2K]
U_l	Overall heat transfer coefficient	[W/m^2K]
U_{roof}	Conductive heat transfer coefficient of the roof	[W/m^2K]
V_{bc}	Total volume covered by bees including voids	[m3]
V_{bee}	Volume of each individual bee	[m^3]
V_{fb}	Volume of the fluid at the bottom	[m^3]
V_{fm}	Volume of the fluid at the middle	[m^3]
V_{ft}	Volume of the fluid at the top	[m^3]
V_f	Volume of air	[m^3]

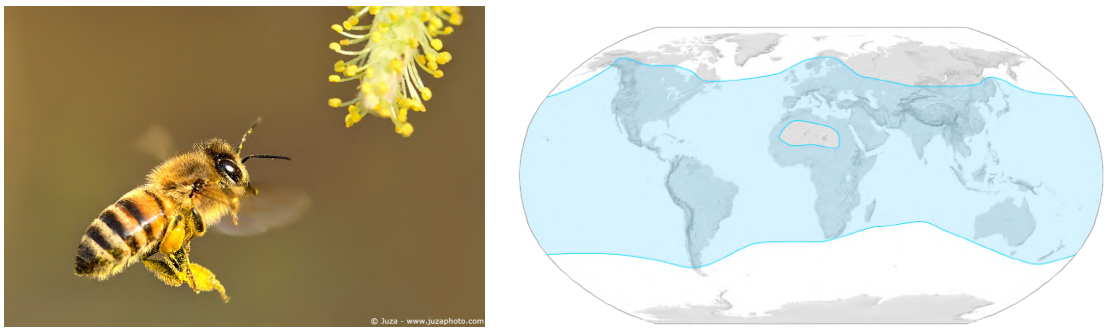
Chapter 1

Introduction

This chapter provides background information, discusses the significance of bees, and then outlines the goals of this thesis. The methodology is finally described.

1.1 Honeybees (*Apis Mellifera*)

When people talk about bees, they frequently refer to the species *Apis mellifera*, which is the most common. Except for Antarctica, this species of bee and its 28 identified subspecies[1] may be found on every continent [2]. Figure 1.1a depicts a specimen of the honeybee, Apis mellifera. It is displayed in Figure 1.1b where the Apis mellifera may be found in each of the geographical zones. Because of their remarkable adaptability, this species of bees has colonised nearly every continent on the earth [3]. They only require adaptations to the local environment, such as adjustments of the colony cycles to the time of the local floral resources, forming a group in colder climates and migratory swarms [1].



(a) (b)

Figure 1.1: (a)Apis mellifera[4]. (b)Distribution map of the Apis mellifera [5].

It reproduces only through the use of eggs. The caste into which they convert will be determined by the sort of genetic contribution they get during their egg stage and the type of food they receive during their larval development. Each caste performs a certain duty within the colony, which varies from one another.

Females are produced from fertilised eggs, whilst drones (males) are produced from unfertilised eggs. Female larvae that feed on royal jelly nectar and pollen grow into queens, while larvae that feed on a regular diet of nectar and pollen evolve into adult workers. The worker bees are females who are not capable of reproducing and are the smallest of the three castes in terms of size. Specifically, their bodies are designed for the collecting and transportation of nectar and pollen. They have a stinger that, if used to sting, detaches from their abdomen along with the poison sac that it contains causing their death. The queen's abdomen is longer than that of the workers, despite the fact that her head and thorax are comparable. It is the sole female in the colony that is capable of reproducing (under regular circumstances). It too has a sting, but when she uses it, it does not result in the death of the user. The drones are a male-dominated caste. They are bigger than those of the female castes, with a broad blunt abdomen at the end that gives them the appearance of a bullet at the end of their bodies. All bees go through a variety of developmental phases (Figure 1.2). They go through a metamorphosis between each stage, however the length of time between each one varies based on the caste. The drone is the caste with the greatest amount of progress, but it is also the caste with the shortest life expectancy. The worker bees go through an intermediate stage of growth, while the queens develop at the quickest rate. Those who survive under optimum circumstances may expect to live up to three years of productive life [2].

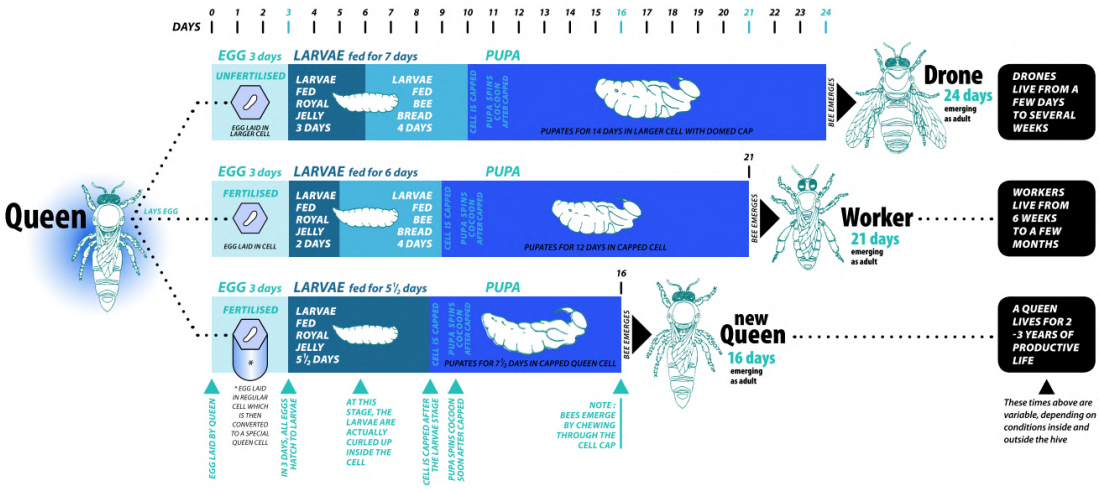


Figure 1.2: Bee life cycle [6].

Distribution of different types of Apis Mellifera

It is important to emphasise that the *Apis* genus has several species (Figure 1.3). Apis Mellifera, although being indigenous to Africa, has spread throughout Europe and Asia (Figure 1.4). Their differences are particularly interesting. Asian species of Apis mellifera are less productive because they live in a tropical environment where they have year-round access to food and do not need food storage during harsh conditions. On the contrary, the European Apis melliera was forced to adapt by developing honey storage tactics in order to survive the winter. European

weather conditions are more difficult for bees. This is the point at which the effect of climate change on bees is shown. According to [7], this explains why the European Apis mellifera has improved honey production capabilities and has been transported to America and Australia.

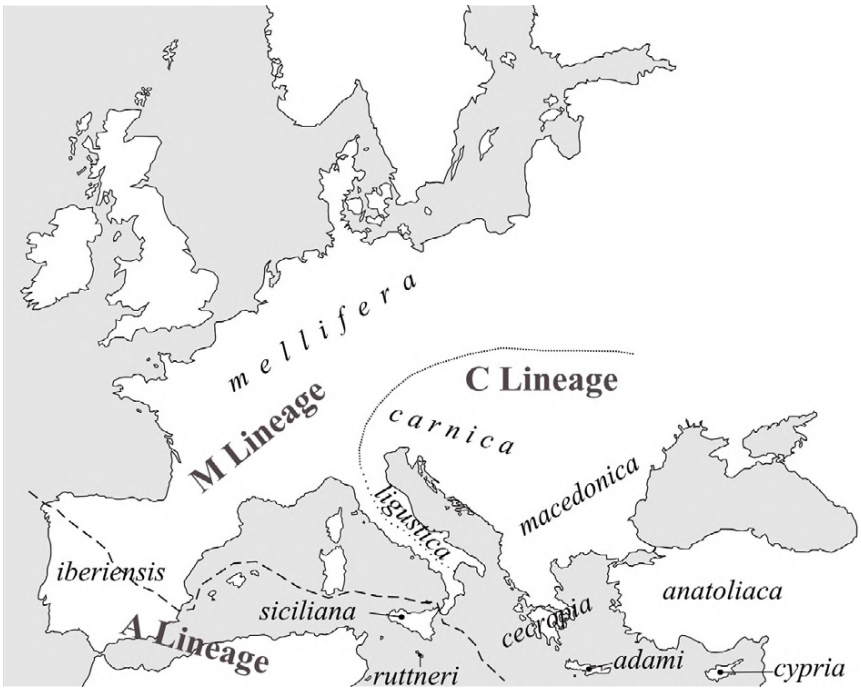


Figure 1.3: Approximate natural distribution of the Apis mellifera evolutionary lineages and subspecies in Europe [8].

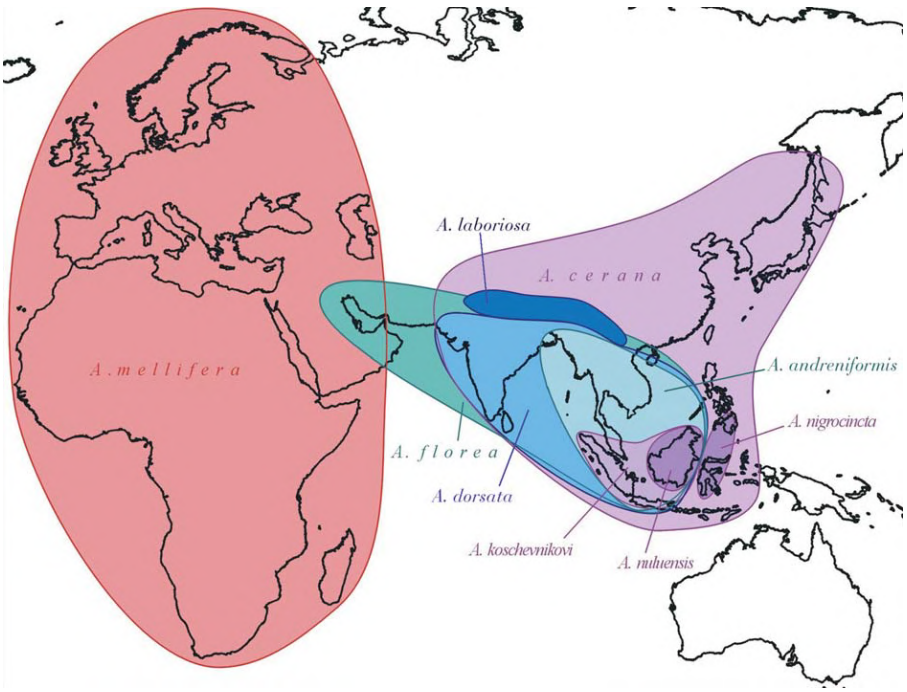
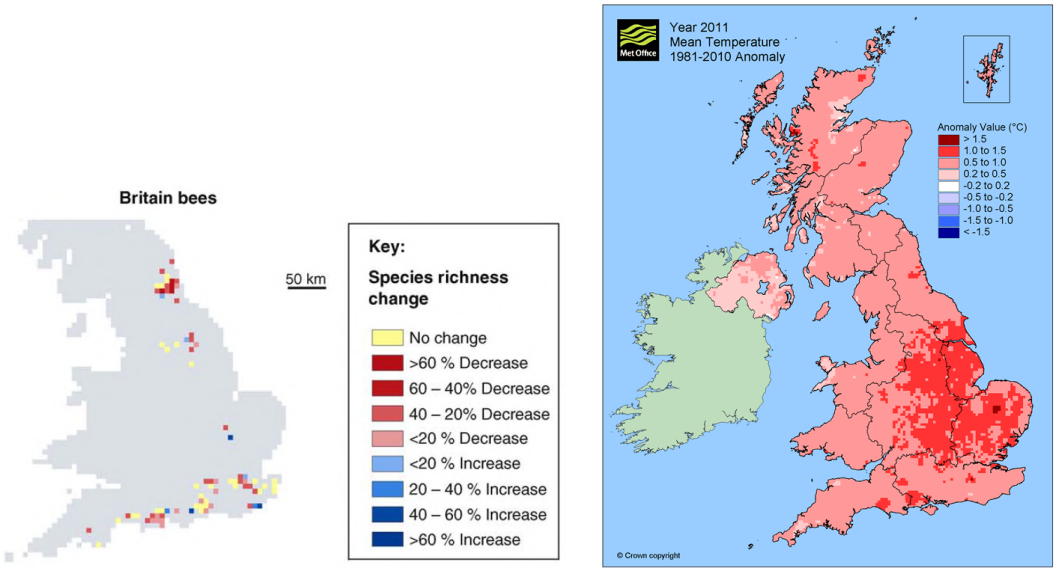


Figure 1.4: Distribution of species of the Apis genus. Reprinted from [7].

The measurement of temperature anomalies is often used in the study of the climate, and it is a simple method. The temperature anomaly is defined as the difference between the current year and an averaged reference period, which is considered to be normal. Figure 1.5(a) demonstrates that bee diversity has overwhelmingly decreased on the landscapes of the United Kingdom. Figure 1.5(b) depicts the anomaly values over the length of the United Kingdom in 2011, using the yearly mean temperatures between 1981 and 2010 as a reference. Both maps maintain a considerable degree of parallelism, which might imply a relationship between the rise in temperature in certain locations and the decline in the number of wild bee species. Although this is not conclusive and an in-depth investigation is needed taking into account other factors such as weather conditions.



(a) (b)

Figure 1.5: (a)Changes in species richness from 1980 to 2010 in 10×10 km grid cells for British bees. Grey cells indicate cells with insufficient data for analysis. Extracted from [9]. (b) Mean temperature anomaly in 2011 with 1981-2010 as reference. Reprinted from [10].

1.1.1 Importance of bees

It is often believed that bees are mainly beneficial for producing honey. The pollination of flowers, on the other hand, has the largest ecological influence on bees in the natural environment. For the whole of their lives, bees make around 10 visits every day, delivering pollen from the stamens to the receptive area of the flower. Fertilization and the growth of fruits and seeds, as well as the production of fruits, are accomplished in this manner. Plants and trees would cease to reproduce if this mechanism were not in place.

Many plants rely on the assistance of certain species of bees for their reproductive success. Because of this, commercial pollination in the agro-food business has started on a wide scale, which is a positive development. Because it does not

pollinate plants at random, the Apis mellifera is the most commercially important species on the planet. It is able to narrow its attention to pollinating a single plant species on each trip. A single bee has the ability to pollinate thousands of flowers every day [11]. Pollinators, mostly bees, are responsible for the production of 70% of the 124 major crops used for human consumption across the globe. In a similar vein, pollinators are directly responsible for pollinating 84 percent of the food cultivated in Europe [12]. The number of bee colonies that formerly existed in the United Kingdom has dropped dramatically, from 250,000 in the 1950s to just under 100,000 in 2015. (Figure 1.6). Only 2% of the total number of bee species found in the United Kingdom pollinate 80 percent of the crops grown there. As a result, the cultivation of fruit is adversely affected. For example, 45 percent of strawberry harvests need on bees to thrive, but other crops, such as apples, rely on bees to the tune of up to 85 percent to thrive. Only those two crops contributed £ 200 million to the British economy in 2012 [13]. The importance of bees has been recognised by the National Audit Office, which estimated their contribution to the economy of the United Kingdom. In 2007, it was estimated that the value of bee services was £ 200 million per year. What bees pollinate is worth more than £ 1 billion in retail profit, according to estimates [14]. They have raised their entire economic contribution by 191 percent since 1996, moving from £ 220 million in 1996 to £ 651 million in 2012 [13]. Bees have a significant influence on the environment, and this tendency is expected to continue in the future years.

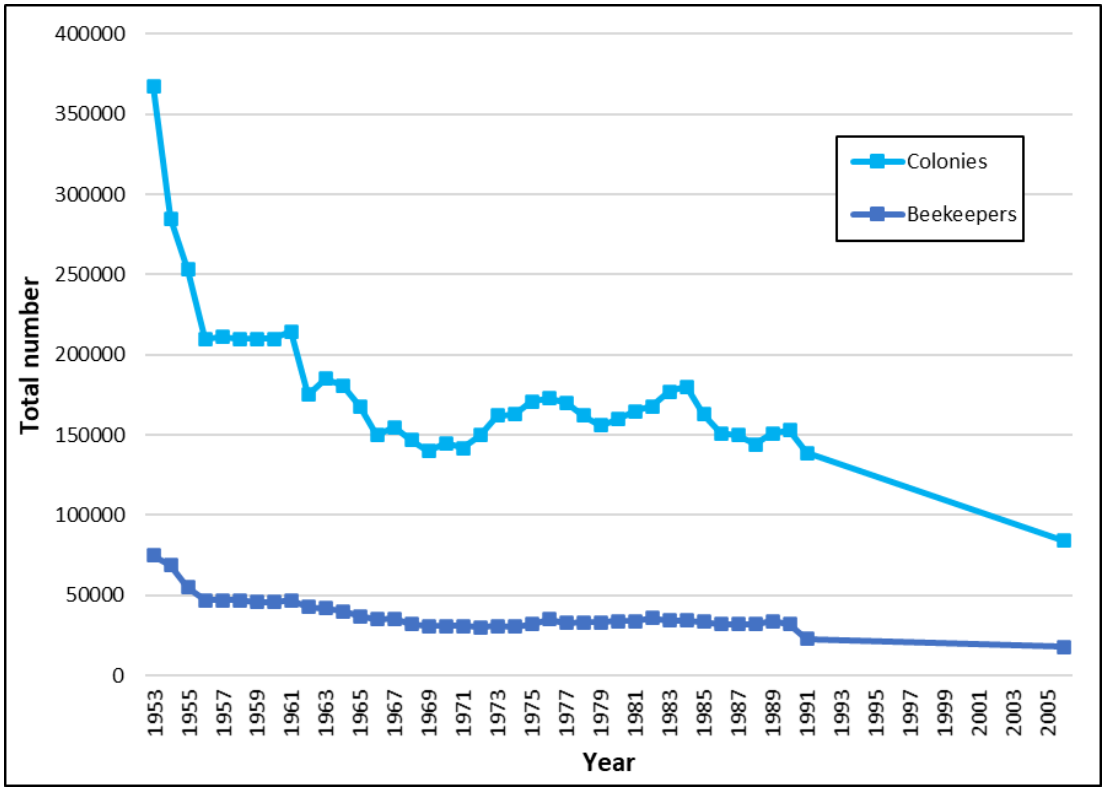


Figure 1.6: Total number of colonies and beekeepers in England 1953-2003. Reprinted from [15].

If it were the man who was in charge of pollinating flower to flower, then

the price of the products would rise to unsuspected limits. For example, these insects pollinate the sunflower, which is responsible for the production of oil. They also do the same with plants such as coffee, tea, and cocoa. Furthermore, their job is essential to the survival of the fodder that animals such as cows consume. Therefore, the situation that would unfold if the honeybees were to go extinct would be catastrophic. The significance of bees for human beings, as well as the urgent necessity to take action to prevent their unjustified and gradual extinction, are both well established. The paradox is that people continue to cultivate more crops that need bee pollination, while the precarious position that these insects are in is frequently overlooked.

1.1.2 Threats on bees

Despite extensive investigation into recent large-scale honeybee colony losses, no one factor has emerged as the definitive explanation of the phenomena.

Nowadays bees are exposed to a wide range of stresses and challenges. Most of the time, they had to deal with the natural obstacles that their environment presented, such as temperature, humidity, and predators. Pests and diseases, environmental stresses (e.g. starvation), and a lack of genetic variety and vitality are all possible direct drivers.

Natural hazards such as those outlined above are exacerbated by indirect drivers that also contribute to bee decline. In contrast to the preceding factors, this indirect drivers are the result of human activity. Industrial agriculture, parasites brought by humans, and climate change are all indirect factors. The volume and variety of flowers, as well as the cocktail of agrochemicals to which they are exposed, are decreasing as a result of these stresses in addition to the other drivers. Climate change is the most significant element impacting pollinator health, much more so than the other components combined [16]. On the other side, they are also at risk of contracting parasites that have been spread by human activity.

The bees are being stressed by a variety of factors, none of which are independent of the others. In Figure 1.7, a diagram depicts the many interactions between direct and indirect drivers and their effect on bee loss. While the list of possible causes is not new, the evidence for interacting effects is substantial and rising. These interactions are particularly concerning since the sub-lethal effects of one driver may increase the lethality of another driver. For example, a bee that has been exposed to pesticides due to industrial agriculture, may have altered immune system function, making it more vulnerable to parasite infection or to stronger weather conditions due to climate change [17].

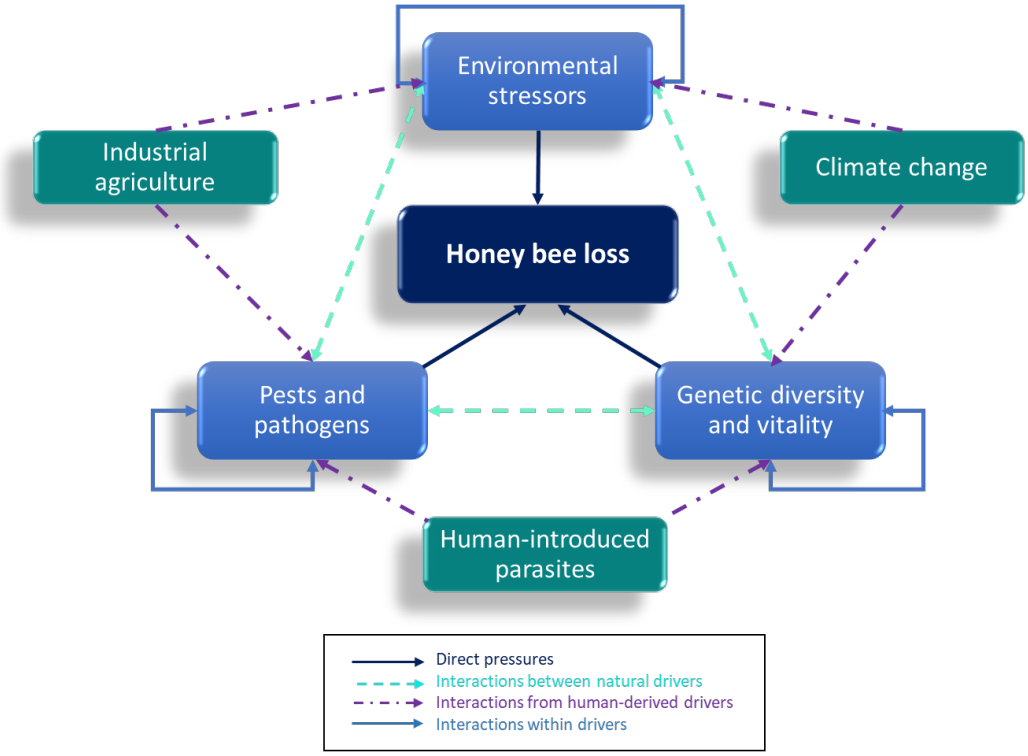


Figure 1.7: Interactions between the contributing drivers to honeybee loss.

1.1.2.1 Industrial agriculture

As large-scale agriculture has become more technologically advanced, monocultures have grown in number, fragmenting natural areas and diminishing biodiversity. All of the factors listed above, as well as activities such as pesticide and herbicide spraying, diminish the ability of bees to lay eggs, making industrial agriculture one of the most serious threats to pollinator populations [16]. As a result of interaction with pesticides, some honeybees become debilitated, making them more susceptible to illness and parasite infestation [16].

On the insecticides side, the neonicotinoids are those whose usage has increased more quickly in recent years due to the fact that they are employed to control a broad range of pests. At the same time, it has been discovered that these compounds have the potential to have negative impacts on pollinating insects [18].

1.1.2.2 Climate change

Temperature increases, changes in rainfall patterns, and more irregular and harsh weather patterns are all expected outcomes of climate change that will have a significant influence on pollinators in the coming years [16]. If this occurs, it is possible that crop pollination will be inefficient. The possibility that bees would emerge earlier in the growing season as a strong response to climate change, whereas their favoured flowers respond less strongly and bloom later, is concerning. This temporal phase-out might be harmful to both pollinators and plants, and it could have a negative impact on the yield of many crops [19]. This shift in phenology may also

occur in the other way, i.e., if spring begins earlier than usual, the flowers would blossom earlier than usual, and it is uncertain whether the bees will be able to keep up with that pace, which would have serious implications [20].

Extreme temperature fluctuations are also a concern, since severe temperatures are detrimental to bees' health. It is well known that bees manage the inside temperature within an optimal range between 33 and 36 degrees Celsius, regardless of the temperatures in the surrounding environment of their hive [21][22]. Thermoregulation is achieved by bees via a variety of heating and cooling actions. As a result, bees dedicate their efforts throughout the year, in addition to their usual activity, to maintaining freshness during the hot season and retaining heat during the winter [23]. In order to maintain the appropriate temperature, the bees regulate the interior temperature of the hive, and it is the collective activity of hundreds or thousands of bees that results in microclimate thermoregulation [21].

In [24] Almeida performed an experiment in which an increase in temperature resulted in swarms of bee colonies. It was discovered that when the outside temperature reached 41 degrees Celsius and the internal temperature reached 40 degrees Celsius, the bees gave up attempting to cool the hive and started to swarm. In this experiment, the colonies swarmed between 3 and 4 days, indicating that, although bees can withstand high temperatures for short periods of time, it is the persistent exposure to extreme heat that drives them to quit their hives [25]. The abandonment rate is raised as a result of climate change, which is caused by changes in weather and temperature. It is difficult for bees to adjust to new environments since the regions where they may live have been reduced [26]. Researchers in [27] contrasted pollinator activity between 1901 and 1974 with activity in the previous decades, during which the environment changed drastically. Bees in northern nations failed in their attempts to move closer to the North Pole due to climatic conditions, while many colonies in the southern hemisphere succumbed. Bees travelled around 200 miles in both Europe and North America during their migration. Numerous communities have perished on the southern end. Over the course of the century, bees have lost a total of almost 200 miles of range in both North America and Europe. The research, which looked at land use changes and pesticide use in addition to meteorological factors, concluded that climate change was to blame for the decrease [26].

Climate change seems to be contributing clearly and powerfully to the steady reduction of the ranges of pollinator species around the planet [27].

1.1.2.3 Parasites

In several southern European nations, parasites such as *Nosema ceranae* are extremely adverse to bees. However, it has been shown that the external parasite mite *Varroa destructor* is the greatest threat to worldwide apiculture in recent years [16]. The following chapter will delve deeper into this subject.

1.2 Research objective

The general objective of this research work is to reduce or eliminate the greatest danger to bees, Varroa mites, through the application of sustainable energy technologies such as phase change materials.

1.2.1 Secondary objectives

This project arises after having understood the great importance of the bees and knowing what their biggest obstacles are. Despite the fact that bees face similar challenges all over the globe and not only in the United Kingdom, this research focuses on local beekeeping and environmental circumstances.

It was investigated which temperatures affect bees and which ones affect Varroa, in order to know the target window. It was decided to use a phase change material (PCM) due to its new properties as an energy storage medium. Later, it was determined what PCM could achieve this temperature and how it might be encapsulated for use. Based on CFD simulations and laboratory tests, the manufactured prototypes were tested in three different apiaries.

Another objective of this project was to design a functional prototype that was simple enough for beekeepers to use. As it is a PCM, the prototype could be reusable, which by default would give it an advantage over other solutions available on the market.

Additionally, this research sought to demonstrate that the heat treatment is a non-harmful approach for bees and their products.

The current investigation explores the potential of phase change materials (PCMs), particularly Sodium Acetate Trihydrate (SAT), to be applied as a heat source for thermal treatment. The findings of this study will contribute to open a whole new niche for PCM applications. The simulations produced could help other studies interested in heat transfer within the beehive. The test results will serve as a reference in biological investigations about the use of thermotherapy. Additionally, this study will rise awareness about thermotherapy among beekeepers as an alternative to chemical treatments and will act as a source of information for companies interested in developing a sustainable product for the heat treatment of bees in order to eradicate the problem of Varroa mites by developing a product that is environmentally friendly, reusable, and sustainable.

1.3 Research innovative features

Despite the challenges of this project, one of the biggest impacts lies in its originality. This project features several aspects of uniqueness, among the most significant ones are the following.

- The prototype is one-of-a-kind: Stands out for being unlike anything else in the beekeeping sector. Heat treatment has been used in a variety of methods in the past, but never before like this.

- The use of a unique heat source: opposed to other thermal treatment methods in beekeeping, this approach does not involve electrical energy, chemical substances, or their application or reaction.

- The process is a physical, rather than chemical treatment and avoids problems of honey contamination. This also avoids exposing bees or their larvae to potentially dangerous compounds.

- On-site, non-invasive application: Most of beehives are located in remote areas. It is not easy to move a large number of bee frames/hives to another site to use thermal treatment and result in greater disturbance of bee activities. Our PCM pack does not require frames to be moved.

- The use of novel materials and development of techniques for their application: most notably an innovative use of the Sodium Acetate Trihydrate (SAT). It is a substance that is becoming more prevalent in common items such as hand warmers, but it is being employed in a field that is quite distinct from what is typically done.

- The treatment using a PCM pack is repeatable and works in most weather conditions because it does not depend on solar radiation. It can be applied at any day/night time and around the year.

- Retrofit application: Because the PCM pack is designed to be backward compatible with conventional commercial beehives, no changes or modifications to the beehives are necessary for usage.

- No additional energy source is required for the thermal treatment at the beehive: The heat released by PCM pack is sufficient. Therefore, no in-situ power supply is needed increasing its potential application in remote areas with no or limited access to power.

- The heat treatment is a simple and inexpensive method: Unlike solar powered thermal control methods, the temperature of the PCM pack can be easily controlled and it will not melt the honey and/or honeycomb wax.

- PCM packs are easily installed: As they are placed at the bottom of the beehive. It is an effective thermal treatment, as the heat rises and reaches all parts of the colony within the hive.

- It is not necessary to be aware of the extent of infestation: Thermal treatment can be used to rectify an infestation of Varroa in the hive, but it can also be used in the absence of mites without harming the bees. Anti-Varroa therapies are often administered on a regular basis.

- It can generate new ideas for future studies in a variety of disciplines: including but not limited to biology and renewable energy sources. For instance, there may be an analogous problem in another species besides bees that can be treated in a similar fashion.

1.4 Research methodology

A methodology that follows to the set of phases in the flow chart shown in Figure 1.8 was used to carry out this project. Generally speaking, action research was used to build this project. In action research, a type of applied research, the researcher aims to provide outcomes or a solution that is useful to the participants in the study while also advancing theoretical knowledge. By directly addressing issues, the researcher hopes to provide useful, frequently emancipatory results while simultaneously attempting to update pre-existing theory in the area under study.

The following is a description of the procedures used to generate this study.

1. Identification of the problem: The issue was discovered when a serious Varroa mite infestation was detected at a local apiary. As previously discussed in this chapter, this problem has become more prevalent in the UK.

2. Background research: The bibliographical research started at this point. It was discovered in the literature that it is feasible to apply heat until a temperature of between 40 and 47 degrees Celsius within the beehive for a period of 150 minutes in order to eradicate the Varroa mite without harming the bees or their brood. There were also some products available on the market that utilised the same thermal therapy or hyperthermia operating principle. At this stage, it was established that the aim of the study would be to use thermal therapy applied from a sustainable energy technology to eradicate or minimise the infection of Varroa mites in a beehive.

3. Hypothesis construction: The hypothesis was developed based on the research described above as well as the fact that this project was created within a working group that focuses on the study of sustainable energy technology, for which knowledge of the operation of phase change materials (PCMs) and some experience in their use was known. Therefore, the hypothesis formulated was that it may be feasible to employ a phase change material to efficiently heat treat bees in order to lessen or completely eradicate the Varroa mite parasite that infests beehives.

4. Simulation and mathematical modelling: The temperature exchanges within the beehive are the subject of the suggested mathematical simulation. This served as the foundation for a number of simulations that were created using the ANSYS software to be able to approximate how these thermal interactions would appear over the time necessary to administer the thermal treatment. Simulating requires mimicking a system's behaviour. In circumstances like this one, when it would ordinarily be challenging to address problems analytically, simulation is employed. It is challenging to develop a simulation sufficiently realistic such that it resembles actual events, just like with experimental research methods. In this instance, it was quite challenging to model and mimic the bees' presence.

5. Design of a prototype: This was done after more phase change material research was conducted to find the best one for usage with bees. It was also desired that it not harm bees and that it be enclosed in a packaging that was both durable enough to be reused and had enough thermal permeability to effectively comply with the treatment in addition to satisfying the thermal requirements listed

in the literature.

6. Tests in laboratory: Lab tests allow for the identification of exact correlations among a small number of variables that are thoroughly researched in a structured laboratory setting using quantitative analytical techniques in order to make generalisations that are applicable to real-world circumstances. Due to the simplicity of the experimental condition and the separation of such settings from the majority of the factors found in the real world, the main shortcoming of laboratory experiments is the limited extent to which identified associations exist in the real world.

After carrying out the first experiments, it was verified that the concept was proven, in other words, that the PCM could be activated and placed inside the beehive and that this would cause a temperature increase that was in or close to the range of the heat treatment (40 - 47 °C). This study featured a flexible design where the generated data were used as feedback to go back to the previous stages.

7. Data analysis: A code was created in the MatLab software to make the gathering, management, and interpretation of data easier. In these experiments, only quantitative analysis was used. The PCM's performance was evaluated by its temperature graph, and it was desired that it attain a surface temperature of 55 °C and maintain that temperature for at least 150 minutes.

Regarding the thermal treatment, it was mainly necessary to check the temperature increase curve in the beehive's centre to see if the PCM successfully heated it to the treatment's target temperature range and that it stayed there for 150 minutes.

At this stage, other options for the PCM container's materials and methods of enhancing its functionality were investigated, such as altering the solution's water content or thermal insulating the beehive.

8. Tests on-site: Field experiments take laboratory tests outside of the lab and into actual scenarios and real-world circumstances. This increases realism and reduces the likelihood that situations will be condemned as being manufactured. It was challenging to find apiaries and beekeepers that were willing to participate in experiments, and it was even more challenging to maintain enough control to allow for successful replication.

9. Analyse data and draw conclusions: These results underwent both quantitative and qualitative examination. The quantitative investigation was identical to the analysis carried out when viewing the temperature curves during laboratory experiments. The qualitative analysis was completed at the same time the therapy was administered. It involved observing how the bees responded and behaved in response to the heat created by the PCM within the beehive. The responsible beekeepers in each instance provided assistance with this observation.

After that, exploratory research was conducted, which entails examining a data collection and identifying probable relationships between variables in order to produce a posteriori hypotheses. In this approach, fresh ideas for lab tests were put forth while the prototype's design was also improved. This cycle was repeated as many times as possible.

10. Evaluate the application: Following the development of a prototype (PCM pack) that satisfied the necessary thermal performance requirements, an assess-

ment of the application was made by counting falling varroas. Unfortunately, even though 5 beehives were treated, they could not be followed up for the required amount of time since the bees' life cycles are tied to the seasons, therefore more time than was spent on this research would be required to provide an acceptable follow-up.

11. Communicate results: The most significant results were disseminated in various media such as papers, conferences, websites and especially this thesis.

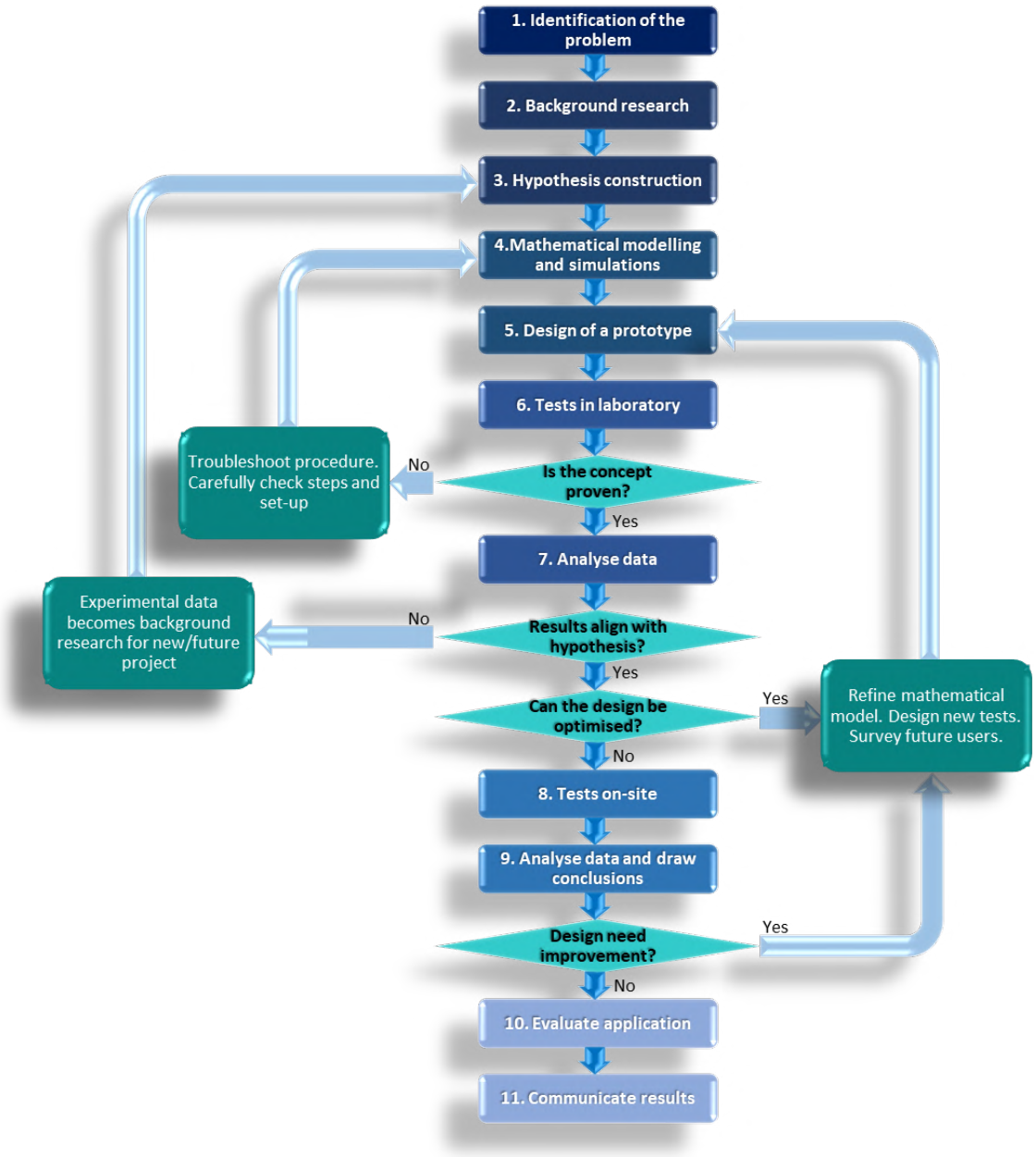


Figure 1.8: Research methodology flow diagram.

1.5 Structure of thesis

The first part of this thesis concentrates on giving a detailed literature review, since it is recognised that, due to the nature of this interdisciplinary project, a strong bibliographic foundation is required in order to comprehend the biological elements from an engineering perspective. A description of the many threats to bees is provided, as well as a reason for why the Varroa mite is the most dangerous of these. Furthermore, the method by which the epidemic spreads is outlined, and recent remedies to this issue are discussed.

Later in this thesis, the mathematical modelling is shown, along with some simulations that served as a basis for developing the prototypes, and the suggested solution is defined, the material selection criteria are presented. Additionally, considerations for the design and fabrication of prototypes are discussed.

Finally, a synopsis of the tests conducted in the laboratory and at the apiaries is presented, as well as an explanation of the testing methodology used. The most outstanding results are also displayed and analyzed.

Chapter 2

Literature background

This chapter covers the fundamental information about bees. It describes their beehives in detail, emphasising those that were created by humans. The Varroa mite's life cycle and mode of attack are then described. Finally, a description of the many thermotherapy-based devices that have been produced to date follows.

2.1 Beehives background

A beehive is any cavity that contains a bee colony. In nature these appear as holes in rocks, hollow trees, etc [28]. These hives are created by a swarm of worker bees.

Which choose a suitable cavity that allows them to construct interiors suspended over the bottom. They maintain a gap of around 3/8" in the inside of the honeycomb throughout construction, which is referred to as "bee-space". Bees will always attempt to construct in a way that large regions are reduced to bee space.

The combs may be used for cooling or heating purposes. They are made up of hundreds of cells, typically hexagonal. Bees store honey and pollen in these cells and also use them to incubate their larvae. As seen in Figure 2.1, the distribution of these components is well defined. In both wild and commercial hives, brood cells are positioned at the bottom of the combs, near the beehive entrance. The nectar is stored at the top of the hive, and when the liquid component evaporates to become honey, the storage cells are sealed with wax and the next row of cells is filled, spreading the band of ripened honey downward. Pollen stores are far less abundant than honey stores and are often deposited in clusters of cells between the brood and honey areas.

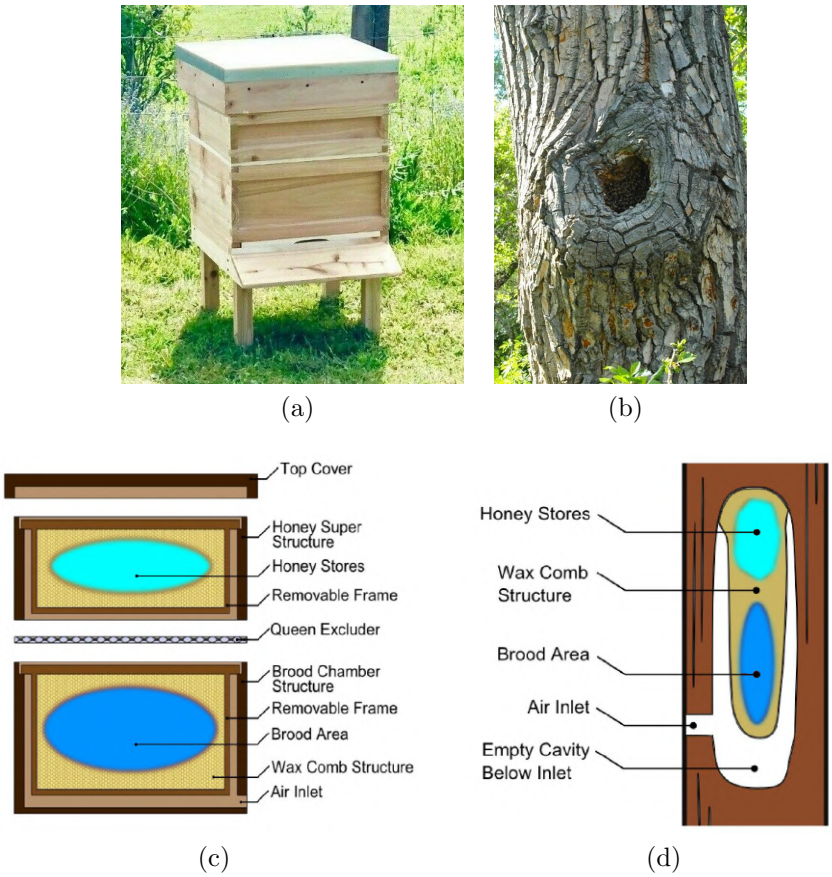


Figure 2.1: (a)Commercial beehive. (b)Tree containing a natural beehive. (c)Cross-section of commercial beehive. (d)Cross-section of natural beehive.

2.1.1 Natural beehives

Honeybees are very selective about their nesting places, according to research. Honeybees prefer hollow tree holes with a single entrance at the bottom [29]. Numerous aspects distinguish the normal natural nest from the commercial standard. For instance, the natural nest profile is elongated vertically and has a circular cross-section. Honeybees begin building wax combs at the top of their nest when they establish a new nest location. To prepare the chamber, bees file off any rough or rotting surfaces, exposing clean, solid material appropriate for comb attachment [29]. Similar modifications are made at the hive entrance, where bees file away rough surfaces that line the inlet tunnel and apply smoothed propolis. The intake tunnel is estimated to be on average 15 cm deep before it joins the cavity, and the entry diameter varies between 20 and 40 cm [29]. While entrance positions vary considerably, feral colonies seem to prefer holes with a single hive entrance. With a single entrance, displacement ventilation is avoided, and honeybees can exert more control over the environment and are less vulnerable to predators or other external threats.

2.1.2 Man-made beehives

Since man has developed beekeeping for the purpose of obtaining honey, a vast number of man-made beehives have been manufactured. They replicate the structure and environment of a natural beehive and in most cases, provide the optimum conditions for the production of honey bees. These hives are harvested several times a year by the beekeeper, the person in charge of managing the hive. The beekeeper is also responsible for monitoring the bees and making sure that they are in good health otherwise the product will not be useful [30].

A typical artificial beehive has mobile frames inside where bees should only remain. The frames make control and manipulation simpler, it also facilitates the detection of pests and threats to bees.

The worker bees are very important for the operation of the hive, they take care of the queen and the newborn ones. They make constant excursions to the beehive to collect nectar and pollen. They also help to keep the hive clean, to make honey production the best and even to regulate the temperature of the beehive when necessary. A type of worker bee is in charge of protecting all the members of the colony and making sure there is enough water [30].

There is a great variety of designs for these structures. However, commercially in the world dominate the Langstroth, Smith, Dadant, Commercial, WBC and National, the latter being the most popular in the United Kingdom. In beekeeping centres, the same model is usually used in all beehives to facilitate maintenance and exchange of parts [28]. The British standard appeared in 1946 after a committee composed of different British, Scottish and Welsh associations of beekeepers. The specifications of the National Standard beehive, which is a modification of the Langstroth model, were then defined [31]. In the following section its components are described.

In the last 50 years there has been a decrease in the number of wild bee species in the United Kingdom. However, the honeybee population in farm environments has increased, particularly recovering in number due to the scourge that caused the appearance of *Varroa mite* in 1992 [32]. According to statistical censuses, in 2017 a population of approximately 247,000 honey bee beehives was calculated in the United Kingdom [33]. According to Sustain website[34], 44,000 amateur beekeepers handle the majority of the beehives and 200 beekeepers from the association of bee farmers handle around 40,000 colonies, the rest is divided among smaller producers.

2.1.3 Types of commercial beehives

The National beehive is a standard form of the Langstroth type. It is a beehive formed by boxes stacked, with frames inside hanging vertically. The lower box is for the queen to deposit eggs and their develop. The top boxes is where honey can be stored. At the base, an entrance for the bees and at the top a roof to protect them against the weather. All these components are modular and can be easily disassembled and interchanged [35].

The interior frames make it easier for bees to build honeycombs. Its design allows the beekeeper to handle the bees and prevent them from adhering to the

combs of adjacent frames. The key to this design is to respect the "bee space", a gap of 6-9 mm where bees can transit but not build honeycombs [35].

Table 2.1 shows a comparison of the most popular models in the United Kingdom: National (in 3 variants), Commercial and WBC.

Table 2.1: Comparison of the most common beehives in UK [36, 37].

	National Single Brood Box	*National "Brood And A Half"*	*National Double Brood Box*	*Commercial*	*WBC*
Exploded view					
Roof	Flat	Flat	Flat	Flat	Gabled
Housing	Single walled	Single walled	Single walled	Single walled	Double walled
Cells in brood box	50,000	75,000	100,000	75,000	45,000
Interchangeable hive parts	Yes	Yes	Yes	Yes	No
Interchangeable frames	Yes (WBC compatible)	Yes (WBC compatible)	Yes (WBC compatible)	No	Yes (National compatible)
Pros	Single brood chamber. Most popular hive in the UK	Flexible system	Flexible system	Single large brood chamber. Same external dimensions as a National hive. National supers on top can be used.	Has double insulation. Deep brood box. Gabled roof.
Cons	Brood chamber not big enough hence increased possibility of swarming.	Two brood boxes to inspect, two sizes of frames (due to different sized brood boxes)	Two brood boxes to inspect, top brood box is heavy.	Heavy. Small hand holds.	Brood box too small, so is not very practical to remove the extra layer before the hive can be examined

2.1.4 Design overview of the National Standard beehive

In general, the National Beehive's design can be divided into three main sections. In the lower section is the base that holds the boxes, a table that serves as the bottom of the hive and a slot for bees to enter and exit. The National Beehive can be easily distinguished from other models by the type of entry. In the middle section are the boxes that contain the frames where the honey is deposited, the propolis and pollen. In the lower boxes are the brood. Inside all these boxes is where the bees are. This section is the one that increases if the beekeeper considers that more space is needed for the beehive to expand. Finally, there is the upper section that consists of a board that covers the top box and an outer cap that works as a roof for the entire structure[35], In the Figure 2.2 the different components of a national beehive are shown.

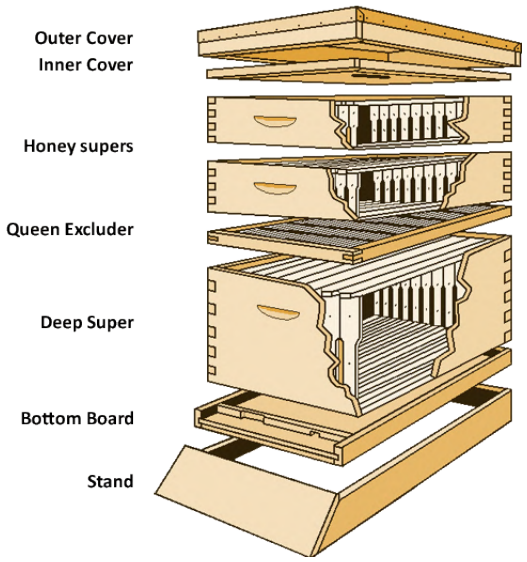
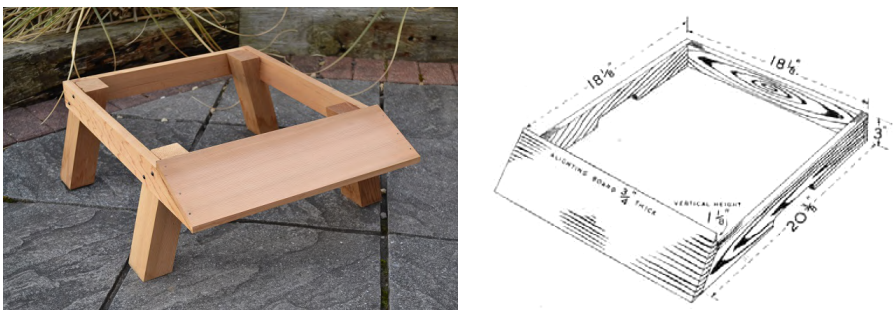


Figure 2.2: Assembly of the National Beehive [38].

2.1.4.1 Stand

The stand is a support over which are the other components of the beehive. It usually has a landing ramp for bees. Its function is to keep the beehive separate from the ground and can favor the comfort of the beekeeper. It is usually a simple wooden structure. In the national beehive a stand is suggested as shown in the Figure 2.3.

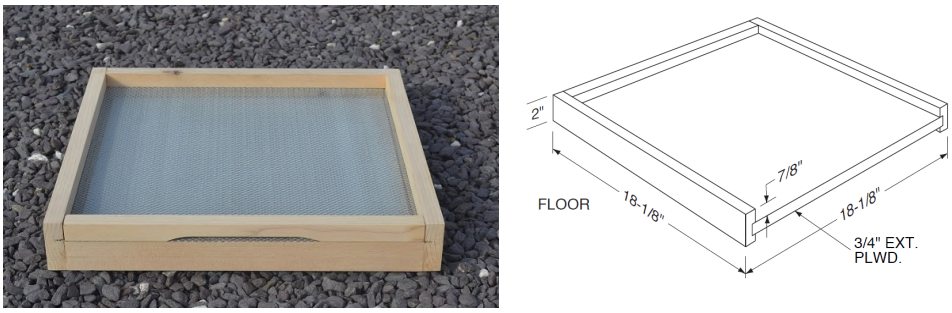


(a) (b)

Figure 2.3: (a)Picture of a National beehive stand [39]. (b)National beehive stand specifications [40].

2.1.4.2 Botton board / Floor

This is the piece that rests on the stand and supports the entire weight of the hive. It can be of two types: solid or screened [41]. The latter comes with an adhesive insert that serves beekeepers for pest management, for example counting dead Varroa mites, which fall to the bottom. Figure 2.4 shows a photograph and its suggested measurements.

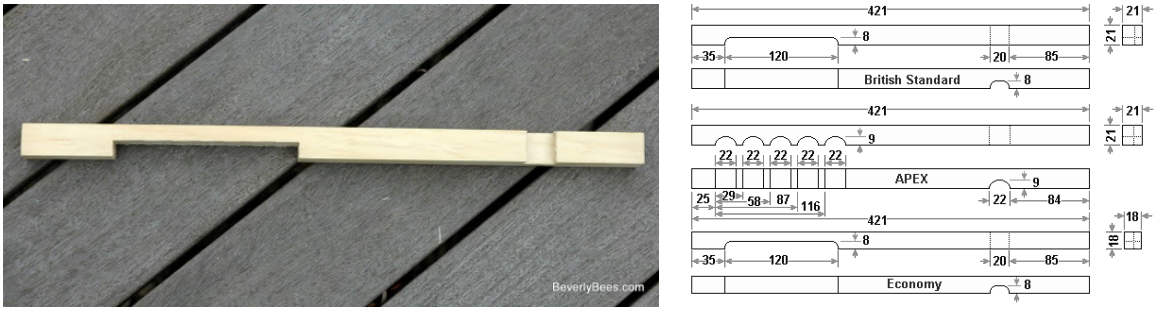


(a) (b)

Figure 2.4: (a)Picture of a National beehive bottom board with entrance reducer [42]. (b)National beehive bottom board specifications [43].

Entrance Reducer / Entrance Block

This is a small wooden bar that fits over the bottom table and under the box above. This piece prevents intruders or predators from accessing. In Figure 2.5 this piece is shown.



(a) (b)

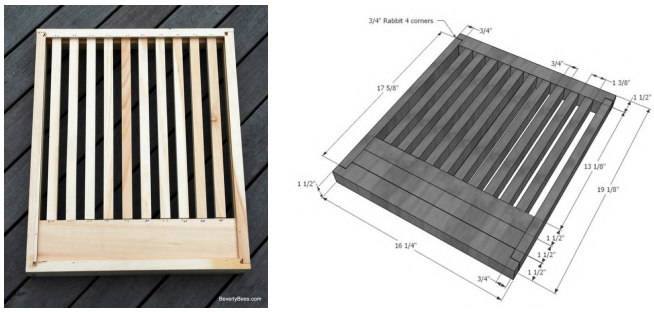
Figure 2.5: (a)Picture of a National beehive entrance reducer [41]. (b)Different entrance reducers specifications [44].

2.1.4.3 Slatted Rack

This piece is mounted on the entrance and under the breeding chamber. Its use is optional. It gives an extra space to the bees, which favors the entry of fresh air. As the brood are protected from incoming winds, the queen will tend to deposit her eggs to the bottom of the frame more frequently than she would do without this piece [41]. In Figure 2.6 this piece is described.

2.1.4.4 Brood chamber / Deep Super

This piece is placed on top of the previous ones. It is a large box where 10 frames hang inside on which the bees build wax. The modular design of the National Beehive allows to place more than a single deep super. This could represent an



(a) (b)

Figure 2.6: (a)Picture of a National beehive slatted rack [41]. (b)National beehive slatted rack specifications [45].

increase in honey production if the beehive allows it [35]. Different sizes of super can be mixed, but regularly the brood box is the deepest. Figure 2.7 shows the empty super, the frames and its dimensions.

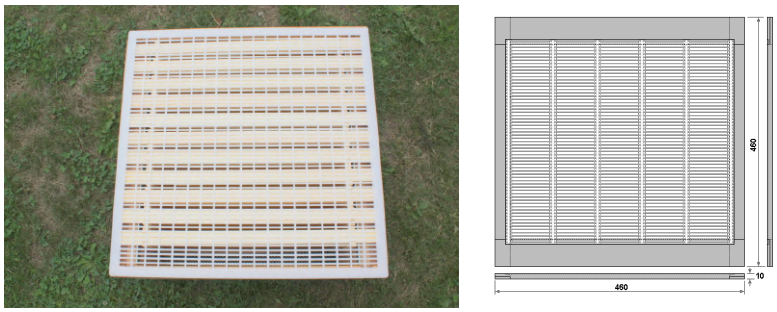


(a) (b) (c)

Figure 2.7: (a)Picture of a National beehive Brood box [46]. (b)Picture of a National beehive Brood box with frames [47]. (c)National beehive brood chamber specifications [43].

2.1.4.5 Queen excluder

This piece is optional, it is a mesh that divides the boxes and it is used to prevent the passage of the queen bee. Its function is to block the queen from laying eggs in the honey super. Figure 2.8 shows a photograph and its suggested measurements.

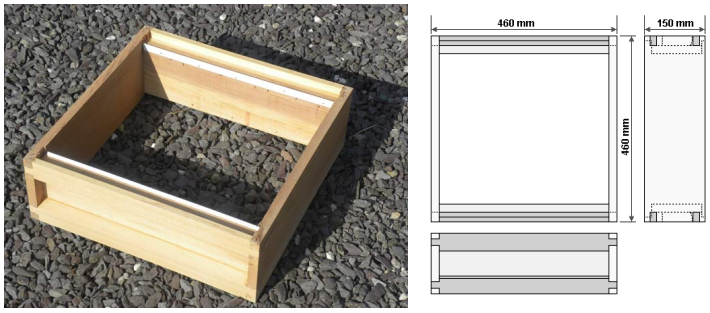


(a) (b)

Figure 2.8: (a)Picture of a National beehive queen excluder [47]. (b)National beehive queen excluder specifications [48].

2.1.4.6 Shallow / Honey Super

This piece is mounted on the previous ones, it contains the frames where the bees deposit their honey. Like the brood chamber this super contains frames but they are less deep since honey can be heavy for the frames [41]. The frames contained in this super are where honey is extracted by beekeepers. As many supers of this type can be stacked as the beekeeper deems necessary. There are variations of this piece with various depths. In Figure 2.9 this piece is showed.

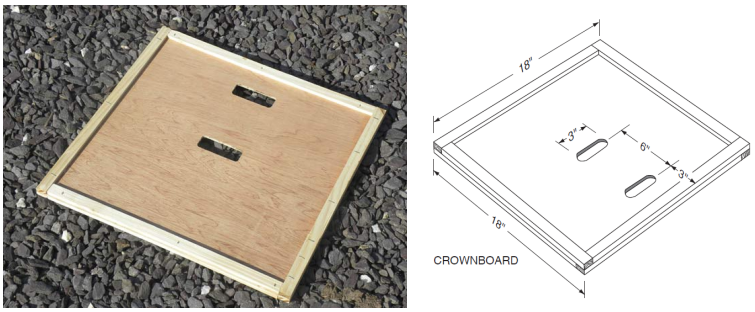


(a) (b)

Figure 2.9: (a)Picture of a National beehive honey super [49]. (b)National beehive honey super specifications [50].

2.1.4.7 Inner cover / Crownboard

This piece is a wooden cover that protects the top super. It has a pair of holes, one in the middle and another one as entrance to the outside. This cover is of utmost importance for the proper handling of the hive. One side is used for winter and the other for the rest of the year [41]. The details of this piece are shown in Figure 2.10.

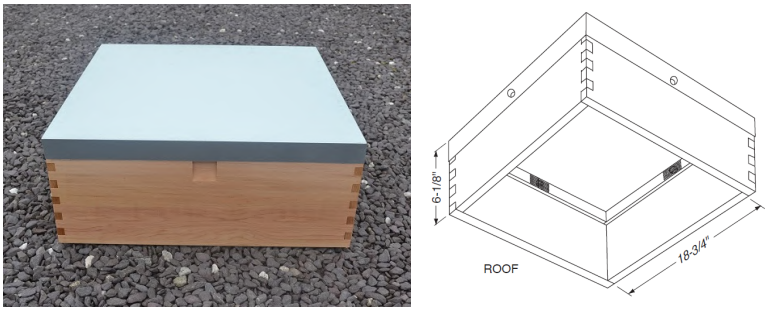


(a) (b)

Figure 2.10: (a)Picture of a National beehive crownboard [51]. (b)National beehive crownboard specifications [43].

2.1.4.8 Outer cover / Roof

There are several types of outer cover. The standard of the National beehive consists of a telescopic type roof, it means that covers the crown board with protruding sides. A variation of this is lined with a galvanized metal plate to provide greater protection against the weather. The details of this piece are shown in Figure 2.11.



(a) (b)

Figure 2.11: (a)Picture of a National beehive roof [52]. (b)National beehive roof specifications [43].

2.2 Impact of climate change on bees

Climate is described as the interplay of several terrestrial variables, including the land surface, bodies of water, the atmosphere, and the biosphere. Generally, we refer to weather only in terms of its atmospheric component. Typically, the weather is described in terms of temperature, wind, and precipitation throughout a particular time period [53]. However, in order to quantify climate change, a variety of distinct factors must be analysed, including the following:

- *Temperature* This is the most straightforward to quantify or infer. As previously stated, it has a significant effect on bees.

- *Precipitation* Provides data on relative climatic fluctuation. With regard to bees, the quantity and quality of water, and especially the level of relative humidity is very important [54].

- *Chemical composition of air* Greenhouse gas concentrations are a widely accepted indicator for interpreting climate change. Bees are highly sensitive and responsive particularly to environments with high carbon dioxide content [55].

- Biomass Vegetation patterns indicate how an ecosystem is being affected by climate. It is this factor that enters the study of bees.

Other parameters to measure climate change that have less direct impact on bees are, for example, volcanic activity, solar radiation and sea level.

The temperature has a significant effect not only on bee mortality, but also on their surroundings, notably on vegetation, which is critical for the honey bee's foraging season and colony growth [56].

Global warming is a threat to every aspect of the environment. Thus, another industry that has been impacted by temperature increases is beekeeping.

The fact that summers are drier, winters are wetter, and atmospheric events occur outside of the typical dates contributes to the fact that the blooming cycle and the bee cycle do not meet, preventing pollination. Climate change may influence the quality of the surrounding vegetation, hence affecting the colony's harvesting capability. Climate change has the potential to accelerate the spread of new invasive species. Additionally, it has the potential to redefine bee range and drive them into new regions where they may compete with other species or come into touch with new parasites and illnesses. Another effect of this would be seen in beekeeping, where beekeepers would be obliged to adapt their techniques and locations for apiaries; they may even choose to import foreign races to demonstrate their value in new environments [7].

Through studies conducted by researchers, based on interviews with beekeepers, it has been concluded that the main impacts of climate change on bees are:

- Higher mortality at local level due to extreme weather events.

- Increased virulence of pathogens such as Varroa, decoupling and variability of pollinators and pollinating cycles.

- Less flowering and with a considerable decrease in pollen quality and the appearance of new invasive and more aggressive exotic species (e.g., Asian wasp).

- Decoupling between the life cycle of bees and flowering. The flowering period is increasingly shorter, it is advanced and works with less intensity.

- Finally, a lower availability of water that affects bee populations.

Although it is currently impossible to measure the effect of climate change on bees with precision, we do know that the implications of climate change will affect

bee behaviour and development. Climate change has the potential to limit the lifetime of bees in three ways: oxidative stress, heat stress, and starvation [57]. For instance, in a climate with increased rainfall, flowers such as acacia become unattractive to bees due to the nectar being diluted. Similarly, when conditions get drier, flowers such as lavender cease nectar production. In such instances, the bees' status is jeopardised, and they may perish from malnutrition [7].

Flores [58] undertook a two-year experiment in which the quantity of pollen reserves is evaluated and compared by season. It was discovered that there was a significant decline in the second year, which was ascribed to the blossoms being drastically shortened. In [59], detailed observations of bees exposed to harsh weather circumstances resulted in perilous blossoming in their surroundings are discussed. It was concluded that the flowers that survived the extreme climate were not a sufficient nutrient source for the bees and caused decrease in the body mass of the adult bees and a low proliferation of larvae.

Numerous research and publications demonstrate that climate change has aided in the reduction of bee populations globally. In Pakistan, for example, export honey production has decreased by up to 50% owing to non-seasonal rainfall, hailstorms, deforestation, and pollution, which are the primary causes affecting the output, which exceeds 40,000 tonnes [60].

Another example is Greece, where Bacandritsos [61] investigated the likely reasons of huge losses in bee populations in the Peloponnese area in 2009. Concluding that, among other factors, this drop was mainly caused by abrupt changes in temperature and humidity.

In Benin, beekeepers have had to adjust to increasingly adverse circumstances brought about by climate change. Most of the adaptation strategies lead to more destruction of wild colonies to compensate the economic shortfall because of the reduction of honey production which is one of the consequences of climate change [62].

In general, extreme temperatures and unfavorable conditions cause high levels of oxidative stress to bees. Heat stress disrupts the bees' redox metabolism, resulting in oxidative stress. This implies that heat stress is detrimental to bees and may be the primary source of oxidative stress [63]. At the molecular level, oxidative stressors are connected. They produce premature ageing signs in bees and may limit their life span. It has been discovered that over generations, it is possible to develop a better tolerance for certain oxidative stresses. However, a sudden appearance of these stressors is relentless for individuals, although susceptibility varies from individual to individual [63].

2.3 Temperature influence on honeybees

Temperature is an essential factor for the sustenance of animal life. It is involved in most biochemical and physiological processes. Examples of these processes are respiration and metabolism, where temperature determines the possible relationships between a living being and its environment. In the case of insects, there are countless studies focused on describing the influence of the temperature of their habitat on them.

Although a significant reduction in the population of bees in our environment may seem like a minor event, it would lead to a series of powerful negative effects, magnitude and importance. Of course, this affects beekeepers who are dedicated to the production derived from honey bees, but also agriculture would suffer a large number of alterations and problems in most crops, resulting in huge economic losses for rural people and a very important price increase in consumers.

The decrease in honeybee populations due to extreme climate changes would strongly affect the ecosystems and the environment, with the consequent deterioration of both animal and plant life and with a high probability of a total alteration of the balance of that natural environment. This could cause its collapse and imbalance, with the consequent disappearance of numerous species, the total destruction of large areas and possible worldwide famine.

Table 2.2 shows a summary of some of the critical temperatures for bees.

Table 2.2: Bee temperature table.

Temperature [°C]	*Effect on bees*
50	Lethal temperature
>38	Bees thermoregulate the beehive
35-37	Young bees preferred environments
31-36	Old bees preferred environments
15-18	Ambient temperature where cluster disperses
15	Ambient temperature where bees cluster
11-12	Bees loose mobility
9	Chill coma in prolonged exposure
6-7	Body rigidity

2.3.1 Thermoregulation (homeostasis)

With respect to the honey bee (Apis mellifera), it is well established that temperature control inside their nests is critical. Bees have receptors in their antennae that are capable of monitoring temperature fluctuations of 0.2 degrees Celsius [64].

Unlike many other animals, bees lack a temperature-regulating mechanism in their bodies. To defend against ambient thermal threats, bees may use a variety of thermal regulation methods. Some of these methods can be carried out individually, however as a species that develops in an organized group, bees rely on each other to regulate nest temperatures.

A high temperature shortens the larval phase and lowers defective brood. Generally, queens mate at temperatures below 25 degrees Celsius. Extremely high (or extremely low) temperatures have a detrimental effect on mating flights [64]. The brood region requires a temperature of between 30 and 36 degrees Celsius to produce the brood. According to [65], juvenile bees like temperatures between 35 and 37 degrees Celsius, whereas adult bees prefer temperatures between 31.5 and 36.5 degrees Celsius. When removed from the colony, bees are endothermic during moments of motor activity and ectothermic during periods of inactivity. When they are a member of a colony, they work together to keep the temperature almost constant throughout the year. They are capable of sustaining activity at ambient

temperatures ranging from 7 to 46 degrees Celsius in a variety of locales ranging from tundras to deserts [66].

Regardless of the temperature, bees will not fly if there is no light [67]. During the night, the bees remain dormant outside the hive, even if there is sufficient moonlight [64].

Honeybees are more aggressive at severe hot and low temperatures. At low temperatures, they save their honey supplies; at hot temperatures, they defend their young from predators.

2.3.1.1 Low temperature regulation

Bees are more susceptible to difficulties with lower temperatures, since their freezing temperature can be easily found in most cold weathers (Figure 2.12). Bees' muscles are effectively paralysed by freezing temperatures. Normally, exposure to cold temperatures results in mortality. Freezing temperatures can also have an effect on the nectar's viscosity. Even if the bees are able to travel in freezing conditions, the nectar from the blossoms may be too dense for them to gather, or the flowers may close due to the weather. In the autumn, workers expel drones from the hive, since they provide no useful services and instead waste resources. Brood production is also lowered for the same reasons.

Winter bees have a life expectancy of months, compared to the 6 weeks or so that typical worker bees have throughout the other seasons.

Switanek's research [56], revealed that bee colony mortality is highest in winter in Austria, when the preceding months are drier and warmer. Particularly in February, mortality is high as a result of the cold. This month is critical for bees because, in addition to the low temperatures, it is often the time when bees are breeding and there are again resources for the foragers.

The mortality of bees related to winter can be attributed to different factors and the interactions between them. Some of these causes, in addition to low temperatures, include nest management, pesticide usage, and habitat degradation.



Figure 2.12: Frozen bee.

According to [65], bees lose movement between 11 and 12 degrees Celsius and become stiff between 6-7 degrees Celsius. They may enter a cold coma if the exposure is extended and the temperature is between 9 and 12 degrees Celsius.

An analysis conducted by [67], showed that the most critical factors influencing the start of the honey bee's flight are temperature and sun radiation. This research demonstrates that bees cannot fly if the temperature does not reach 9 degrees Celsius, regardless of the amount of light [67].

The thorax of bees is critical for temperature control due to its body shape. Flying muscles generate a lot of heat, which is why they are the primary thermal source for bees. Heat created by the lengthy flight muscles of the bird must be dispersed in the brood chamber [68]. The bee's thorax is coated with tiny hairs that help them retain heat in their bodies, among other functions.

Bees consume honey reserves in cold conditions, such as winter, to raise the temperature within the beehive. When the ambient temperature is reduced from 28 to 17 degrees Celsius, the metabolic rate of the colony rises from 7 to 19 watts/kg [68]. Its high metabolic activity requires an adequate exchange of respiration gases for individuals, particularly those at the colony's core [69].

The methods by which bees combat the low temperatures are explained below.

Heater bees Using temperature-sensitive film, it was discovered that some bees can boost their body temperatures around 10 degrees Celsius higher than typical bees by fast muscular contractions. The thorax of each of these bees is then pressed against the top of a growing capped pupa, keeping it warm. After warming their abdomens, some of these bees walk headfirst into isolated vacant cells located in brood nests, where they stay for around 30 minutes, or until their bodies return to normal temperature. A heater bee nestled inside one of the vacant cells distributes heat more efficiently to the growing pupae [70].

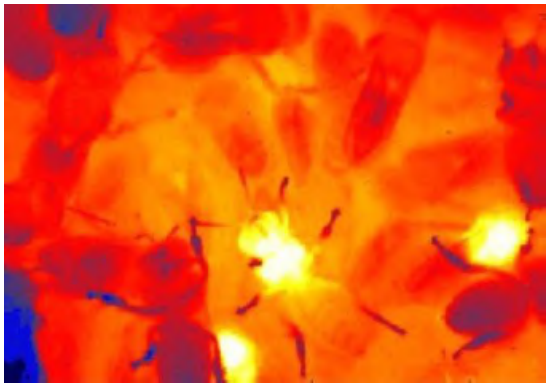


Figure 2.13: Heater bee captured by thermal camera.

Clustering Unlike other insects, bees do not hibernate throughout the winter and are not tolerant to frigid temperatures. When the temperature outside the nest falls below 15-18 degrees Celsius, the bees cluster together within the beehive to maintain a constant temperature. To live, they must maintain a temperature of around 35 degrees Celsius in the brood zone's core. As the temperature cools, the bees cluster tightly together on the nest's combs. The queen and brood are located in the cluster's centre, which is the hottest part. A group of at least 2000 bees is necessary to survive in freezing temperatures [71]. Worker bees will alternate

between the outside and inner layers of the cluster, and most likely return to the outer layer, in a continual cycle until temperatures increase again.

Even if food is available in a remote section of the hive or on another frame, the temperature may be too low for the bees to leave the cluster and reach it. This results in starvation and death.

The bee cluster disperses when the temperature exceeds 15 degrees Celsius [71]. Low temperatures kill bees in small groups (1500 bees), whereas big groups (16,000 bees) can endure temperatures as low as -80 degrees Celsius for at least 12 hours [71].



Figure 2.14: Thermal image of a cluster inside a beehive.

As a result of excessive cold, the bee cluster compresses in size and becomes abnormally dense, suffocating a large number of bees [72]. Under cold weather and cluster circumstances, unventilated water vapour generated during honey absorption condenses and sometimes freezes on the chilly internal surfaces of the beehive and frames with comb. Without an appropriate supply of oxygen, the bees will be unable to absorb the honey and will perish due to high carbon dioxide concentrations [73].

2.3.1.2 High temperature regulation

According to Free [74], bees cannot endure temperatures beyond 50 degrees Celsius. The brood is prone to overheating when the ambient temperature surpasses 36 degrees Celsius [64]. Domestic bees have been shown to be less resistant to extreme temperatures than wild bees [64]. Bees that are older are more vulnerable to hot temperatures [57].

Bees are impacted in a variety of ways during heat waves. One of them is that the severe heat dries off the flowers, discouraging bees from leaving their colonies, resulting in little honey output. A shortage of nectar-producing flowers is called a nectar dearth. During this, the bees are unable to locate nectar, so they attempt to steal it from other colonies. This begins the violent action referred to as robbing.

Cooper [75] discovered that bees can fly at very high temperatures by regurgitating droplets from their honey stomach that would evaporate later, boosting the

rate of heat loss and preventing the body temperature from rising [66]. On the other hand, it has been shown that bees may enhance hemolymph flow from the thorax to the abdomen, despite the latter's lack of heat insulation. This creates a cooling effect by using the abdomen as a heat exchanger. This effect has been examined mostly in bumblebees because it is not as effective in honey bees [66]. In adult bees, heat shock protein induction is initiated in order to withstand the assault of a heat wave. The higher the temperature, the more heat shock protein is produced [64]. The presence of these proteins alters the vascular system of bees.

In [76], a research is conducted on the metabolism and thermal limitations of two Apis mellifera races (*lingusitica* and *carnica*) that inhabit two climatically distinct locations (see Figure 1.3). Following a series of trials, it is shown that temperatures slightly above 50 degrees Celsius have no discernible effect on bee mortality in less than four hours. Following that time, it was determined that the deadly temperature for Carnica bees was 50.3 degrees Celsius and for Ligustica bees was 51.7 degrees Celsius. This research demonstrates the evolutionary mechanism through which bees have adapted their physiology and behaviour in response to exposure to severe short-term temperatures. These modifications play a vital role in bee dispersal. Certain Apis mellifera subspecies, such as *Apis mellifera jemetica*, can withstand temperatures of up to 68 degrees Celsius [64].

In hot conditions, bees attempt to cool the beehive to 35 degrees Celsius by fanning their wings, transporting water and evaporating it to cool the nest, or even partially swarming to cool the surroundings. Water consumption is increased in hot weather, either as a result of dehydration or as a way of cooling the hive. In periods of extreme heat, a colony of 10,000 bees may require around 5 litres of water every day. Another disadvantage of heat waves in desert areas is the absence of rainfall, which makes finding water sources difficult for bees [77].

All efforts to regulate the temperature, separate the bees from their common labors. Naturally, this might result in less pollen and nectar collection, which will likely result in decreased honey production [78]. These are strenuous physical activities that need considerable metabolic energy and water to be effective. For example, beating their wings excessively to ventilate the hive might result in severe stress, shortening their life span by up to two weeks.

Shielding Apart from the several functions performed by worker bees, fewer than half of this caste "work". The remainder are often referred to as "unemployed," and they are responsible for maintaining the nest's status until they are qualified to become "employed." Starks [79] suggests that in times of extreme hot, jobless bees protect their brood combs, forming a barrier and absorbing excess heat.

Bearding It is a simple method of regulating the interior temperature of the hive. In particularly hot weather, when the interior temperature of the hive may reach dangerous levels and the hive population is large, bees find their way out and cluster in large numbers outside the hive, where they can escape the heat and stay cool. Honeybees do this primarily to prevent the inside of the hive from overheating and harming the brood, as well as to assist in temperature regulation

of the brood nest.



Figure 2.15: Bearding bees.

Fanning This procedure involves refreshing the interior of the beehive by the organized movement of the bees' wings (Figure 2.16). As the name indicates, certain bees point their fanning wings toward the beehive's entrance, increasing the flow of air inwards and creating air exchange at rates of up to 60 l/min [71]. In this way, they keep the brood's temperature steady by blowing fresh air and vacating space inside the nest. In natural (non-man-made) beehives, bees use propolis to seal up all secondary openings, leaving just one for ventilation. When there is at least one single air intake, fanning is not feasible, since fanning involves exchanging fresh air for stale air through a net outlet [69].

This behavior also regulates the temperature, the breathing gases and the humidity to a certain limit. Bees' antennae have carbon dioxide sensors. When carbon dioxide levels are elevated, independent of oxygen levels, these receptors are triggered, signalling the bees to ventilate [69].

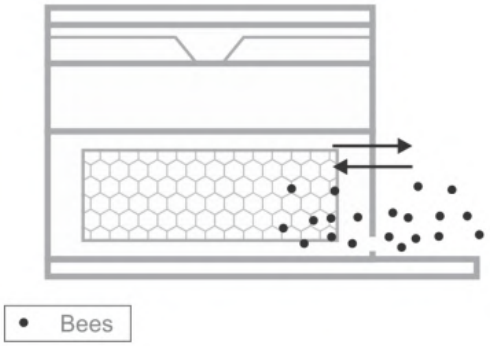


Figure 2.16: Fanning behavior. Extracted from [25].

Evaporation To avoid overheating, forager bees go to nearby water sources and gather drops in their honey stomachs. The water and diluted nectar droplets are deposited along the hive's perimeter and on the walls of egg and larval cells. Cooling is given by the loss of latent heat caused by water evaporation. Additionally,

moisture conditions are improved, preventing the larva from dying of dehydration. Also, in the same way they collect nectar, worker bees maintain a thin layer of water in their proboscis. Water evaporates quickly cooling the nest [69].

Swarming It is called swarming when part of the colony leaves the beehive taking the old queen, while the bees that remain in the beehive must create a new queen. Usually a colony that swarm separates into two. However, sometimes they are all bees that leave the nest [80]. Swarming by abandonment in general, is the response of bees to stressors such as humidity, temperature, lack of water or predators [25]. With regard to the relationship with the weather, the main reasons for swarming are:

- The temperature is too high, which requires more space to maintain an optimal temperature.
- The beehive does not have good drainage or adequate ventilation [72]. If the nest cannot be ventilated and the temperature tends to rise, bees are likely to leave the nest.
- High humidity and poor gas circulation make the beehive an unbearable place for bees.

2.3.2 Ventilation

An adequate amount of air exchange between the interior and exterior hive environment is required for bee colonies in order to thrive. During the air exchange process across the intake border, waste gases, excess heat, and water vapour are released, and new air is taken in to replace the old. When the temperature of the surrounding air is low, hive ventilation happens passively as a result of a driving force generated by the temperature difference between the brood box and the surrounding air temperature. When the packing density of a honeybee cluster is changed, honeybees may have an impact on the passive ventilation rate [81]. As mentioned before, bees exert effort in order to control ventilation levels. Temperature regulation is essential during the incubation of the brood and ventilation becomes even more critical during this period.

Because of the complexity of researching bees, it is very difficult to evaluate hive conditions with high precision. As a result, ventilation of a beehive is a subject that has not been well covered in the literature to yet. Because of this, hive ventilation studies often measure total air exchange rates and qualitative explanation of group-fanning techniques at the beehive intake. Bees also have an impact on hive ventilation by altering the density of the brood cluster.

2.4 Varroa mite (*Varroa destructor*)

Varroa destructor, previously known as *Varroa jacobsoni*, is a mite species that is an external parasite of bees. While it was originally restricted to parasitizing the Asian bee, during the last several decades it has expanded to the western

bee, Apis mellifera [12]. Because the Apis mellifera is a newly introduced host for this parasite, it lacks the natural defences that would otherwise protect it from infection. This mite may feed on both larvae and adult bees, depending on the species. Using sharp parts in its mouth, it perforates the body walls of the host in order to feed on its blood (haemolymph) [12]. Female Varroa mites have an oval and flat body with a reddish coloration on the underside (1.6 x 1.1 mm). Males are smaller and more discoloured than females, and they only live in brood cells (Figure 2.17) [12]. When populations of this mite overrun a bee colony, a disease known as Varroosis develops, a condition that can destroy the colony within two to three years if it is not treated [82].



(a) (b)

Figure 2.17: (a)Composition of a "Varroa family" within a honey bee worker brood cell [83]. (b)A worker bee with four Varroa mites [84].

Varroosis

In order to attack, the female mite must first establish contact with a bee that will transport it to the honeycomb. Once there, it attempts to enter an open cell. It conceals itself within the larvae's food supply. After the larva has finished eating its nourishment and the cell is still sealed, the mite begins its reproduction. The mite will have laid up to seven eggs between one and two days following the initial deposit, with only two or three of those eggs developing into adults. The mites then feed on pupae that are still in the development stage. It is at this stage that the mite has the potential to transmit illnesses to the pupa. Once the bee has emerged, the mite adheres to it until it is taken to a fresh open cell with a larva inside [82].

Currenlty, the Varroa mite can be found on all continents with the exception of Australia. The first reports of its presence in the United Kingdom date back to April 4, 1992, according to Devon [82].

The Varroa mite (destructor) is often regarded as the most hazardous and damaging pest in the beekeeping industry [83]. This danger distinguishes itself from others for a variety of reasons:

1. The Varroa mite, which parasitizes the honey bee Apis mellifera, is a relatively recent parasite. Particularly prevalent in the United Kingdom, where it was discovered for the first time in 1992 [12]. As a result, there is an imbalance between the host and the parasite, and beekeepers lack the necessary expertise to cope with this disease.

2. The Varroa destructor parasite has spread throughout the world's major beekeeping centres.

3. In temperate climes, a colony of bees might be destroyed within two to three years as a result of the activities of the Varroa destructor.

4. Beekeepers must incur additional costs in order to eradicate the Varroa destructor, and frequent treatment may necessitate the use of chemicals that degrade the quality of their honey products.

5. In addition to the worldwide reduction of pollinators, the Varroa mite has had an important role in Europe's decline in the number of honeybee colony populations [8].

Varroosis can be detected starting in the autumn when the number of brood being reared decreases and the number of mites is at its peak, and continuing until the beginning of spring. Figure 2.18 illustrates how the phenomena is recognised.

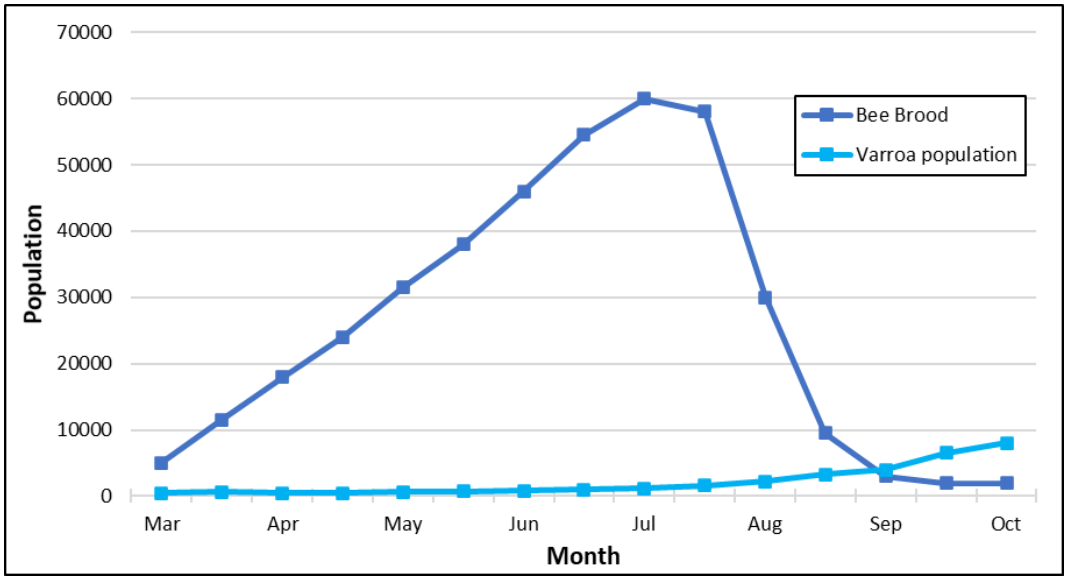


Figure 2.18: Bee Brood-Varroa growth population [12].

The infection of Varroa can result in the overall weakening of a colony, atrophied abdomens, malformed wings, or even the whole loss of a colony if the infestation is severe enough. Varroa is a viral transmission agent for bees, and it has the potential to harm their health and limit their lifetime if left untreated [82].

The transmission of the Deformed Wings Virus (DWV) has been dissipated by human means when transporting bees or some other infected material. Environmental factors such as the habitat in which pollinators develop link together

populations of pollinators, providing ideal circumstances for the rapid dispersal of the Varroa mite across the globe [85].

2.4.1 Varroa control methods

Varroa mites must be managed in order to maintain the health of the colonies. For the most part, there are two forms of treatment for them, plus one that has evolved more lately.

2.4.1.1 Biotechnical controls

These methods seek to reduce the population of mites through physical means. They take use of the fact that mites proliferate in bee brood to further their own interests. The most common method is to trap the mites in a drone comb, which is subsequently removed and destroyed along with the mites it contained. Spring and summer are often the best times to employ these techniques (See Figure 2.18) [82].

2.4.1.2 Varroacides

This method consists of using substances designed to kill and control the Varroa pest. They are quite efficient, yet they may be detrimental to the bee or its products if used excessively. It is possible to divide them into two categories: those that include patented chemicals and those that contain naturally synthesized substances [82]. According to European research, bees are significantly healthier when pesticides are not used. Aside from that, they have longer life cycles and are more resistant to viral infections [86].

2.4.1.3 Thermal treatment

This method is relatively new compared to the aforementioned. It entails the use of heat at various intervals in order to remove Varroa infestations. Despite the fact that it is a potentially dangerous therapy, it has shown to be beneficial. It has been discovered that Varroa can be controlled by applying temperatures near to 40 degrees Celsius; however, the concern is that this temperature is close to the deadly temperatures for bees [87]. The next section this thesis elaborates on details of this new method and some of its current applications.

2.4.1.4 Alternative techniques

It is also possible to use alternative ways that are more environmentally friendly and do not jeopardise the health of bees or the quality of their output. They are, however, still in the early stages of development. If their efficacy is confirmed, they might be utilised as a supplement to thermal methods in certain situations. There are primarily two approaches that stand out.

One of them is composed of noises with frequencies ranging between 14,000 and 15,000 Hz with a decibel level of 90. Because it is unpleasant for the mites,

this acoustic disturbance has an effect on their ability to eat. After being exposed to this stress, it has been discovered that the mites are unable to feed and die after 10 to 20 days of being exposed to it. Apparently, this noise has no effect on the bees' behaviour in any manner [88].

The second approach attempts to inhibit mite reproduction by introducing pheromones into their breeding cycle, causing a disruption in their mating cycle. In this case, a chemical is used to induce male mites to have sexual activity at an inopportune period in the reproductive cycle of females, while also causing sexually active females to have less sex activity than they would otherwise. Mites would eventually die as a result of a failed reproductive cycle, which would occur eventually [89].

2.4.1.5 Comparison of the main control methods

Table 2.3 shows the advantages and disadvantages of the use of the three methods mentioned above. From this vantage point, thermotherapy stands out since it does not wreak havoc on the environment in the way that chemical therapies do. The primary impediment to thermal therapies is a scarcity of alternatives on the market, and those available are fairly difficult to employ.

Table 2.3: Advantages and disadvantages of biotechnical methods, varroacides and thermotherapy.

	Advantages	*Disadvantages*
Biotechnical methods	✓ Do not require the use of chemical varroacides ✓ Can be combined with summer management ✓ Inexpensive or free	× Can be time consuming × Some need a high level of beekeeping skill × Generally, not sufficient if used alone × Misuse can harm colonies
Authorised varroacides	✓ Proven efficacy ✓ Proven safety ✓ Convenient to use	× Mites likely to develop resistance × Residue problems in bee products if misused × Can be expensive
Thermotherapy	✓ Proven efficacy ✓ Do not require the use of chemical varroacides ✓ Does not affect the health of the bees nor the quality of their product	× Are laborious to use × Misuse can harm colonies × There are not many commercial offers × Can be expensive

2.4.2 Thermotherapy / Hyperthermia

It has been revealed that the parasite Varroa destructor is responsive to increases in temperature. This organism is incapable of reproducing in an environment with temperatures that are several degrees higher than the optimal. In accordance with Bičík [90], it is probable that enzymes involved in protein production are the first to be altered by the mites' response to the effects of temperature on their bodies.

As a result, the Varroa mite dies at temperatures over 40 degrees Celsius and suffers severe damage at temperatures below 38 degrees Celsius [91].

Even at higher temperatures, between 49 and 50 degrees Celsius, harmful effects on bees begin to manifest. Bees begin regurgitating and to have acute fatigue, as well as clumping. If bees are clumping at the critical moment of warming, they can cause overheating, which would be detrimental to the effectiveness of the treatment as well as the health of the bee population [92].

Also known as hyperthermia, the thermotherapy treatment consist in rising the temperature inside the brood chamber is raised to 40-47 degrees Celsius and held there for a period of 2.5 hours, the mites in the sealed brood are removed while the bee brood is not damaged [90]. To achieve 100 percent efficacy against the Varroa mite in sealed broods, it is necessary to maintain a temperature of 40 degrees Celsius or above for a period of 150 minutes, with a maximum temperature of 47 degrees Celsius. It has been shown that two sessions of heat treatment are required to produce the optimal effects in most cases. Seven to fourteen days following the first heating session, the second heating session should be performed [93].

Because of its high comparative efficiency, it has the potential to be used as a chemical alternative [91]. If the thermotherapy procedure is carried out correctly, it is not particularly aggressive for bees, and it is far less violent than a chemical treatment.

Table 2.4 summarizes, on a comparative scale, the temperatures at which bees or Varroa mites present significant alterations in their health or behavior in contrast to the temperature range in which thermotherapy operates.

Table 2.4: Key temperatures for bees (*Apis mellifera*) and Varroa mites (*Varroa destructor*).

Brood box temperature [°C]	*Effect on Bees/Varroa*	*Additional notes*	*Reference*
<10	Bees cannot fly	Honey bees are cold blooded.	[94]
20	Brood led to higher mortality	If they are submitted for a period greater than 12 hours.	[95]
<27	Bees keep inside and thermoregulate the hive	This inner temperature reflects an outside temperature of 9°C.	[94]
26-33	Varroa is capable of reproduction	It also needs stress less conditions.	[90]
32.5-33.4	Optimal temperature for the development of Varroa	Often found inside the brood nest.	[22]
32-36	Normal temperatures in the brood chambers	Bees keep the brood nest at a constant temperature.	[96]
>36	The reproductive capability of female mites significantly decreases	Synthesis of proteins is affected.	[90]
>38	Varroa die without engaging in reproduction.	Female mites are damaged and become infertile.	[90]
40-47	Thermal conditions for Thermotherapy	It has to last 150 minutes. starting from the moment when the temperature reached 40°C at the floor.	[90]
>40	Increased mortality in adult bees	Bees die exposed to higher temperatures for more than 48 hours.	[90]
>41	Bees start swarming	When they cannot regulate the temperature for a long period (3-4 days).	[21]
43-44*	Thermoregulation of bees	Bees heat their bodies to raise the temperature of the beehive. Their thorax achieves up to 44°C.	[22] [94]
46	Bees still can fly	While their thorax is still at 45°C.	[97]
>49	Wax loses its mechanical strength	During thermotherapy the structural integrity of the work remains.	[90]
49-50	Bees overheating	They get lethargic and regurgitate if the lapse is prolonged.	[92]
60-62	Cooling thermoregulation of bees	During thermotherapy no signs of damage to the brood or abnormalities in oviposition by the queens have been registered.	[90]

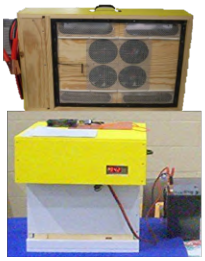
***Not inside the Brood box**

2.4.3 State of the art of thermotherapy devices

Throughout the time that thermotherapy has been studied, there have been different types of approaches, three of which stand out. Cunningham [92] provides a description of one of them, where using a basic cabinet-type heating unit, the bees are removed from the beehive for a short period of time while the heat treatment is being provided to it. Another approach, given by Linhart [91], comprised of a thermal hive, which was powered by solar energy. Using sun irradiation, this system gets the temperature at which mites will be eliminated. Finally, an approach that reached enough standards to become a commercial product such as the Victor. These are thermoelectric devices that may be installed at many locations including the base, the top, and even within the beehive itself to heat it.

Table 2.5: Timeline and state of the art of thermotherapy devices.

Year	*Product*	*Location*	*Operating temperature*	*Operating time*	*Cost*	*Heat /Power source*	*Features*	*Ref*
1981	**Hanko's thermo cube**	Czechoslovakia	45°C	12 mins	N/A	Solar	A heating box made of acrylics. Inner cavity with wire mesh. Use sun energy to increase the internal temperature of the box. Tested on 300 infested bees. Exposed to direct sunlight.	[98]
1983	**The thermo-bell**	Czechoslovakia	>45°C	7 mins	N/A	70°C water	Hollow-bell structure with wire cavity. About 200 infested bees were placed inside the interior cavity. Dip into hot water bath. Internal cavity (dry) external (wet).	[98]
1986	**The Kamler** 	N/A	46 and 48°C	10 mins	N/A	Fuel burning	The Thermobox consisted of a rotating round cavity placed inside a larger box. Treating bees not broods. A source of heat (a gas burner for example) would be placed underneath larger box. Preheat Thermobox at 50 °C. Infested bees (brood free) placed in the interior cavity.	[98]
1997	**Cunningham's**	USA	46-48°C	15 mins	N/A	Electric AC	A portable wooden cabin that contains a conventional "milk house" heater and a metal mesh cylinder to hold the bees inside while they are heated. The cabin has plexiglass windows to ventilate and allow observation. The bees were removed from the beehive and placed in this device for treatment. The device created worked from a 1500 watts conventional electric heater.	[92]
2001	**Mite Zapper**  	USA	43-45°C	5 mins	95 EUR	Electric DC	A drone comb with built in heating element. Depending on treatment time the mortality rate of mites was between 59-100%. It can be powered using a portable or running car battery. Food grade materials are RoHS compliant. Used in any temperature conditions during the drone rearing season. Treatment should be every 18-23 days. In MI, USA this is around 5 times per year. Claims to kill mites in scaled brood cells. EHT reports that this equipment was too expensive for many keepers and so they stopped stocking it.	[99]
2006	**Thermovar** 	Greece	42°C	480 mins	N/A	Electric AC	It has adjustable temperature and time. Target both bees and broods. The hives' lid was first removed, then a bee-safe screen is placed. The hot chamber is placed on top of the beehive. A closed air circuit with entrance at the hole on the drawer an d exit through the shaft. Gradually heat the spaces between the combs of the beehive. With electronic controller which keeps the whole system at the desired temperature at constant level.	[100]
2010	**Varroa terminator**  	Slovakia	42°C	180 minss	362 EUR	Electric AC	Uses two heating panels (120 W) to elevate beehive temperature. Uses 0.3-0.4 kWh per treatment. It claims to not harm bees, larvae or eggs. It features for evaporators to prevent bees from accessing water to cool the hive down. This also ensures that RH is kept between 60-70%.	[101]

Year	Product	Location	Operating temperature	Operating time	Cost	Heat /Power source	Features	Ref
2010	**Linhart Thermosolar Hive** 	Romania	40-47°C	150 minss	700 EUR	Solar	The hive cover and boxes are fitted with windows. When treatment begins a cover is removed, revealing a thermosolar ceiling, this creates a greenhouse effect which raised the temperature inside the hive. The sun will heat the hive up to 47°C with an average temperature of 40-47°C for 150 minutes. The heating is largely focussed on the brood combs. Claims to increase honey collection potential between 25-75% Claims to speed up spring expansion of bee colonies.	[91]
2011	**Varroa Controller** 	Germany	40-47°C (120 mins)	120 minss	2388 EUR	Electric AC	A thermally insulated housing which automatically runs the treatment program. Sealed broods are exposed to high temperature. They don't treat the adult bees because the majority of mites are in the broods. Frames are dropped into the box after worker bees are brushed away. 100% Varroa efficiency.	[102]
2013	**The Victor** 	USA	42°C (150 mins)	150 minss	240 USD	Electric DC	Heats brood area. A second treatment can be applied 12 days later leading to a 95%+ reduction in mites. Unit fits on top of the brood box. Automatically shuts off after 3 hours of being at temperature. It requires a 12v 55Ah deep cycle battery to do one treatment. Recommend treating 2 weeks before honey supers go on in the spring and right after the honey is removed in summer. 2 year warranty and 30 day satisfaction guarantee.	[103]
2017	**Bee Ethic** 	Italy	42°C		550 EUR	Solar and Electric DC	Features thermostatically controlled frames which apply heat treatment directly to the hive. It automatically treats the hive each month. It heats the comb to 42°C It proved to have a 80% efficiency; increased honey production by up to 30%; saves beekeepers' work by up to 50%	[104]
2017	**Mighty Mite Killer** 	USA	43°C	5 minss	300 USD	Electric AC	This is an industrial grade heater blanket with electronic controls which are easily installed and removed on the floor of the breeding box. It uses a pair of temperature sensors as thermostatic control system. It has an on and off interface; and it switches itself off once the thermotherapy cycle ends.	[105]
2017	**Bienen-sauna** 	Germany	41°C	180 minss	1300 EUR	Electric AC	This system is inserted in a box additional the regular ones in the beehive. It is placed below the bottom box. Controls internal temperature and humidity. Its main function is to provide a high temperature to favour the production of bees. Additionally, it can be used to apply thermotherapy. Although its principle of operation is not public, it can be inferred that it is an arrangement of resistive plates that convert electrical energy into heat. These plates work along with a system of fans and humidifiers.	[106]

2.5 Chapter conclusions

The literature review was extremely beneficial to understand the current circumstances of bees in the environment selected for this study and also gave us an idea of the potential scope of this project. The features of commercial beehives were identified, which served as the foundation for the thermal treatment concept. Beehives' physical size and restrictions are now well understood. Additionally, by knowing the materials used to construct them, their thermal properties may be determined.

On the other hand, the difficulties that bees confront are well-known, particularly in terms of severe temperatures. What aided in the compilation of a table that condenses the temperature ranges that have the greatest effect on honeybees.

Understanding their behavioural mechanisms of heat control enabled us to anticipate these actions before to experimentally applying the thermal therapy.

After thoroughly studying the Varroa mite's biology and attack mechanisms, it was feasible to select hyperthermia as the most sustainable technique of mite elimination and so justify this endeavour.

Finally, the study of the state of the art in heat treatment devices was very useful in terms of understanding what has been accomplished over time and also identifying areas of opportunity where other devices have demonstrated deficiencies or obstacles, which distinguish the solution proposed in this thesis. For instance, it was highlighted that the great majority require on-site electrical power and that many are arduous procedures that are incompatible with commercial beehives and require bees to be relocated for treatment. In the pursuit of a more environmentally and user-friendly technology, it has been tried to avoid the hassles associated with prior devices.

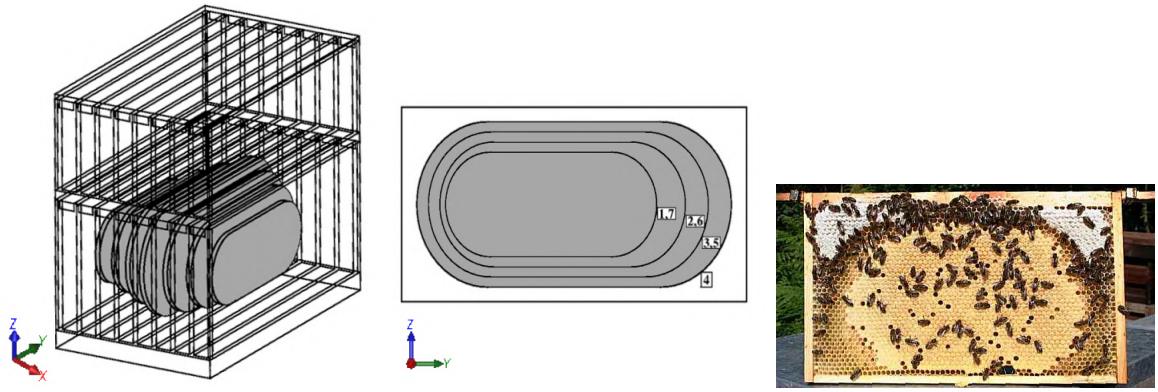
Chapter 3

Mathematical model and CFD simulations

This chapter explains the thoeretical base used to size the phase change material (PCM) and identify the qualities necessary to provide a solution to the issue. The simulations that were run and used as the foundation for following tests are also detailed.

3.1 Mathematical model

The brood chamber of a National Standard beehive is the focus of this research project. Figure 3.1 illustrates a comb surface on a brood chamber frame, with the centre portion mostly filled by brood combs. The brood region on combs towards the beehive's centre exhibits the unique pattern of brood, pollen, and honey in a brood box. It is composed of three unique regions: a centre brood area, a pollen-filled ring encircling it, and a huge honey-filled periphery zone surrounding it.



(a) (b) (c)

Figure 3.1: (a)Isometric view of a model beehive with eight frames and a single honey super. (b)Front view of the frames and the different bee cover volumes [81]. (c)Central brood area, surrounded by pollen and capped honey.

3.1.1 Steady state analysis / PCM sizing

For the present research, detailed modelling of a beehive's thermoregulation is very time demanding. Therefore, a simple mathematical model was constructed. A model of the box in steady-state was initially made to determine the quantity of PCM necessary to maintain the target temperature in the centre of the beehive (i.e. 40 - 47 °C) for 150 minutes.

$$\frac{m_{pcm} L_{pcm}}{dt} = h_{pcm} A_{pcm} \left(T_{pcm} - T_{beehive}\right) \tag{1}$$

$$\frac{\rho_f C p_f V_f dT}{dt} = h_{pcm} A_{pcm} \left(T_{pcm} - T_{beehive}\right) - U_l A_{beehive} \left(T_{beehive} - T_a\right) \tag{2}$$

The first term in the left hand side of (1) is corresponding to the change in the enthalpy of the PCM control volume. In this study it was only assumed the change in the enthalpy during phase change. The term on the right side represents the net of heat exchanged between the surface of the PCM pack to the space inside the beehive by convection. The latent heat of crystallisation L_{pcm} was set at 256 kJ/kg based on the measurement made by the provider. Meanwhile, $U_l A_{beehive}(T_{beehive} - T_a)$ in (2) represents the overall heat loss from the beehive. In this study, we have set T_{pcm} as 55 $^\circ$C which is the average melting temperature of Sodium Acetate, T_a as 20 °C and $T_{beehive}$ as 40 $^\circ$C. which is the average minimum temperature that must be reached by the internal hive for the heat treatment method to become effective.

From the simple steady state analysis, plugging in the values described above and solving to obtain m_{pcm}, the predicted amount of PCM required for heating duration of 150 minutes is 3.4 kg. Considering the PCM's density of 1426.28 kg /m3, the volume of the PCM pack required inside the beehive would be 2383.82 cm3 or 2.3 litres. Given the limited area available inside the brood box, it was chosen to limit the mathematical modelling to the option of placing the PCM horizontally on the brood box's floor. However, preliminary simulations and several tests were conducted both in the laboratory and on-site for the vertical arrangement.

3.1.2 Transient analysis

The primary constraint on the steady-state study is that the PCM's average temperature and the fluid temperature were assumed as constant. Meanwhile, in real-world circumstances, the average temperature inside the beehive varies over time due to the heat capacity of the fluid contained within.

As depicted in Figure 3.2, the brood box has been split into four control volumes: T_{pcm} for the PCM pack, T_{fb} for the beehive's bottom region, T_{fm} for the beehive's middle or centre area, and T_{ft} for the beehive's top area. To build the temperature nodes, the layers of the beehive were analysed in the Y-Z plane, with a particular emphasis on the Z-axis.

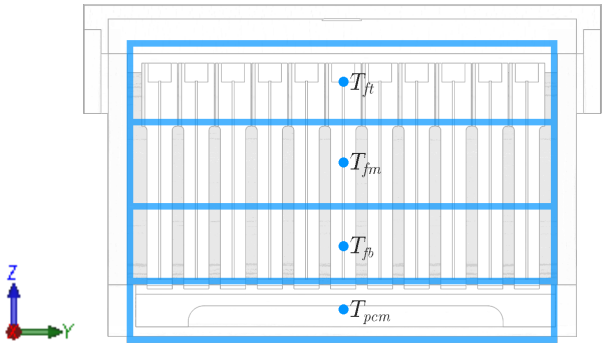


Figure 3.2: Temperature nodes assigned in the beehive.

The following assumptions were taken in order to create the mathematical model:

1) The area of the air and honeybees are considered to be one fluid zone.

2) It is considered that the heat delivered to the brood through thermoregulation effort is lost to the region's air space. The honeybees' heat transmission is modelled using the obtained equation from [81].

3) As in the experimental study published by [90], the cooling impact or ventilation of the fanning bees is believed to be insignificant.

4) Because the temperature gradient along the X-Y plane is deemed minimal, the temperature nodes are regarded to be at the control volume's average point.

5) The primary mode of heat transmission is spontaneous convection from the surface of the PCM pack upward into the beehive areas.

6) It was assumed that heat transmission between the control volumes in the beehive area and the PCM control volumes occurs purely as a result of natural convection in the fluid. As a result, conduction of heat between fluid control volumes becomes a significant method of heat transmission.

7) Heat loss to the ambient from the beehive's bottom control volume is believed to be insignificant.

8) Both the external wind and solar radiation are considered to be negligible.

The following energy balance equations were developed under transient conditions. D'Avignon's model [107] was used as an example, as its geometry is similar to the one proposed above. In their instance, they designed a horizontal storage tank with a rectangular cross section. Values from the previous time step are indicated with m while values from the present time step are indicated with $(m+1)$.

$$\frac{\delta H_{pcm}}{\delta t} = h_{pcm_f} A_{pcm} \left(T_{pcm}(m) - T_{fb}(m)\right) + U_{floor} A_{floor} \left(T_{pcm}(m) - T_a(m)\right) \tag{3}$$

The first term in the left hand side is corresponding to the change in the enthalpy of the PCM control volume H_{pcm}.

In this study, it was only considered the change in enthalpy during phase change. The term $h_{pcm_f} A_{pcm} \left(T_{pcm}(m) - T_{fb}(m)\right)$ represents the net of heat exchanged between the surface of the PCM pack to the fluid at the bottom region of the beehive by natural convection and the term $U_{floor} A_{floor} \left(T_{pcm}(m) - T_a(m)\right)$

represents the heat loss from the PCM pack to the ambient through the floor of the beehive.

$$\frac{\rho_f Cp_f V_{fb} \left(T_{fb}(m+1) - T_{fb}(m)\right)}{\delta t} = h_{pcm_f} A_{pcm} \left(T_{pcm}(m) - T_{fb}(m)\right) - \frac{k_{air} A_{pcm}}{\delta_{air}} \left(T_{fb}(m) - T_{fm}(m)\right) \quad (4)$$

The term on the left represents the net rate of energy stored in the fluid control volume over a certain time step, with $\rho_f Cp_f V_{fb}$ being the fluid's heat capacity. The term $\frac{k_{air} A_{pcm}}{\delta_{air}} \left(T_{fb}(m) - T_{fm}(m)\right)$ represents the net rate of heat conducted from the bottom to the middle fluid region.

$$\frac{\rho_f Cp_f V_{fm} \left(T_{fm}(m+1) - T_{fm}(m)\right)}{\delta t} = \frac{k_{air} A_{pcm}}{\delta_{air}} \left(T_{fb}(m) - T_{fm}(m)\right) - \frac{k_{air} A_{pcm}}{\delta_{air}} \left(T_{fm}(m) - T_{ft}(m)\right) + q_{bees}(m) \quad (5)$$

The term on the left represents the net rate of energy stored in the fluid control volume over a certain time step, with $\rho_f Cp_f V_{fm}$ being the fluid's heat capacity. The term $\frac{k_{air} A_{pcm}}{\delta_{air}} \left(T_{fm}(m) - T_{ft}(m)\right)$ represents the net rate of heat conducted from the middle to the top fluid region. A colony's population of bees is predominantly confined to the brood box. As stated at the beginning of this chapter, the highest concentration of bee volume is located in the brood chamber's central region. The term q_{bees} corresponds to the heat created organically by bees during their metabolism, in accordance with Sudarsan's results [81], which establish the rate of metabolic heat generation as a function of local temperature and the density of the cluster of bees. This relationship is illustrated in Figure 3.3, and from it the correlation between the quantity of heat emitted by bees per cubic metre and the local temperature $q_{bees} = -70.5(T_{fm}) + 460.5$ was derived.

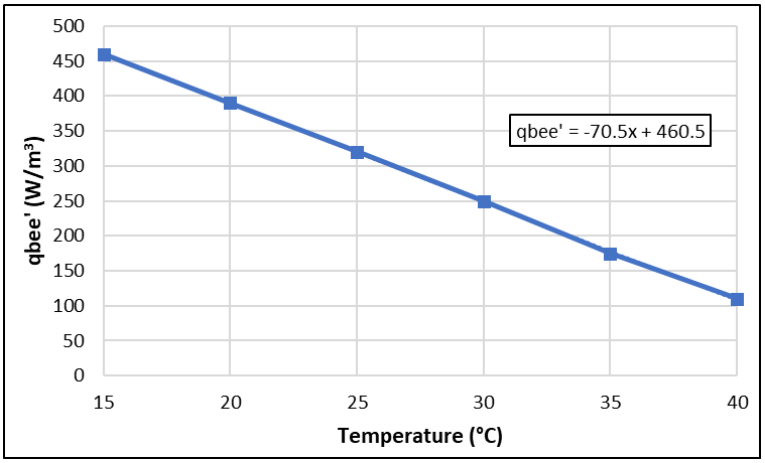


Figure 3.3: Heat generation rate per cubic metre of honeybees.

$$\frac{\rho_f Cp_f V_{ft} \left(T_{ft}(m+1) - T_{ft}(m)\right)}{\delta t} = \frac{k_{air} A_{pcm}}{\delta_{air}} \left(T_{fm}(m) - T_{ft}(m)\right) - U_{roof} A_{roof} \left(T_{pcm}(m) - T_a(m)\right) \quad (6)$$

The term on the left represents the net rate of energy stored in the fluid control volume over a certain time step, with $\rho_f Cp_f V_{ft}$ being the fluid's heat capacity. The

term $U_{roof}A_{roof}\,(T_{pcm}(m) - T_a(m))$represents the heat loss from the PCM pack to the ambient through the roof of the beehive.

Between the surface of the PCM pack and the central brood region, the heat transfer rate is mainly driven by natural convection and heat conduction via the air layer. According to the model, the closer the pack is to the centre region and the larger the surface area of the PCM pack for heat transmission, the greater the heat transfer coefficient (HTC). Additionally, the HTC can be enhanced by eliminating the mesh floor above the PCM pack, reducing heat loss due to the lateral heat conduction to the side of the hive through the metal mesh floor. Figure 3.4 illustrates the temperature fluctuation in the central brood region as a function of the HTC value.

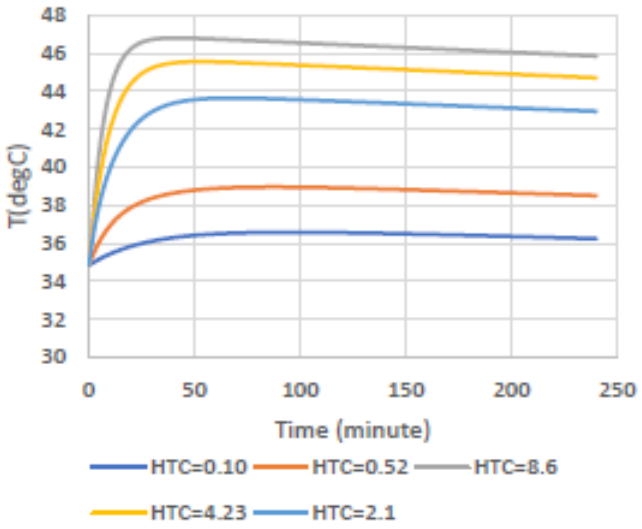


Figure 3.4: Variation in temperature in the centre of the brood box with 5 different HTCs.

3.2 CFD simulations

The computational fluid dynamics (CFD) model of the beehive has been demonstrated on the ANSYS Fluent tool to evaluate the temperature profile generated due to the heating element on the beeswax, wooden box outside and the insulating material.

This stage of the project is critical since it occurs prior to the experiments. Specifically, one of the simulation's aims is to confirm the PCM's selection while also avoiding a disaster for the bees in subsequent experiments. The experimentation in this sort of project is very sensitive, since it involves the lives of living creatures. It is important to remember that the purpose of this initiative is to assist these living creatures and to alleviate one of the difficulties for which humans are responsible. In such a way that no experiment may fail, which would happen if the heat delivered surpasses the thermotherapy temperature and reaches the bees' suffocating and overheating temperatures. This is the phase at which

material or configuration changes must be made, therefore it is critical to conduct a well-founded simulation using reasonable parameters.

As previously stated, this study analysed a National Standard beehive. The treatment should focus on the brood chamber; therefore, the supers were ignored. In practise, it is possible to separate or thermal insulate the supers from the box to be treated.

3.2.1 Boundary conditions

Boundary conditions involve specifying the simulation's inlets and outlets. The beehive box, on the other hand, is a closed device with just one vent for entrance or outflow. Due to the fact that the pressure within the box will increase as the temperature rises, the vent is termed the pressure exit. ANSYS Fluent handling of pressure inlet boundary circumstances may be thought of as a lossless transition from stagnation to inlet conditions. This is performed in ANSYS Fluent for incompressible flows by applying the Bernoulli's equation at the inlet boundary,

Other boundary types include barriers that supply heat input. The Table 3.1 below details the border.

Table 3.1: Boundary conditions.

Serial No.	*Boundary*	*Boundary type*
1	Inlet	None
2	Outlet	Pressure outlet 0 Pa
3	Frames	Coupled solid liquid
4	Brood box walls	Temperature 20 °C
5	PCM pack walls	Temperature 55 °C
6	Insulation floor	Coupled solid liquid

The simulation used the following materials (Table 3.2). Due to the fact that the materials were not available in the Fluent database, they were developed manually.

Table 3.2: Material properties used in the simulation.

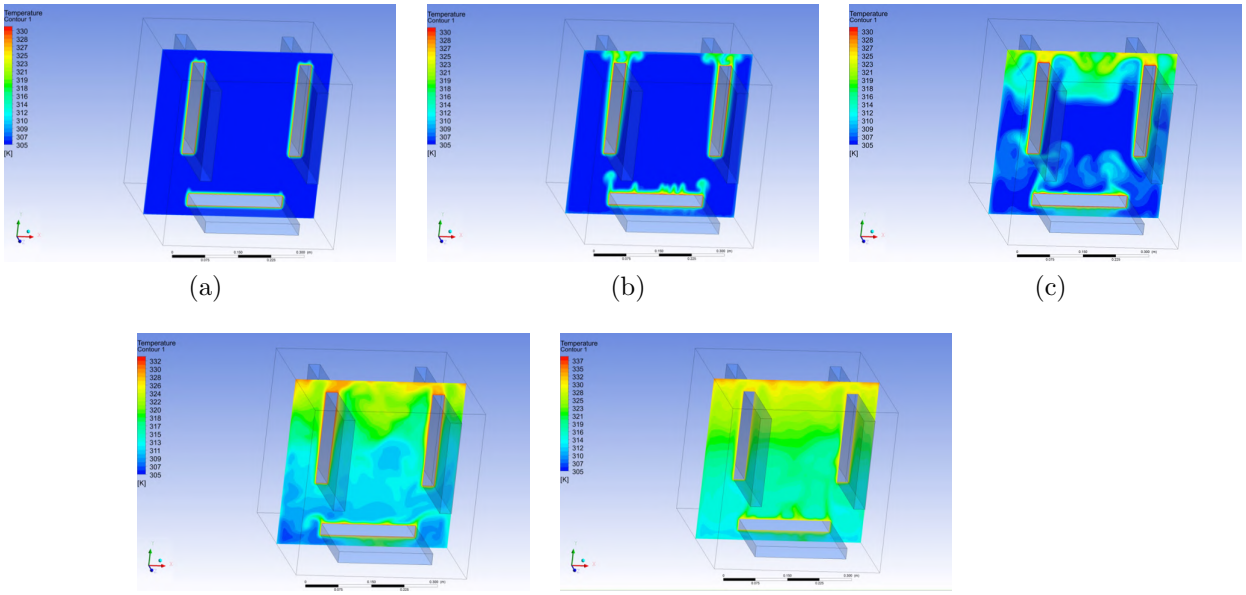
Material	*Property*	*Value*	*Unit*	*Ref.*
Wood (red cedar)	Density	380	kg/m^3	[108]
	Thermal conductivity	0.106729	W/mK	[109]
	Specific heat	2310	J/kgK	[109]
	Initial temperature	33	°C	
PCM pack	Density	1426.28	kg/m^3	[110]
	Thermal conductivity	0.518	W/mK	[110]
	Specific heat	3460.037	J/kgK	[110]
	Initial temperature	55	°C	
Frames	Density	960	kg/m^3	[111]
	Thermal conductivity	0.25	W/mK	[111]
	Specific heat	3400	J/kgK	[112]
	Initial temperature	33	°C	
Insulated floor (Polysocyanurate)	Density	40	kg/m^3	[113]
	Thermal conductivity	0.026	W/mK	[113]
	Specific heat	1500	J/kgK	[114]
	Initial temperature	20	°C	
Air	Density	Incompressible ideal gas		
	Thermal conductivity	0.0242	W/mK	
	Specific heat	1006.43	J/kgK	[115]
	Initial temperature	20	°C	

3.2.2 Preliminary simulations

Preliminary simulations were conducted to ensure that the parameters and boundary conditions were appropriate. The first simulation shown in Figure 3.5 examines the vertical and horizontal placement of PCM packs in an empty beehive.

Figure 3.5a shows the initial temperature conditions. as previously described. Then the PCM packs start to transfer heat like when they are triggered (Figure 3.5b). As shown in Figures 3.5c and d, the heat transfer is mainly driven by natural convection since the fluid motion is not generated by external means such as air circulation fan.

At equilibrium (Figure 3.5e), theoretically, the centre in-hive temperature could reach up to 52 °C. However, it is worth emphasizing that the heat transfer from the PCM pack placed horizontally on the floor of the beehive is not as high as the heat transfer rate from PCM packs that are arranged vertically. This is due to the distance of the pack to the centre brood area, and also due to the small heat transfer surface area of the PCM pack. This observation was put to the test in the following preliminary simulations.



(a) (b) (c)

(d) (e)

Figure 3.5: Transient thermal simulation of three PCM packs inside an empty brood chamber.

Figure 3.6 shows a steady thermal simulation of two PCM packs placed vertically inside a broodbox with 7 frames. As demonstrated in the previous simulation, since heat transmission occurs only by natural convection, the horizontal area is critical for achieving an effective heat distribution. However, throughout the stage of on-site testing, this was also investigated in a beehive containing bees.

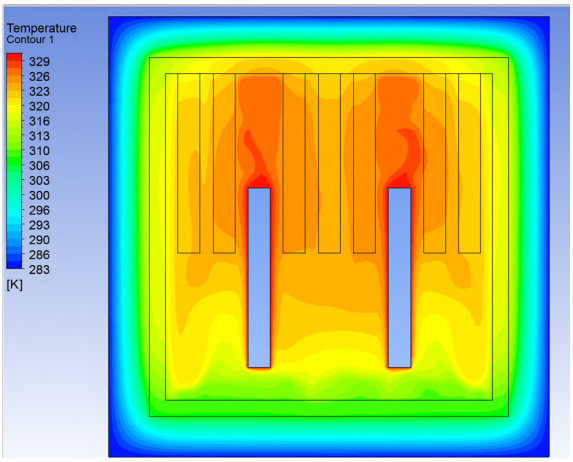


Figure 3.6: Steady thermal simulation of two PCM packs inside a broodbox.

The next simulation examined the horizontal positioning of the PCM pack. The top of the PCM pack is corrugated to improve the surface area for heat transmission. Being at the bottom section enables this, despite the fact that it has more frames with its interior than the previous simulation.

The results clearly illustrate the advantages of this setup (Figure 3.7). The temperature increases quite evenly and reaches an average of 53 °C. Additionally, it was noted that the frames nearest to the lateral walls have a lower temperature; nevertheless, according to the literature research, these frames often lack brood.

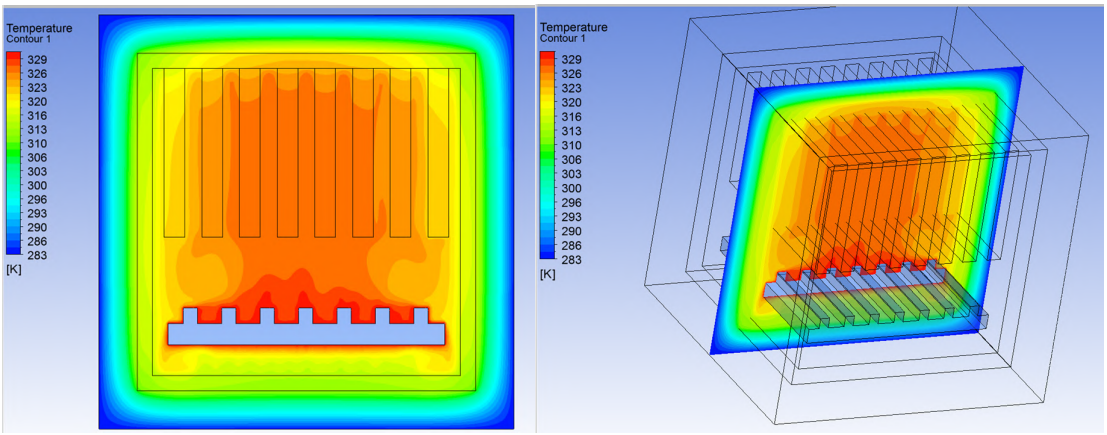


Figure 3.7: Steady thermal simulation of a ridged PCM pack inside a broodbox.

3.2.3 Main simulations

Following the previous results, it was decided to create a more realistic set of simulations. Therefore, the exact measurements of the beehive were used and 11 frames were assumed inside as this number of frames is the most common in practice (Figure 3.8). Additionally, the PCM pack's model was refined considering it as a simple block. It was dimensioned based on the mathematical steady state modelling described in the previous chapter, which indicated that 3.4 kg is required to heat the centre of the brood box to temperature of 40 degree Celsius, and hence

treat the beehive. The equivalent height for the PCM pack was determined using the density of the SAT and looking to occupy the largest surface area at the base of the beehive. The PCM pack was designed as a basic parallelepiped to simplify the geometry and avoid overstressing the computer equipment, while also considering the worst-case situation, since any package that is not flat improves thermal performance.

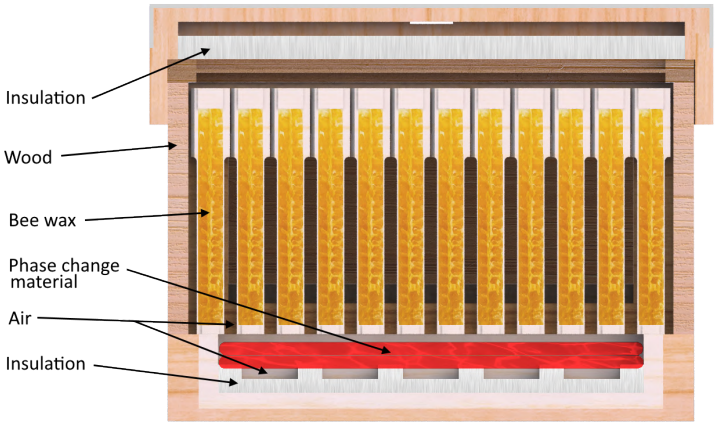


Figure 3.8: Cross section of the 3D render used for simulations.

Because the resulting value for the PCM pack height exceeded the available space of a regular floor of a National Standard, it was determined that in order to introduce the PCM pack into the brood box, the beehive floor should be changed to a more appropriate one. Parallel to the simulations, this new floor was designed.

To provide a reference for laboratory testing, a temperature of 20 °C was selected as the ambient temperature, the same to laboratory conditions. For the internal temperature, the literature consulted and the preliminary experiments on-site conducted agree that the average temperature within the beehive is 33 °C. Finally, the PCM temperature was set using the average of the measurements on preliminary laboratory experiments. The simulations did not include the moment prior of activation of the PCM and instead assumed the PCM at constant temperature throughout the simulated time span.

The body was separated into multiple sections to facilitate meshing. Tetrahedral cells were created in all parts with mesh count less than 512000. The cells have a maximum skewness of less than 95%, indicating that the mesh is of acceptable quality. Below are the specifics of the grid domain statistics for both fluid and solid.

The figure below shows the meshing.

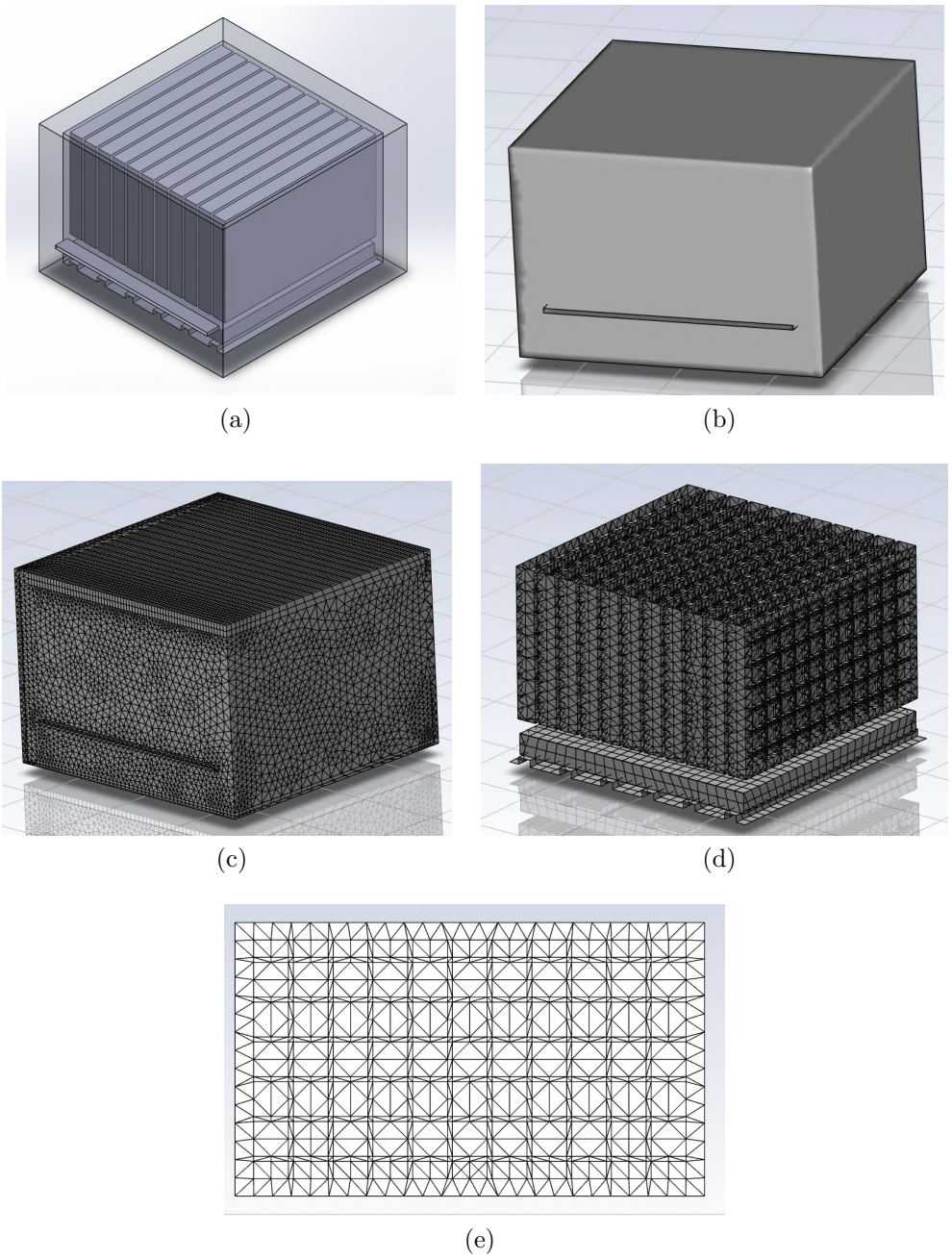


Figure 3.9: (a)3D model of the brood box and internal components. (b)3D model imported to ANSYS. (c)Meshing on external box. (d)Meshing on internal components: 11 frames, PCM pack and internal face of insulation. (e)Side view of mesh of one frame.

3.2.3.1 Case 1: PCM pack inside an empty beehive

This simulation was designed to determine the PCM pack's thermal performance. It will also be used to assess an extreme example of a null colony, i.e. excluding the presence of bees inside the brood box. The result would indicate if the PCM's thermal capacity and pack size are sufficient for the application. Additionally, it

will aid in determining the temperature distribution and velocity. Finally, with the colony depleted, it is predicted that the result of the simulation would reveal the colony's maximum temperature. If it approaches or surpasses the deadly temperature for bees or brood as described in the literature, a redesign of the treatment may be necessary.

3.2.3.2 Case 2: PCM pack inside a beehive with bees

This simulation is similar to the previous one, except that it considers the presence of bees within the brood chamber. To incorporate bees in the simulation, their volume within the beehive was formulated as a porous medium. To implement the concept of porous zone in ANSYS, an average bee length of 15mm was assumed, and that these were compressed leaving a 33% void fraction of air between them. The permeability (α) and inertial loss coefficient (C_2) were calculated using these data and the following equations from the ANSYS Fluent theory guide.

$$\alpha = \frac{D_p}{150}\frac{\varepsilon^3}{(1-\varepsilon)^2} \tag{7}$$

$$C_2 = \frac{3.5}{D_p}\frac{(1-\varepsilon)}{\varepsilon^3} \tag{8}$$

In these equations ε represents the void percent, which is defined as the volume of voids divided by the volume of the packed bed area. As previously stated, it was assumed as 0.33 for this scenario. As indicated before, the average diameter of the particle used in these calculations was 15mm. By solving the aforementioned equations with these values, we get the values of α=1.20E-07, $^1/_\alpha$ = 8327536.2 , and C_2 = 4350.20; and hence applied in ANSYS.

The findings form this simulation will be the most valuable since this is the most accurate representation of a real scenario. This simulation will be validated by on-site trials.

3.3 Simulations results

In order for the solution to be converged, the continuity, velocity components and energy curves must reach a stable value. The iteration was run for 13200 seconds (about 3.6 hours) to get the results from every flow time so that it could be ensured that the equations have reached the state of convergence. The values of temperature in the central cross section in X-axis were monitored and animations in the form of .jpeg images were generated every five minutes of flow time. The convergence curves show the calculation of the convergence curves for energy, velocity and turbulence. The continuity, velocity components and turbulence variables have reached a stable value, indicating that they meet the residuals' convergence conditions. In the transient simulation, the real time based results can be obtained. The CFD post tool may be used to post-process the simulation data for varied flow times.

For case 1 the Figure 3.10 illustrates that the fluid within begins to warm up after the first 40 seconds, due to the temperature of 55 °C of the PCM pack. In the mark of 3300 seconds, the heat from the PCM is dispersing to the beeswax but

in a slow pace. In 13200 seconds, or roughly 3.6 hours, the temperature of the box rises significantly from the brood box's midpoint to 43 °C. The box temperatures for case 1 are as follows.

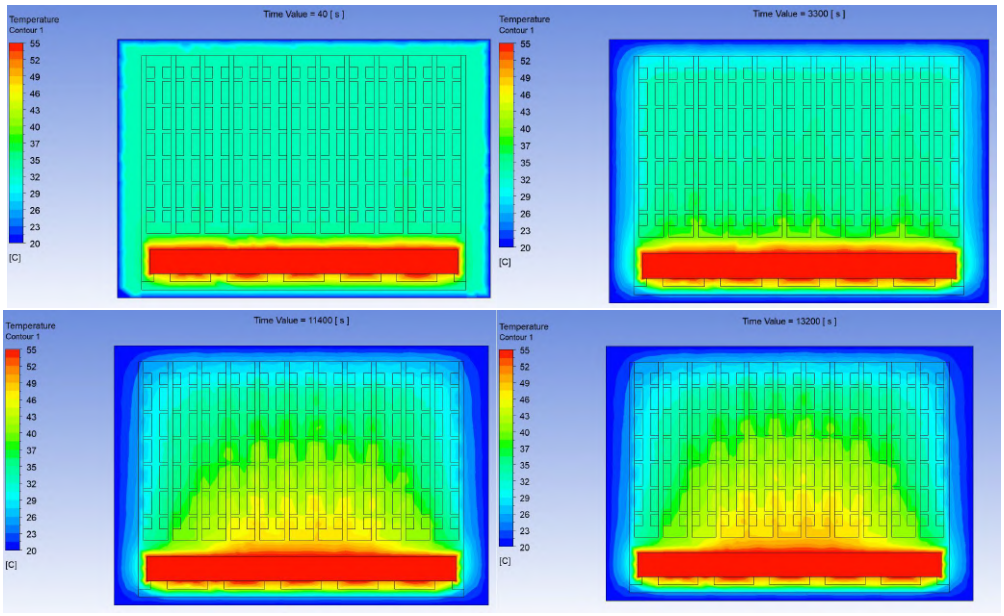


Figure 3.10: Temperature plots on a transient simulation case 1.

For case 2, the Figure 3.11 shows that after 10 seconds, the fluid within begins to increase in temperature due to the PCM pack's 55 °C temperature, similar to previous case. The heat from the PCM disperses to the beeswax at a very sluggish pace during the 3300 seconds owing to the beeswax model and the barrier caused by the bees inside the beehive. In 13200 seconds, or roughly 3.6 hours, the temperature of the box rises to 40 °C. The temperatures in case 2 are as follows.

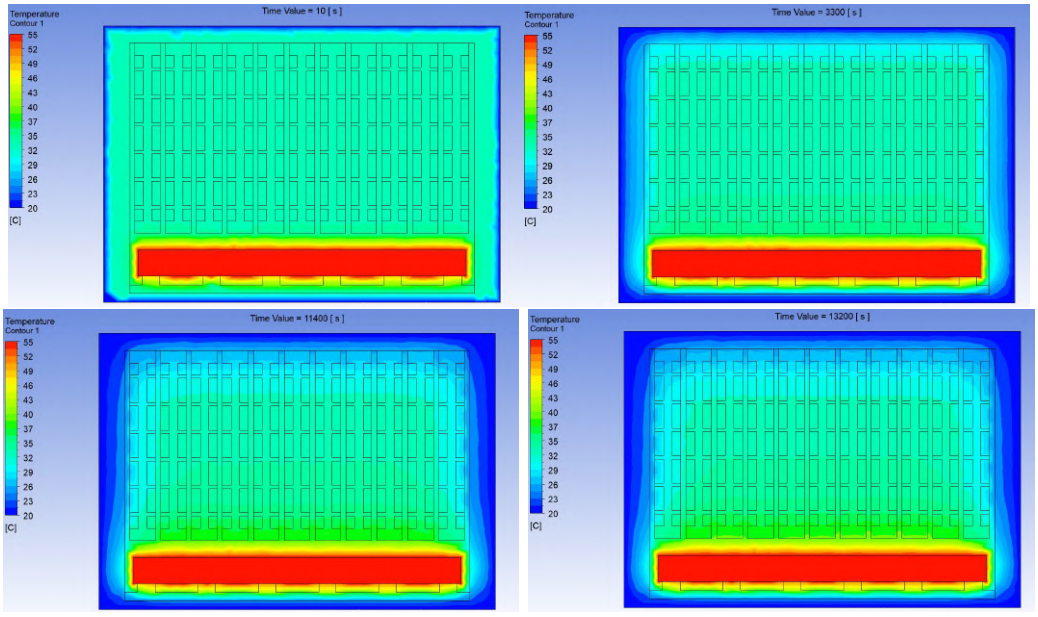


Figure 3.11: Temperature plots on a transient simulation case 2.

Comparing these simulations with the preliminary ones, it is observed that increasing the quantity of PCM simply improves the speed at which the required temperature is attained, not the maximum temperature. This hypothesis was later confirmed in the on-site experiments. The chemical composition of the PCM used defines its thermal performance and therefore its maximum operating temperature.

Both simulations demonstrate that putting a quantity of 3.5kg of supercooled SAT and activating it inside a enclosed brood box, with and without bees, resulted in a temperature increase sufficient to attain the thermotherapy range of temperatures (40-47 °C) mainly in the central area of the brood box, which is where the highest concentration of bees, broods and therefore Varroa mites are found. The validation of this hypothesis would take place in the experimental stage.

3.4 CFD simulation vs on-site test

Some environmental factors, such as solar radiation, had to be disregarded in order to make the simulations easier; just the ambient temperature was taken into account. Furthermore, as previously mentioned, it was unable to model the behaviour of the bees in terms of temperature control in the simulation where the bees are represented as a porous medium. However, it can be observed that the results are not drastically different when the beehive's central temperature from a successful on-site experiment is compared with the simulation. In Chapter 7, the development of the on-site experiments is discussed in detail.

For this comparison, temperature data from one of the deemed successful on-site trials were used. In other words, the CFD simulation (case 2) is compared to the outcomes of a thermal treatment that, in a real-world setting, succeeded to raise the temperature of the centre of the hive between 40 and 47 °C for an hour. In Figure 3.12, the central temperature determined from the simulation is compared to the central temperature measured in the tests.

As can be observed, the results are quite similar, despite that several environmental and behavioural factors were omitted from the simulation, as previously stated. From this, a root means square error of 1.22 was derived for the simulation. This result appears to validate the CFD analisys.

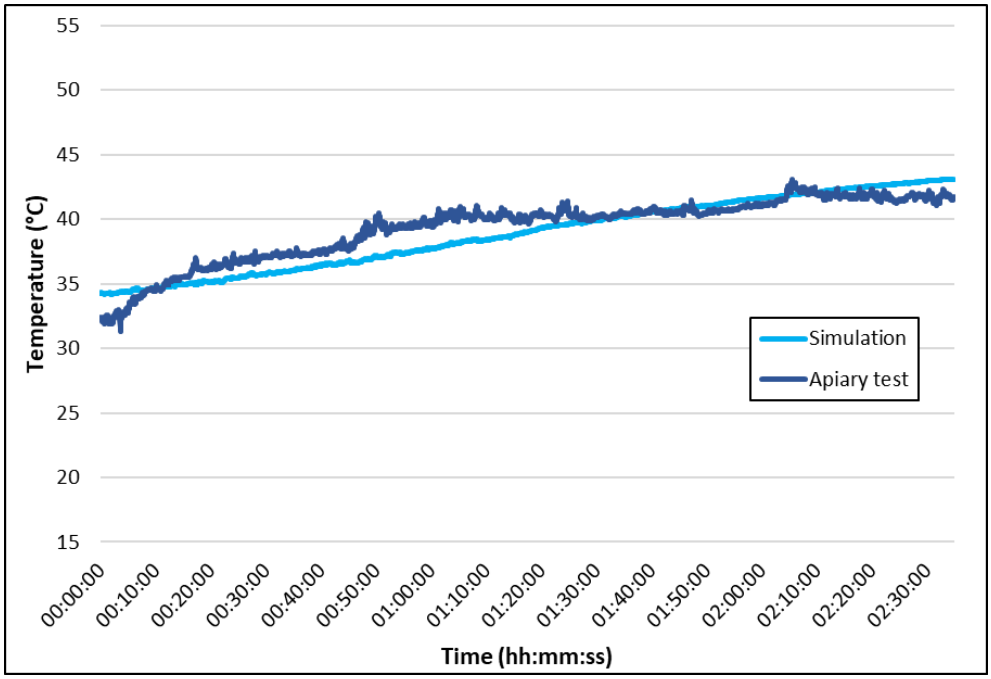


Figure 3.12: Comparison of simulations and experiments for validation.

3.5 Chapter conclusions

It was possible to develop a simple mathematical model that approximates the thermal interaction that occurs within the brood box when an active PCM pack is added. Due to the absence of air currents within the brood chamber, heat is transferred vertically from the base by natural convection. The study was conducted at four nodes positioned in the middle of the beehive's major regions: the PCM, the bottom, the centre, and the top. This analysis assisted in sizing the PCM pack and determining that around 3.4kg is required to attain the thermotherapy temperature in the brood chamber's centre.

Preliminary simulations were also conducted to assist visualise the heat movement inside the beehive and determine if, given the temperature of the PCM pack, a thermotherapy temperature in the required range (40 - 47 °C) would be obtained, or if overheating would occur. The results demonstrated that, even under perfect working circumstances, the PCM pack is incapable of overheating the beehive's interior. Naturally, in a real-world scenario, there is a genuine risk of overheating, since the temperatures achieved were extremely near to the bees' maximum tolerable range. Additional variables like as humidity and bee density must be considered.

While certain assumptions were made to simplify the computations, the primary simulations aided in predicting the behaviour of the PCM pack, determining the temperature distribution, and estimating the time required to attain the thermotherapy temperature. This prediction was compared to laboratory and apiary outcomes. Then, it was noted that the temperature change within the brood chamber was quite similar to that seen in laboratory testing and comparable to

that reported in apiary studies. Thus validating the simulations.

There are several precedents for mathematical modelling of the thermal interactions inside a beehive, but since this application is novel, there are no precedents for CFD analysis of a beehive employing a heat source. This simulation can prove helpful as a reference for future thermotherapy research.

Chapter 4

PCM pack design

The technology used to store thermal energy, phase change materials (PCMs), is discussed in this chapter. The selection criteria are described, and the techniques considered for their application are covered in depth. The many prototypes created and their properties are displayed.

4.1 Phase Change Materials

In recent years, phase change materials (PCM) have gained prominence, particularly in the field of construction engineering. The term PCM refers to any material that is capable of storing and releasing huge quantities of thermal energy during phase transitions. As a result, they are useful for heating and cooling applications.

When melted or frozen at certain temperatures, PCMs either release or absorb thermal energy. When a material is heated, its internal temperature increases as long as no phase change occurs. This is known as sensible heat. In general, it refers to a material's ability to absorb heat energy as a result of a rise in temperature [116]. PCMs, on the other hand, get their high energy density from fusion's latent heat. When a substance is heated and undergoes a phase shift, its internal temperature does not dramatically rise, but a considerable quantity of energy is absorbed or released [117]. PCM storage of latent heat may be obtained by any phase changes between liquids, gases, and solids. However, the solid-liquid phase transition is the only one employed for commercial PCMs. Due to the enormous amounts or high pressures required to store the materials, phase changes from gas to liquid or solid to gas are not viable for thermal storage. For solid-solid PCMs, heat is generated by a change in the crystalline structure; it is well established that the heat generated by this transition is far less than that produced by solid-liquid PCMs [118].

Although water is the most well-known phase change material, any chemical compound undergoes phase change at a specific temperature and pressure [117]. Numerous PCMs are available with a broad operating temperature range of -5 to 190 degrees Celsius [119]. One of the primary uses has been human comfort; operating at temperatures ranging from 20 to 30 degrees Celsius, the PCM is very practical due to its ability to retain up to five to fourteen times more heat per unit of storage space than conventional materials such as water. PCMs are employed

in cooling and heating applications because they imply significant energy savings. As a result, it is a material that is thriving in the building industry, due to its proven high efficiency.

Typical usage consists of a container enclosing the PCM, for example in solid phase; as the ambient temperature rises, the core of the PCM absorbs the heat energy from its surroundings, melts, and transitions to liquid phase, when the temperature lowers, the PCM cools down reverting to solid phase and releasing its heat energy to the surroundings. Therefore, any interest in energy saving in a building should contemplate the incorporation of PCMs.

4.1.1 Classification of PCMs

Currently there are around 200 substances that stand out as promising PCM because of their characteristics [120]. PCMs can be classified according to their type of material. Based on the chemical composition, solid–liquid PCMs are divided into organic, inorganic and eutectics as shown in Figure 4.1.

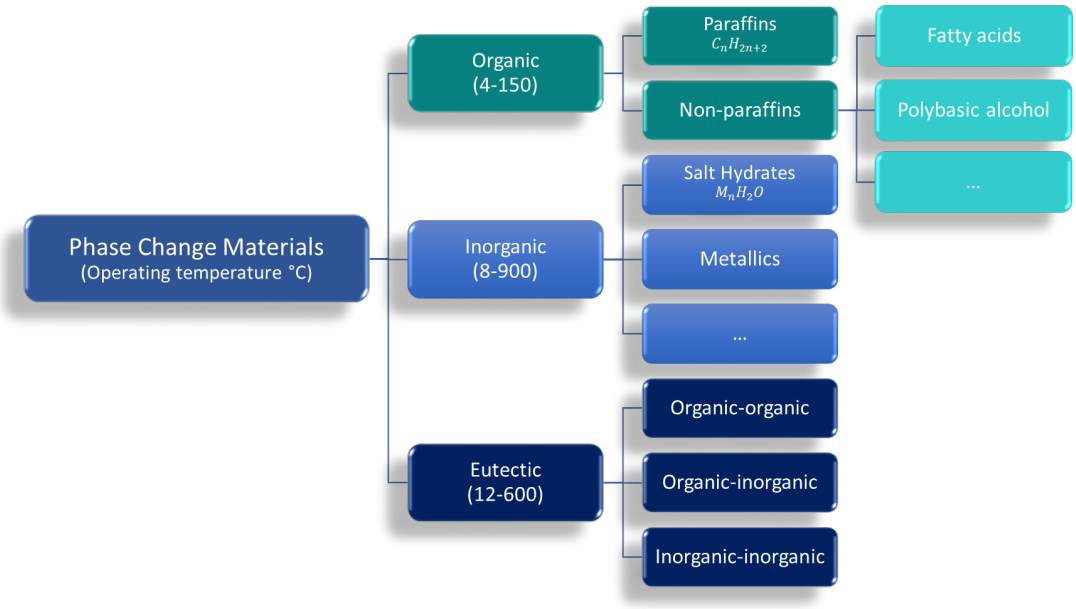


Figure 4.1: PCM classification according to their material [117, 118, 121, 122].

In general, they can be organic, inorganic or a combination of these. An example of organic materials are paraffins, which are thermally and chemically stable. Although they have the disadvantage of low energy storage capacity and are more flammable with respect to inorganic ones. An example of inorganic are hydrated salts, which stand out because they are more difficult to treat than organic and have less stability. Table 4.1 reviews the advantages and disadvantages of the main types of PCM.

Organic compounds

As the name implies, they are compounds with carbon as a constant component in a molecular structure. The most used organic PCM for thermal energy storage are paraffin waxes, alkanes and other compounds such as sugars, amides, ketones, dienes, among others [118].

They are classified as paraffins and non-paraffins, the latter includes but not limited to: fatty acids, esters, alcohols, etc. Experimental tests that involve cycles of melting and freezing, have demonstrated that upon crystallization they present little or no subcooling in addition to being mostly non-corrosive and chemically very stable [123].

Inorganic compounds

Opposite to the previous category, in these compounds carbon is not the main component, while others such as water can be fundamental. Inorganic PCMs are classified as salt hydrates, metals, metal alloys, etc. The most suitable PCMs are metallic salts such as nitrates, sulfates, flourides and carbonates, highlighting the sodium sulfate decahydrate and magnesium chloride hexahydrate [118].

Eutectics

These materials have been specifically engineered to satisfy certain thermophysical properties. They are the result of the integration of two or more components (molefraction) in the eutectic point derived from its phase diagram [118]. The components that are integrated in these types of materials can be either organic, inorganic or a mixture of both. These compounds are designed to prevent the segregation of their components when melting or freezing. The eutectic PCM melts practically at constant temperature [123]. This category includes metal eutectics and salt eutectics.

Table 4.1: Advantages and disadvantages of the different kinds of PCM [117, 118, 121].

Classification	*Advantages*	*Disadvantages*
Organic PCMs	**1.** Availability in a large temperature range **2.** High heat of fusion **3.** Not much super-cooling or sub-cooling **4.** Recyclable **5.** Chemically stable **6.** Good compatibility with other materials **7.** Ability to melt congruently **8.** No segregation **9.** Can be produced from renewable resources **10.** Safe and non-reactive **11.** Self-nucleating properties **12.** Ability to melt congruently **13.** Good thermal performance **14.** Low vapor pressure in phase change process	**1.** Low heat capacity **2.** Low thermal conductivity in their solid state **3.** Low phase change enthalpy **4.** High heat transfer rates are required during the freezing cycle **5.** Relative large volume change **6.** Flammability **7.** Volumetric latent heat storage capacity can be low **8.** More expensive
Inorganic PCMs	**1.** High volumetric latent heat storage capacity **2.** Availability and low cost **3.** Lower volumetric expansion **4.** Sharp melting point **5.** High heat of fusion per unit volume **6.** High thermal conductivity **7.** Grater phase change enthalpy **8.** High heat of fusion **9.** Non-flammable **10.** Less costly **11.** Recyclable	**1.** Corrosive to many other materials **2.** Lack of thermal stability **3.** Phase segregation **4.** Chemical instability **5.** Incongruent melting and dehydration during thermal cycling **6.** High degree of supercooling **7.** High change of volume **8.** Compatibility issues with some building materials **9.** Requires container and support **10.** Need nucleating agents which may become inoperative after repeated cycling
Eutectics	**1.** Sharp melting temperature **2.** High volumetric thermal storage density **3.** No phase segregation **4.** Congruent phase change **5.** Extra water principle can be used to avoid phase change degradation	**1.** Low total latent heat capacity **2.** Limited data of thermo-physical properties is available **3.** Costly **4.** Potential sharp crystals when solidifies, may affect encapsulation **5.** Some suffer from super-cooling effect

4.1.2 Selection Criteria

Similarly to any other engineering material, the requirements of the application must first be known. However, since they are also used as energy storage systems a PCM must also be selected taking into account the thermal needs. The ideal would be to find a material that meets the desirable chemical, technical, thermophysical and economic characteristics, however this is not usually the case. According to [120] the thermophysical aspects such as latent heat of fusion, thermal conductivity and melting temperature should be prioritized. Then it will be necessary

to compensate for the deficiencies presented by the PCM, for example by adding graphite to increase the thermal conductivity or introducing a nucleating agent to avoid supercooling, all in the interest of reducing the inherent disadvantages of its composition. Having these features covered the remaining ones can then be adjusted.

As stated above, not all PCMs have potential application. The essential requirements for PCMs to be used for practical uses according to Lin [122] are:

1. Phase change temperature that satisfies the operation requirements.
2. High latent heat storage capacity.
3. High thermal conductivity.
4. Stable thermal and chemical properties.
5. No or little supercooling.
6. Inoffensive to the environment, non-corrosive and non-toxic.
7. Little volume change.
8. Good availability and low cost.

4.1.3 Incorporation methods

In order to use a PCM in any application, it is necessary to use an appropriate integration method. Since they are phase-changeable, it must be considered that at some point they may be fluid and change later, or that changing their crystalline structure may alter their volume. How the thermal energy will be released has to be considered. The main techniques of PCM integration are direct incorporation, immersion, encapsulation and shape stabilization.

4.1.3.1 Direct impregnation

Early research into the integration of PCMs focused mainly on direct integration and direct immersion. For direct impregnation, the PCMs are simply added into the building materials during their production, either in powder or liquid form. Thus, PCM can be added to concrete, gypsum or other porous materials. The isolation of the solid crust of the PCM is avoided due to the small volume that the PCM occupies inside the pores of the container material. It is this same porous structure of the materials that facilitates the conduction of heat between the pores. Unfortunately, the presence of PCMs in these porosities can detriment the mechanical properties of the container [120]. The biggest advantage of this method is its simplicity, which makes it the most convenient and economical. However, it may present problems with leaks or not be fully compatible with the impregnated material, which hinder its generalized applicability [117].

4.1.3.2 Immersion

Direct immersion is another fairly simple integration method. It consists in taking the bricks, concrete, plaster or any other building materials already manufactured and immersing them in PCM in liquid phase. The porous structure of the construction material absorbs PCMs from its surface through the pores using capillary elevation [121].

Its biggest disadvantage is that after a long number of thermal cycles, significant leaks occur as a result of the PCM being exposed on the material's surface [117]. On the other hand, it has also been discovered that it can affect the material's mechanical properties and compromise its durability due to corrosion. Because of this, this technique has not spread widely.

4.1.3.3 Encapsulation

In this group of techniques, the PCM is enclosed before being used in any other material [120]. In most cases, the PCM goes through a liquid phase during a thermal cycle, in this stage the encapsulation prevents leakage. Thus becoming a straightforward solution of incorporation. The enclosure can be a tank, a coating material, or a capsule formed by embedding the PCM in a matrix.

The enclosure containers must have certain characteristics. They should be a barrier that prevents harmful interaction with the environment or vice versa, for instance, they should not have any chemical interactions [117]. They should also facilitate heat transfer, both for its material composition and surface area keeping enough thermal stability. They must be resistant to corrosion and provide the mechanical characteristics that the application demands, such as flexibility or strength [123]. The shell must be sufficiently robust to withstand the increased pressure caused by the PCM volume change during the phase transition. Occasionally, an air gap is left inside the shell to permit volume variations during thermal cycles [118].

Mostly three methods have been developed, they are classified depending of the capsule size: bulk storage, macroencapsulation (1 mm to >1 cm), microencapsulation (1 lm to 1 mm) and nanoencapsulation (<1 lm). These methods are discussed in further detail below.

Bulk storage This is the most basic encapsulation system, it consists of enclosing PCM in large tanks. The tanks contain the PCM and act as heat exchangers.

This method requires little processing of materials therefore it is highly cost-effective [117]. The problem with this method is that its thermal conductivity is deficient. This limitation has been tried to reduce using particles of high conductivity, inserting fins, metallic structures or fibers in the PCM [117].

Macroencapsulation In this method, the PCM is packed in containers such as panels, tubes, spheres or pouches with dimensions ranging from centimeters to a few meters [123].

This technique is easy to manufacture and solves the problem of leakage. There are also covers that can prevent corrosion and thus allow the encapsulation of inorganic PCMs [117]. In contrast, it has some disadvantages, including low thermal conductivity and the propensity of PCMs to solidify at the corners, impeding efficient heat transfer [121]. These factors have made integration with building materials and other applications complicated.

Microencapsulation In this method of encapsulation, a PCM particle is wrapped in a thin film sealed made of polymer with high molecular weight, capable of retaining form and avoiding leakage. The capsule containing the PCM can have a spherical or rod shape and has a few microns in diameter (1 – 1000 lm) [121]. The manufacture of the microcapsules can be by physical or chemical methods [120].

The capsules are very easy to manufacture and economical to incorporate to construction materials. They are able to preserve their geometric profile after many thermal cycles [121]. The shell is tolerant to volume changes of the PCM [123]. Due to their size, they can be applied in portable heat storage systems. There is better heat conductivity because the PCM can have a larger contact surface. Compared with macroencapsulation, microencapsulation is capable of charge and discharge faster due to its enhanced surface area [118]. On the other hand microcapsules can have a detrimental effect on the mechanical strength of the structures in which they are applied. Another disadvantage is that the shell can affect the thermal properties of the capsule due to its small size. This technique still needs improvement in certain aspects such as reducing flammability [117].

Nanoencapsulation This is the most recent encapsulation technique. In concept it is similar to microencapsulation but its processing is different. Nanocapsules in addition to preventing leakage, like the previous encapsulation methods, have also been shown to improve heat transfer and thermophysical properties. It has also been found to have a long life in the charge-discharge cycles and to have high thermal stability with a minor drop in melting point [118].

4.1.3.4 Shape-stabilized

This technique is simple as it does not require any device or container to encapsulate the PCM [121]. It consists of mixing a PCM with a support material, the result is a shape-stabilized PCM. To mix both materials first high temperature must be applied until both can melt and combine together, then cool the mix until the support material solidifies in such a way that it prevents the PCM from leaking.

Although it has been reported a great apparent specific heat and capacity to maintain its form during the phase change cycles, it is also known that the shape-stabilized PCMs do not have very high thermal conductivity, which makes them unattractive for use in heat storage systems [120].

4.2 PCM selection

The selection of PCM was carried out in accordance with the methods given by Riffat [117]. On the one hand, research was made on the technology that is available, which was discussed above in this chapter. On the other hand, the requirements and specifications were identified, this research is summarised in the previous chapter. From this point on, the process is iterative to refine its design each time.

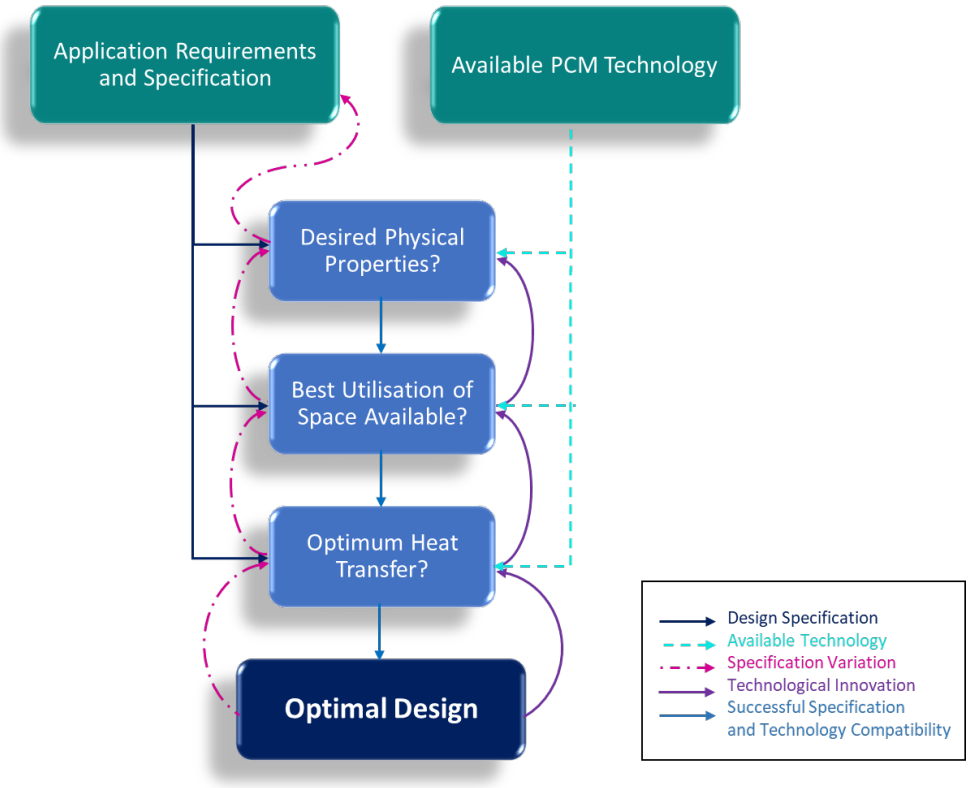


Figure 4.2: PCM selection methodology. Reprinted from [117].

The necessary physical features are only limited by the space available within the National standard beehive and the fact that the material should never come into direct contact with bees. Following the original PCM selection criteria, it became obvious that organic PCMs would be inappropriate for this application due to higher flammability hazards. As a result of this finding, the PCM selection process was reduced down to those based on salt hydrates, namely those that are stable in a supercooled condition, allowing for utilisation on demand.

The main requirement for this application is to reach the temperatures between 40-47 degrees Celsius, which is judged adequate to kill Varroa mites but not harmful to bees. Therefore, the PCM to select must be capable of reaching a temperature of about 50-60 degrees Celsius. Also, in other to store thermal energy and release it on demand, the PCM needed for the system must be capable of supercooling; this is the process by which the PCM cools below its freezing point while remaining a liquid. This process may occur in a variety of materials, but it is critical that the liquid cools to ambient temperature in a stable form.

The only PCM available that meets the project's precise specifications is Sodium Acetate trihydrate (SAT). The following characteristics were considered while selecting this material:

- Small phase transition temperature range, which is between 1-2 degrees Celsius of desired freezing/melting points.
- High volumetric heat capacity.
- High thermal conductivity.
- Uniform freezing and melting.

• Quick crystallisation for successful heat energy recovery.
• Completely reversible freeze/melt cycle.
• No degradation on repeated phase transitions, which together with the preceding point, makes it reusable.
• Compatible with plastics such as HDPE, GRP and metals such as stainless steel for encapsulation.
• Non-toxic, non-flammable, non-hazardous, non-corrosive.
• Low cost and readily available.
• Phase transition temperatures according within tolerance of bee and brood.

Sodium Acetate Trihydrate (SAT) solution is one of the substances with the highest proven potential for energy storage due to its low cost, ease of operation and high stability in metastable state [124]. It is an inorganic PCM with a high latent heat of fusion of 264 kJ/kg yielding 41 kJ for a regular 300 ml pack and a melting point of 58 degrees Celsius [125]. Hirano [126] demonstrated that supercooled thermal heat storage was more efficient than ordinary thermal heat storage using a numerical simulation.

4.2.1 Triggering supercooled SAT

To make practical use of the stored thermal energy, a regulated and, ideally, automated activation of the crystallisation is required, followed by the release of heat. Numerous methods have been discovered in the literature for activating a supercooled PCM at a specific moment. There are just a few devices or methods that may initiate nucleation in the SAT. Sandnes [127] distinguishes two major kinds of crystallisation techniques: dynamic nucleation and seeding.

Since this kind of material has been studied, it has been discovered that the easiest method to crystallise it is to combine a crystallised fragment with the same supercooled substance [128]. When a crystal is placed into a liquid, it absorbs the molecules surrounding it, duplicating its crystalline structure throughout the material as long as there is accessible fluid, all the while emitting heat energy. Dynamic nucleation is the crystallisation process that is triggered by external stimuli such as vibrations, collisions, agitation, or friction. Some of these activation methods have been investigated in the laboratory utilising SAT as a supercooled PCM, and are addressed below. In both circumstances, once nucleation occurs, a network of solids quickly spreads throughout the liquid's interior. When this occurs, the solid reaches near temperatures near 55 degrees Celsius. A more detailed explanation of the nucleation process is provided by Rogerson [129]. However, not all liquids solidify instantaneously, and the pace at which they solidify is governed by the heat transmission to their surroundings, as proven in the experiment below in this text.

To recharge the PCM pack, it is enough to melt the solid again until the crystals are completely dissolved and allow it to cool down to room temperature. According to the literature, this charge and discharge procedure may be repeated hundreds of times. Experiments conducted during the creation of this paper seem to corroborate this.

4.2.1.1 "Cold finger"

The introduction of an element foreign to the substance, which is at a low temperature, generates a cold spot that triggers the crystallization.

4.2.1.2 External seeding

The direct insertion of a physically separated crystal into a liquid substance is one of the most simple techniques for causing crystallisation to occur. An example of a potential use is a valve that, when opened, permits the deposition of the crystal inside the fluid to take place. Crystallization may commence in each PCM container unit with a single activator in this manner if more than one PCM container unit is linked to each other. It is necessary to get access to the PCM from the outside in order for this activation technique to work, which makes it less practical than other methods.

4.2.1.3 Internal seeding device

Commercially, the supercooled SAT is sold in plastic packaging as hand warmers like the one shown in Figure 4.3a. Crystallization is triggered by bending a concave coin (Figure 4.3b) from the outside of the packaging, which occurs when the coin is folded from the outside of the box. When the disc is pressed, the growth of the crystals can be seen to start from their cut slits.



(a) (b)

Figure 4.3: (a)Commercial hand warmer with SAT. (b)Activation disk.

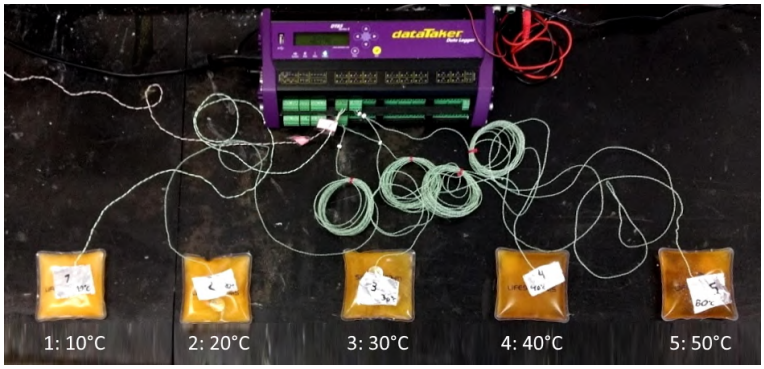
Similarly, there are various auxiliary devices that may be used to initiate crystallisation, such as springs or other types of metal pieces capable of elastic deformation. Sandnes [127] estimates that at a pressure of roughly 50,000 bar, minute shards of crystal are caught in the roughness of the slits. Even if the remainder of the material is at melting point, the seed crystal will not change phase under such pressure. Thus, as long as the device has comparable qualities or offers the same circumstances, an activator of this kind may take on an infinite number of different configurations while still operating on the same principle. According to Sandnes [127], any such activator must meet the following requirements to be reliable:

1. Have opposing surfaces that the seed crystals must be confined between.

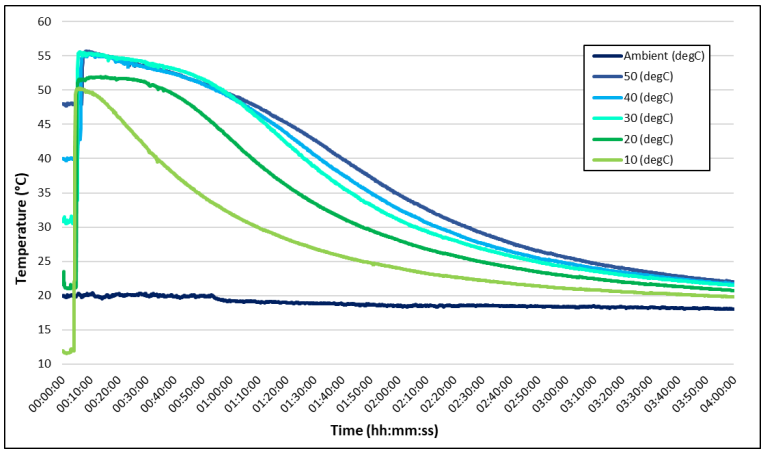
2. Have an opening and shutting mechanism for these surfaces that enables for the discharge of seed particles to initiate nucleation while maintaining the aforementioned pressure to avoid melting.

This approach was validated in the laboratory using five commercially available PCM packs. Each at a different beginning temperature of 10 degrees Celsius, ranging from 10 to 50 degrees Celsius, as seen in the Figure 4.4a.

The results indicate that the PCM functions better at a greater temperature. It was noticed that as temperatures rise, the solidification becomes weaker, with the fifth pack becoming practically liquid at 50 degrees Celsius because to its proximity to the SAT melting point. This is seen in the Figure 4.4b and is consistent with the findings of Hirano's numerical simulation [126], which indicates that when the storage temperature is greater than the ambient temperature, the PCM is more efficient.



(a)



(b)

Figure 4.4: (a)5 commercial PCM packs triggered at different initial temperatures. (b)Results of 5 simultaneous triggering of packs with different initial temperatures.

4.2.1.4 Electrical nucleation

This approach involves submerging two electrodes in the PCM and then placing a voltage between them to begin nucleation [130]. While the procedure varies, a critical aspect in many is the precise preparation of the electrodes. The electrodes

are sanded very precisely and polished to trap small crystals in their roughness. Once the electrolysis process starts, some of these crystals are discharged into the liquid, where they crystallise. It has the benefit of requiring no moving components and allowing for exact control. Additionally, it enables greater container variety for PCM. Sakurai provides a very thorough and extensive description of how to build this sort of mechanism in SAT in [124].

One problem noticed in the studies is that the electrode materials degrade, either via corrosion caused by PCM or degradation caused by electrolysis. Additionally, it has been shown that the SAT becomes polluted after numerous cycles, reducing its thermal performance.

This is in addition to the risk that the electrodes would ultimately run out of trapped crystals, resulting in unpredictable repeatability, which is not desired in an energy storage device. Additionally, it may be considered a drawback since this sort of activation requires an external power source and that the requisite equipment may not be easily implemented or inexpensive [131]. However, the necessary power is not excessive and often does not exceed 5 V.

Silver is a common material for electrodes (Ag). In [132], a research on electrode material combinations is given. For the current research, studies were conducted using Ag as the anode and Cu or Graphite as the cathode. It was established that nucleation always begins at the Ag anode's surface and not at the Cu anode, even at voltages greater than 2.6 V, and that elution of the Ag anode is required. This tests validated Sakurai's hypothesis that high voltages improve reaction time but reduce repeatability [131]. One issue that arised testing this form of activation is the crystals' ability to flow through capillaries, such as the wires employed.

Figure 4.5 shows the sequence of activation of a 300 ml SAT with 15% of water content, using 9 V with Ag and graphite electrodes.

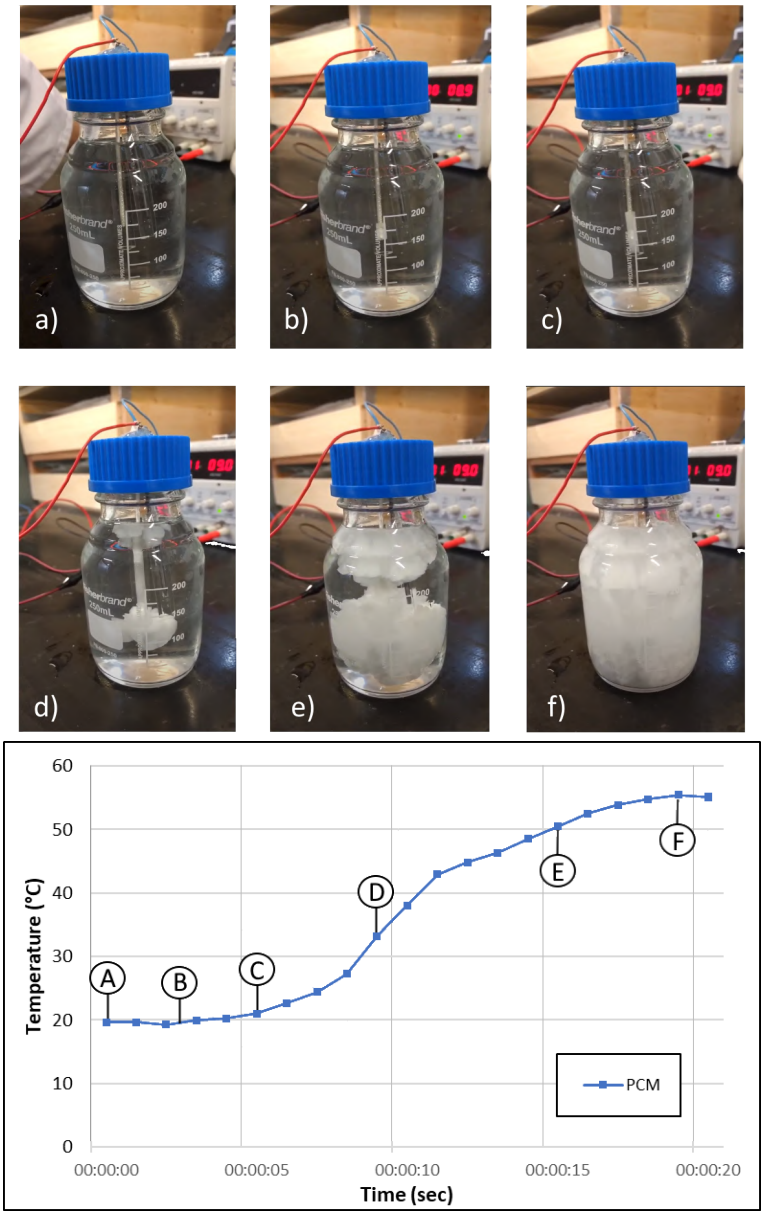


Figure 4.5: Electric activation of SAT.

4.2.1.5 Cavitation nucleation

Sandnes [127] explains nucleation in terms of shock waves, ultrasonic vibration, and friction, highlighting that these stimuli induce cavities to collapse, resulting in the concentration of very high local pressures. In the same document, the author discards the possibility that friction, shock waves, or ultrasonic cavitation might initiate the nucleation of a SAT solution after a series of tests. Simultaneously, Hirano [133] and Rogerson [129] disregard these stimuli effects in compounds similar to SAT. Nonetheless, Hatkar [134] demonstrates that ultrasonic irradiation assists in avoiding purposeful seeding and that the distribution and ultimate average size of the crystal may be changed using the ultrasound operating settings.

4.2.2 Saturation of SAT with water

When working with salt hydrates, a balance must be sought in the proportions to avoid instability in the compound. An unstable mixture is characterised by spontaneous nucleation, this may also be induced by the container's excessive roughness. Additionally, to establish a stable combination, it is advised that lower cooling rates and longer charging durations be used. A variety of saturated samples with water concentrations of 42%, 44%, and 46% (i.e. 4%wt, 8%wt and 11%wt respectively) were evaluated, and it was shown that a higher water concentration enhanced the solution's stability. However, it was discovered that in order to produce this stable supercooling, the sample had to be heated to temperatures more than 80 degrees Celsius. This is seen in Figure 4.6. Additionally, these samples were kept in a supercooled condition for a 5-day period; the totality samples stayed supercooled during that time period.

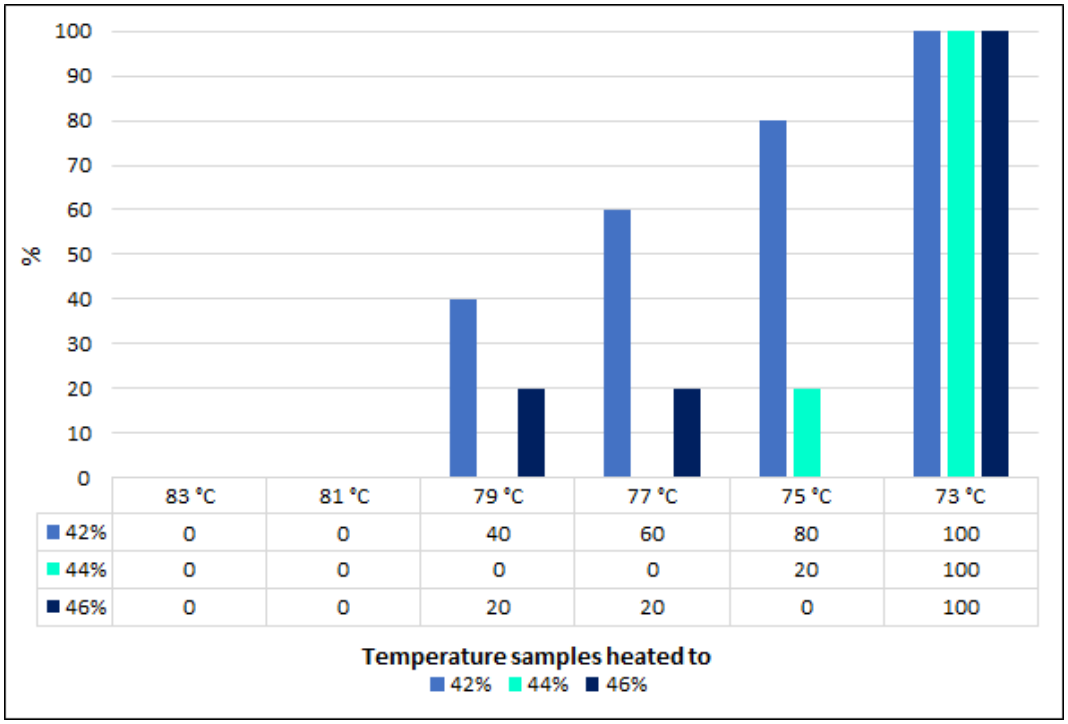


Figure 4.6: Percentage of samples spontaneously nucleated at different solution concentrations.

4.2.3 Stability improvement

This material is notorious for its unpredictability in terms of supercooling characteristics owing to anhydrous salt separation and spontaneous nucleation. Numerous studies have been undertaken on different alterations, such as saturation percentages and thickening agents. To improve steady supercooling, two commonly used additives were tested.

First, xanthan gum was added to the saturated samples, this was to prevent the anhydrous salt dropping out of solution. Samples containing 0.5% xanthan

gum showed no separation throughout the sample due to the latent heats of each section remaining constant. Comparing these results with samples that contained no xanthan, it is apparent there is separation due to the fluctuation in latent heat thus confirming adding xanthan to the sample prevents any separation of the anhydrous salt and therefore prevents spontaneous nucleation.

The second additive tested was ethylene glycol (EG). In this test, samples of SAT/water solution with 2%wt, 3%wt, 5%wt, and 7%wt of EG showed the highest activation temperature of 55.8°C, 54°C, 52°C and 51°C, respectively. All the solutions were very stable at room temperature above 16°C. The highest temperature of the PCM pack without EG can reach 56.1°C. No data showed the samples with EG can provide a longer heating time. So as a conclusion, with the similar activation temperature, the SAT with 2%wt EG can remain liquid in lower temperatures up to 14°C, but the heating capacity is the same.

In both cases, although an improvement in stability was demonstrated, it was accompanied by a decrease in surface temperature, which is critical in this application. Therefore, it was decided to discard the use of additives and use SAT with 44% water, since this was the concentration that obtained the highest surface temperature of 55-56 degrees Celsius.

4.3 Prototype design

Following the review of the state of the art in thermotherapy devices, it was determined that these devices often fell into one of Tihelka's [98] two categories: thermal boxes and thermal hives. However, it was noted that more modern devices can be classified into a new category of thermal inserts. This proposed category includes any feature other than a standard beehive that is incorporated into or replaces any of the more conventional parts, for instance the floor or roof. (Figure 4.7)

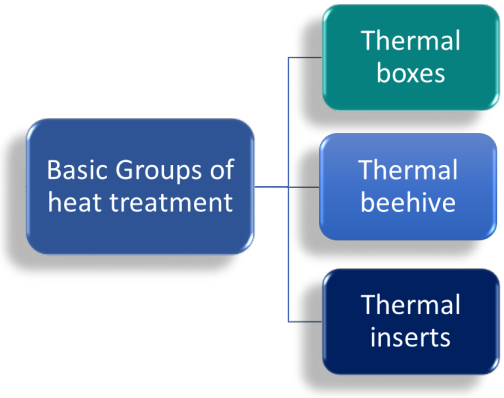


Figure 4.7: Classification of thermal treatment devices.

As a result, the suggested prototype would fall under the latter group. Because the thermal capacity of the chosen material is adequate to attain and sustain the desired heat treatment temperature when inserted into the beehive. This theory was first investigated in simulation, as discussed in the next chapter.

Following that, some concepts of how the PCM could be encapsulated for use were outlined. The objective was to create a container made of a material that would retain the liquid within. In Figure 4.8, some of the conceived concepts are shown. These approaches are based on the premise that increasing the transfer surface area will result in increased heat dissipation to the outside of the package. For instance, a bubbled surface may increase the surface area by up to 30%.



Figure 4.8: Prototype concepts.

Additionally, some alternative proposals were devised, one of which is a PCM panel array with magnetic vibrator activation button. The magnetic vibrators are connected together to a power supply which can be used to trigger the magnetic vibrators to initiate the crystallisation and hence heat release. The amount of heat released can be increased by activating more PCM panels.

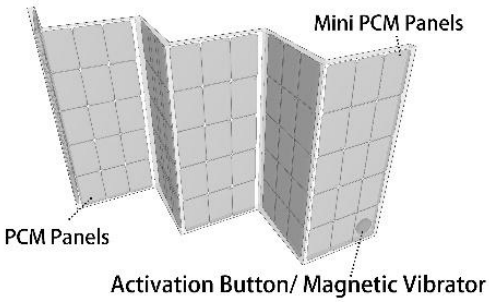


Figure 4.9: Design concept of PCM panel as a foldable screen with multiple PCM capsules.

Another approach developed made use of electrical activation. In this unique design, two electrodes, a signal receiver and controller are employed to trigger the PCM panel nucleation and heat release. A very small current flowing between two electrodes which could be used to induce reaction in supersaturated SAT. Even a small change in pH around the electrodes might be enough for the crystallization activation. The attraction of this idea would be switching on setting directly when required from a micro-processor control unit. And it can be easily activated by remote control. Cu, Ag or Au electrodes could be used. The electrodes, which can be plated Ni rather than pure metals should be smooth and have a reasonably large radius, i.e. not wires, since the small sharp points can induce crystallisation. Figure 4.10 illustrates this concept.

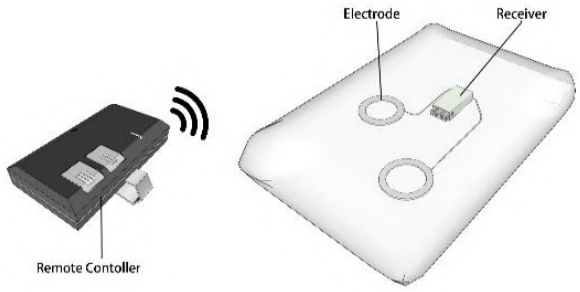


Figure 4.10: Design concept of PCM packs with a signal receiver and controller to trigger it.

4.3.1 Triggering

Following the examination of the different SAT activation methods, the possibility of employing electrical activation was considered, since it would enable the addition of circuits to programme the activation or to do it remotely. However, this concept was abandoned since it needed the addition of more components and, most importantly, a source of electrical energy. Most apiaries lack an electrical power outlet close to the beehives, and utilising a battery would diminish the product's sustainability.

The simplest approach was identified to be the use of a mechanical internal seed solution. Since with commercial hand warmers, including a triggering coin is the easiest form of activation for these sorts of applications, as the user manipulates the package and also has the ability to activate it at whim.

4.3.2 Shape

The shape was determined by the beehive. Because the base geometry of the beehive is rectangular, the packaging should be rectangular to optimise the surface area. However, different sections shapes were explored to allow for folding, which would ease storage and recharge.

4.3.3 Materials

For the PCM encapsulation method, the investigation was directed towards the different materials. When selecting materials, it was important that they were readily available, durable, had a high heat conductivity, and could survive the SAT's recharge temperature (85 degrees Celsius). Simultaneously, it was desired that they be materials with a long useful life and a low environmental impact during manufacture.

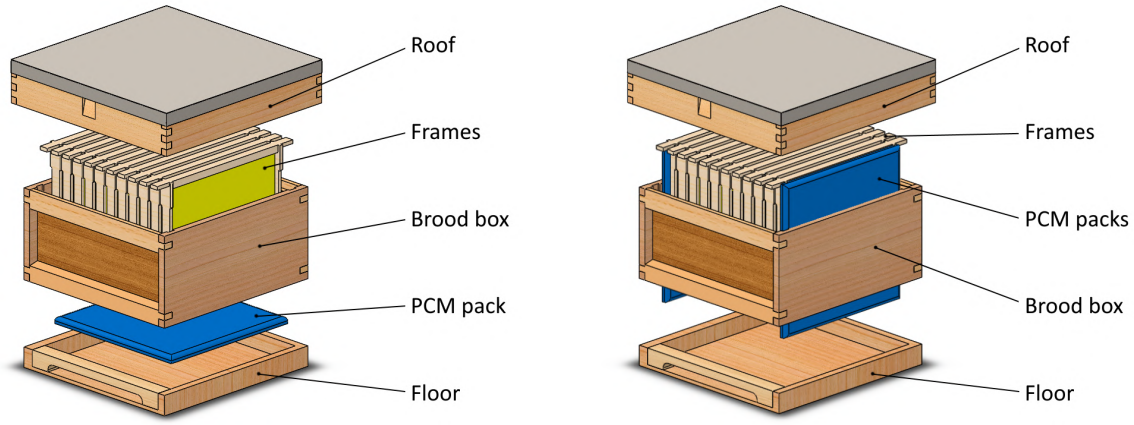
Several of the approaches shown in Figure 4.8 aimed to maximise the package's surface area. However, to obtain such shape factors, a material that retains its stiffness is necessary. While certain polymers were discovered to be capable of being moulded into this shape, they could not withstand the high temperatures

necessary to recharge the material. On the other hand, the materials that were able to survive the high temperatures, lacked thermal conductivity.

Therefore, investigation was directed towards the different materials. Various different materials were trialled and only a handful had acceptable characteristics, such as aluminium, different plastics and mylar.

4.3.4 Position

Due to the limited space inside the beehive, two viable solutions were identified. The first of them was to vertically position the PCM container either between or in lieu of beehive frames. Alternatively, it might be positioned horizontally, either above or below the brood box. The two alternatives were tested.



(a) (b)

Figure 4.11: PCM pack position alternatives: (a)Horizontal (b)Vertical.

4.4 Prototypes produced

Multiple different prototypes were created in order to determine the material with the highest heat transfer and to design a product that may potentially be mass manufactured and utilised by beekeepers. Each of these prototypes was evaluated in the laboratory, with some being evaluated on-site.

The rigid packaging prototypes allow for vertical placement. Small packaging prototypes offer a modular design with few interchangeable parts, and flexible designs can be more easily stored and carried.

For one set of prototypes, prefabricated aluminum boxes 120 by 10mm in size were utilised. Aluminum containers (Figure 4.12) had the highest heat transmission capacities of all six prototype containers, but they were expensive to construct and had a high probability of self-nucleation. Additionally, it was unable to determine whether the PCM had completely melted or self-nucleated prior to testing, making the encapsulation approach too unreliable.



Figure 4.12: PCM aluminum cases (each 333 g).

Another produced prototype was created using a container made of a 50mm corrugated plastic pipe (Figure 4.13). The purpose of the protruding tubular surface was to enhance the transfer area. Additionally, the hose allowed for several configurations on the beehive's floor. An external activation mechanism was developed.



Figure 4.13: PCM Corrugated hose container (4 kg).

Figure 4.14 shows another prototype produced. The Mylar bag provided the second-best heat transmission of the pouches, was very simple to manufacture, and fit snugly into a recharging pan. The only issue was to determine if the PCM had completely melted during the charging process and activating with the metal disc was difficult.



Figure 4.14: PCM Mylar pack (2 kg).

The Mylar sheet has two layers, one of aluminium and one of plastic. The subsequent version was constructed entirely of embossed aluminium foil, obviating the need for an additional layer of plastic. Also, the concept of creating channels along the bag was introduced to increase the contact area and make it simpler to fold; this idea was used in future prototypes. Figure 4.15 depicts this prototype. As with Mylar, this material has the problem of making it impossible to determine whether the material has entirely melted inside the packaging. Additionally, its production was quite complex.



Figure 4.15: PCM embossed aluminum pack (2 kg).

To increase the contact surface area of the PCM pack, a prototype was built

utilising plastic with pre-sealed cushions or bubbles (Figure 4.16). Normally, this material is inflated with air and used to wrap shipments and absorb impacts. It has various benefits in this application, one of which is that, being a transparent plastic, the activation coin is plainly seen. Additionally, it is simple to determine if the inside has melted entirely or has been triggered. Despite its many benefits, due to its composition of high-density polyethylene (HDPE), it lacked durability and was easily punctured.

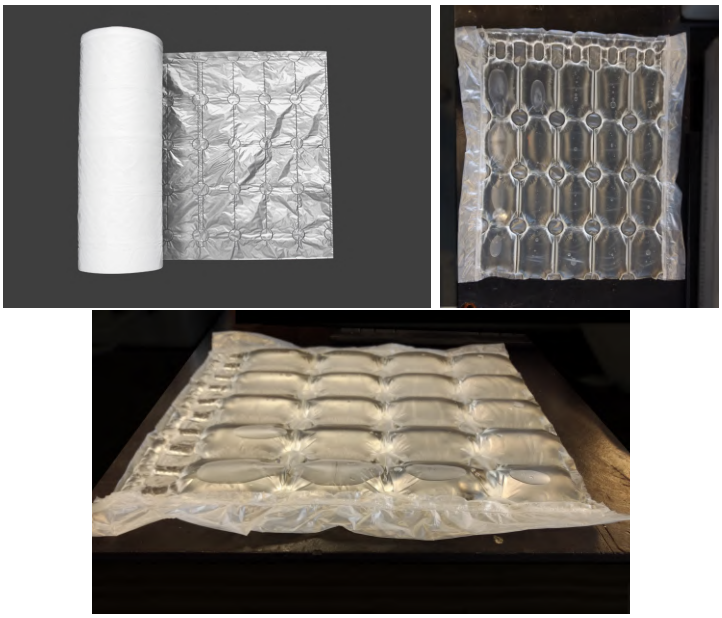


Figure 4.16: PCM HDPE "bubble" pack (2 kg).

A plastic package was manufactured in the same method as the previous prototype (Figure 4.17). This time, Polyvinyl chloride (PVC) was employed in a 0.5mm layer to circumvent the issue of poor mechanical resistance. From this point on, translucent materials were chosen because they are the most useful when using PCM.

Because this plastic is smooth, in comparison to the previous prototype's material, it was decided to seal lines along the packaging, generating grooves. The primary disadvantage of this prototype was that due to the thickness of the plastic, the heat sealers were unable to effectively seal the lines that created the ribs. Additionally, the seals were brittle when heated to recharge the PCM.



Figure 4.17: PCM PVC pack (2 kg).

Nylon was chosen as the material for the second prototype due to the issues with the prior prototypes. Nylon vacuum bags are extensively utilised, particularly in the food packaging industry. They are resistant to high temperature cooking at 120 degrees Celsius. It is a very strong material with very little chance of damaging. This, together with the ease with which they are commercially available, makes them an excellent material for the prototype. The design was simple to manufacture and had a very good heat transfer capability due to the thin material and embossed surface.

Unfortunately, since this material is marketed in conventional sizes for use in the kitchen, no custom sizes were feasible. Also, it was not possible to seal grooves in order to increase the surface area.



Figure 4.18: PCM Nylon pack (2 kg).

To create packs that maximised the beehive floor space, it was decided to investigate different polymers that were also resistant to high temperatures. Therefore, a set of prototypes used the material EVOH (Ethylene-vinyl alcohol copolymer) as shown in Figure 4.19. A 200um thick sheet was employed, which enables this plastic to tolerate temperatures of over 100 degrees Celsius, is very resistant to mechanical damage, and can be heated to recharge the PCM numerous times. The pouch was the easiest to produce out of the prototypes.

Although the heat transmission was somewhat less than that of the nylon prototype, it was adequate for the purposes of this research after the PCM formula was adjusted. One disadvantage is that when exposed to excessive heat, part of the transparency is lost and the plastic becomes whitish. When the plastic is cooled again, it regains some of its clarity.

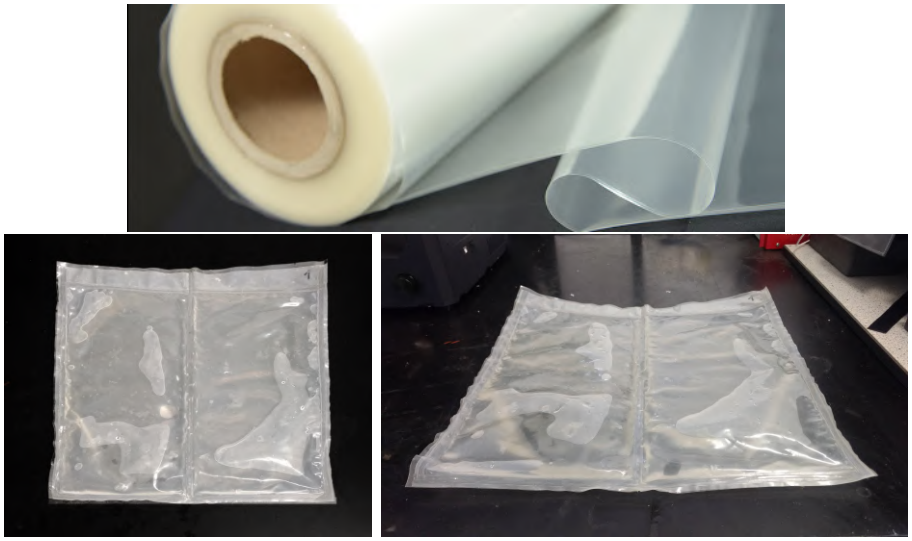


Figure 4.19: PCM EVOH pack (2 kg).

Figure 4.20 depicts a modified version of the previous prototype. The only difference was that this one attempted to increase the pack's portability by sealing grooves forming eight pieces connected in the centre. This pouch proved to be the best to fold. Simultaneously, these lines were supposed to enhance heat flow. However, its construction was difficult and tedious, and it did not provide a considerable benefit over the basic design.

This design showed that the presence of small corners or very sharp angles might allow minuscule crystals that are difficult to melt and can pass undetected, resulting in unintentional PCM nucleation.



Figure 4.20: PCM EVOH "X" pack (2 kg).

To increase the device's sustainability and viability as a marketable product, Polylactic acid or PLA biodegradable was employed (Figure 4.21).

Using what was learned from prior designs, the basic architecture of linked tubular structures was reintroduced; the corners were additionally rounded, and a pocket-like line was sealed to capture the triggering coin.

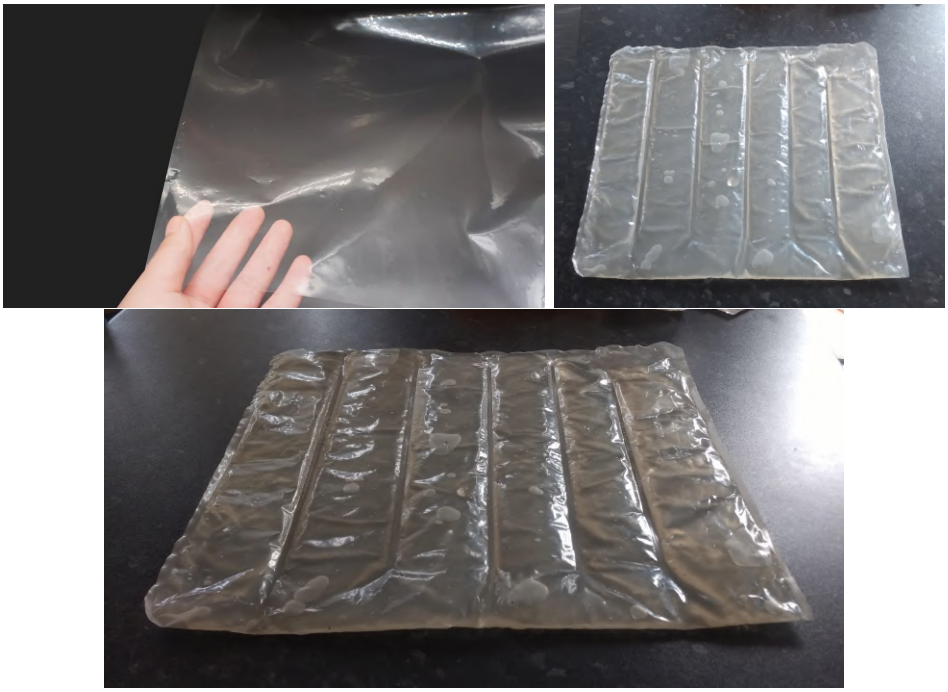
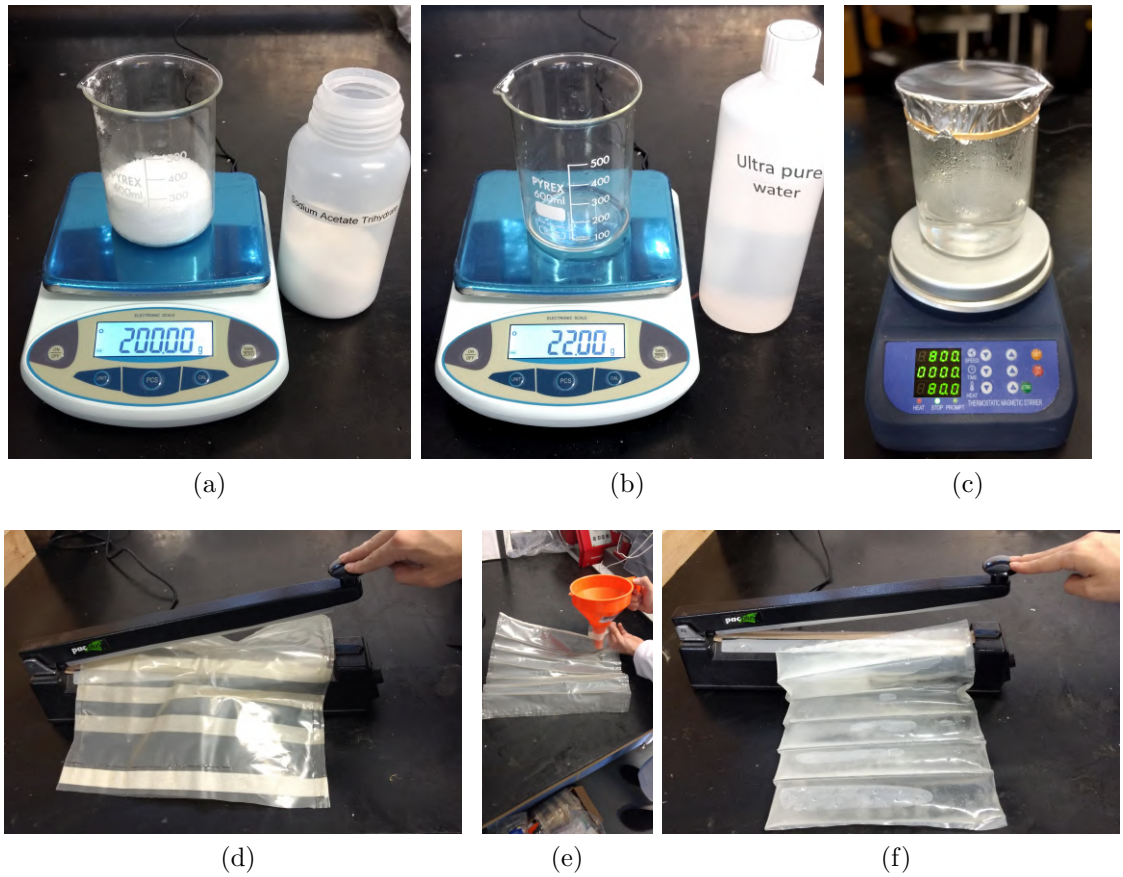


Figure 4.21: PCM Biodegradable plastic pack (2 kg).

For the PCM encapsulation method, it was decided the best option would be a flexible plastic pouch that can be easily transported and recharged at home with every day utensils and able to be readily applied to the beehive.

4.4.1 Manufacturing process

The production procedure was almost same for each prototype. To begin, a mass of SAT crystals (Figure 4.22a) was diluted with ultra-pure water (Figure 4.22b). It was then heated to 80 degrees and stirred until the crystals dissolved entirely and the liquid became homogenous (Figure 4.22c). Cut to size, the flexible packs were sealed using a heat-sealing equipment (Figure 4.22d). After assembling the bags, the fluid was poured into them. The liquid was passed through a funnel and had to be at least 80 degrees Celsius to avoid crystallisation of the PCM (Figure 4.22e). It was found that it was critical to leave a big enough air bubble to enable the PCM to expand upon solidification but not so big that it acted as a barrier between the PCM and the plastic surface. Finally, the aperture used to fill the bags was sealed (Figure 4.22f).



(a) (b) (c)

(d) (e) (f)

Figure 4.22: Prototype manufacturing process.

4.5 Chapter conclusions

A PCM selection methodology and material selection criteria were used in accordance with the requirements described in the preceding chapter. Following a research of phase change materials, it was determined that Sodium Acetate Trihydrate (SAT) was the optimal material for thermal treatment application due to its thermal, physical, and chemical properties. It is a material capable of storing an adequate amount of thermal energy, is inexpensive and low risk to use, is not highly reactive, and may be encapsulated and activated in a variety of ways.

This flexibility allowed exploring different ways of manufacturing the prototypes and were refined until some feasible choices for thermotherapy use were achieved. Plastic materials were discovered to be easier to work with and more affordable. Nylon, EVOH, and biodegradable plastic prototypes were the most successful. Grooved pouches were created to optimise the surface exposed for heat transmission and increase the efficiency of heat exchange. To prepare the SAT supercooled, the formula was improved; the optimal water content is 8% wt. Additionally, the use of thickeners was ruled out in order to achieve the pack's maximum temperature.

By comparison, the cost of any of these non-mass-produced prototypes was

far less than the cost of any of the devices discussed in the preceding chapter. Producing a PCM pack costed approximately £20. The approximate time required to create the packs varied between 2 and 6 hours, depending on the design. It should be noted, however, that this operation was carried out entirely by hand and without the use of specialist equipment.

Chapter 5

Experiment setup

The entire process of preparation for the experiments is covered in this chapter. Included is the design of a special beehive for use in such investigations. Both the experimentation process and the monitoring equipment are discussed. The procedure of data post-processing is also described.

5.1 Experiment rig

All the experiments were conducted using a national standard beehive. Always the beehive was made by E.H.Thorne Ltd., both in the laboratory and on-site, to maintain consistency in material and dimensions. They manufacture beehives in Cedar, either Canadian Western Red Cedar or English Cedar. Cedar is light to work with, stable when dry and contains natural oils which mean it does not need treating with preservatives, which makes it ideal for beehives.

Items such as hive types and materials, solid or mesh floors and stands were discussed. It was decided to concentrate solely on a wooden national hive design using an open mesh floor as a starting point. Later, the type of floor was changed for one with a drawer to contain the PCM pack.

5.1.1 Drawer design

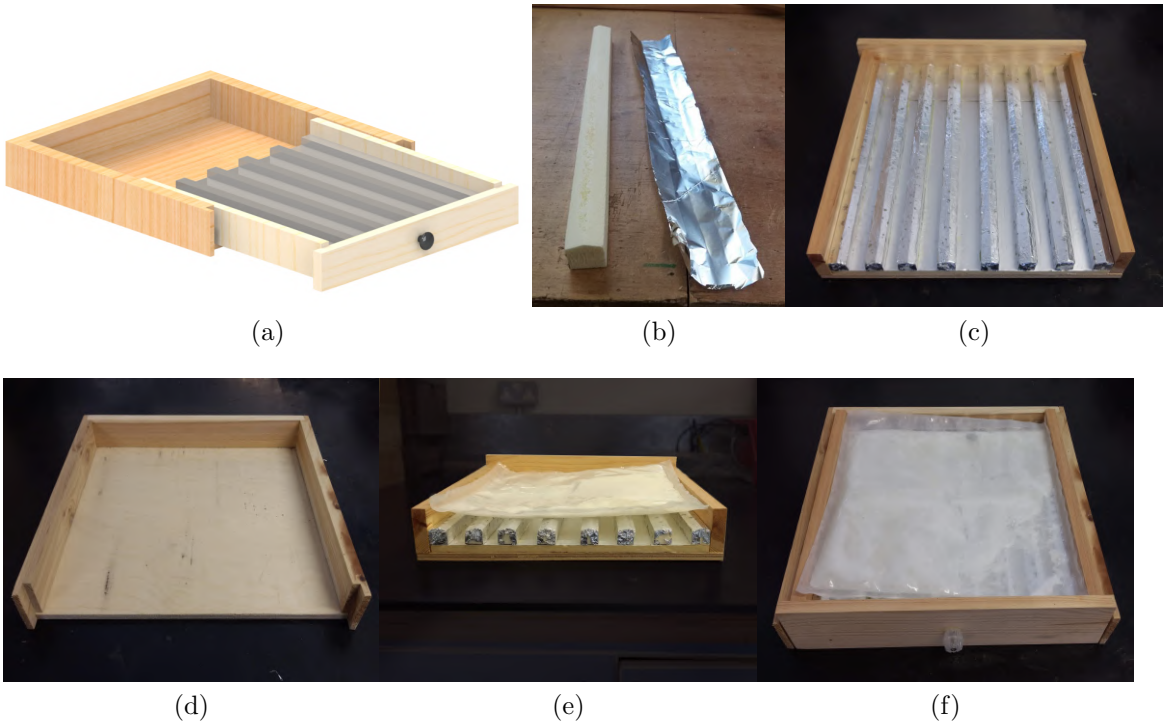
Various methods for introducing the PCM packs were considered however a drawer was decided to be the best method of introduction with minimal disturbance to the hive; Key considerations were:

- Insulated bottom board that should be removable.
- No fine mesh, just the mesh floor, which should be removable. (Figure 5.1a)
- Insulated 'ridges' to maximise the surface heating area of the PCM pack and allow maximum air flow around the pack leading to maximum heat transfer. (Figure 5.1b and c)
- Rebated corners to make the floor as heat 'tight' as possible.
- Use wood as the base, strong and aesthetically similar to the rest of hive. (Figure 5.1d)
- An insulated crown board was also produced.

The drawer was intended to be placed underneath the brood box in order to utilise the natural convection currents of heat rising from the PCM pouch into the brood box. A removable entrance block has been incorporated into the drawer so that the bees can leave the hive and avoid regulating the temperature. The block will then be removed once the hive has reached the target temperature and air flow can aid in the convection process, allowing the cool air to escape.

A mesh floor was found to be superfluous during several testing, and since it functioned as a physical barrier between the PCM pack and the inside of the brood box, it prevented a proper flow of heat from occurring. It was thus decided to eliminate any form of mesh floor from the brood box.

The insulated crown board also plays a vital role in the project, as it ensures that no heat is wasted and the product is running at full efficiency. Further insulation was introduced to the beehive.



(a) (b) (c)

(d) (e) (f)

Figure 5.1: (a)3D render of drawer. (b)Ridge made of foam insulation. (c)Drawer with foam insulation ridges. (d)Drawer base. (e)PCM packs location on the drawer. (f)Drawer floor assembled with a PCM pack.

5.1.2 Observation beehive

It was proposed for all the experiments on-site, an "observation beehive", which is a modification of the conventional National Beehive. It was meant to provide uniform conditions for the colonies housed in three distinct apiaries. Additionally, it was designed to comfortably accommodate various sensors.

It was decided to use a uniform model that allows having similar physical conditions despite the different environmental circumstances. It was also developed

to eliminate the challenges encountered during early trials while mounting and testing sensors. This unique kind of beehive enabled to get a better knowledge of what occurs inside the brood box.

A set of observation beehives was fabricated by E.H.Thorne Ltd. and placed in each accessible apiary, as well as one in the laboratory. The following components comprise an observation beehive:

1. Stand: A modified version of a regular base, with a pair of shelves to place the data loggers and with levelling bolts to counteract any unevenness in the apiary terrain.
2. Floor: It is the drawer specially designed to apply thermotherapy.
3. Brood box: It has two polycarbonate panels for lateral observation. It is a brood body with the capacity of 12 frames, which is the standard of a National beehive.
4. Crown board: It is a slotted polycarbonate quilt to place the sensor probes through.
5. Insulation top board: It is a 25mm foam insulation board (Polyisocyanurate). After laboratory tests it was concluded that its use is highly recommended.
6. Roof: It is a regular roof for National beehive.

A diagram of these numbered components can be seen below in the Figure 5.2.

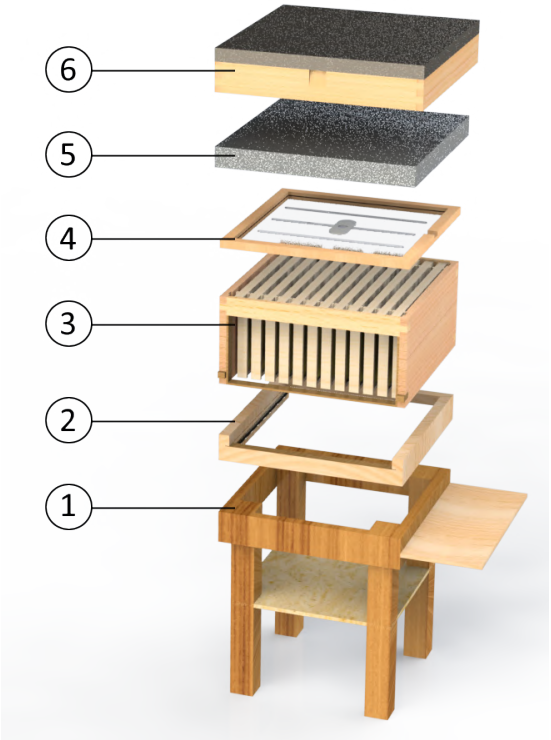


Figure 5.2: Exploded view of the 3D model of the Observation beehive designed.

Appendix 1 of this thesis contains detailed design drawings for the observation beehive. Figure 5.3 depicts the constructed observation beehive. Several units of this beehive were manufactured.



Figure 5.3: Observation beehive constructed.

5.2 Monitoring

Precision Apiculture or Precision Beekeeping is a management method used by beekeepers to monitor, maintain the well-being, and enhance honey bee production. One of the goals of precision beekeeping is to create real-time monitoring technologies that will allow beekeepers to control the bees' life and productivity. The objective is not to replace the beekeeper, but to assist him and make his job easier [135].

Monitoring bees is a straightforward process when one considers that they are a member of a colony, where each component can be simply removed and manipulated. The beehive is a modular construction that allows for the separation of different species of honeybees and the installation of measurement equipment. The colony is referred to as a "superorganism" since it is always active in some manner throughout the day [136]. Researchers have utilised temperature measurements at one or more places in the hive to attempt to identify increases in food intake, the commencement of brood rearing, pre-swarming states, or colony death [137].

Sensors can offer unique humidity and gas temperature data at each given moment in time, depending on the number and placement. The location of a sensor inside the beehive dictates how sensitive it is to external environmental conditions [136].

However, since bees prefer to coat any item outside the hive with propolis or wax, which would interfere with the sensor's functioning and readings, the sensors

should be cleaned on a regular basis. When sensors are placed directly on the brood, extreme caution should be used to avoid interfering with comb maintenance. The movement of the brood cluster may potentially alter data collected by tubes or sensors at fixed locations [136].

Kviesis [138] provides many structures and a selection criteria to select a monitoring architecture approach.

As seen in Figure 5.4, the first technique was selected due to the conditions of the apiaries available for the experiments. This architecture is supervised on-site. Due to the short duration of the trials, there is no need to instantly submit the data to a data processing facility. This is the simplest and least expensive design, since data is gathered and transported for further processing and analysis. The downside of this design is that the sensor system must be installed and unmounted for each experiment.

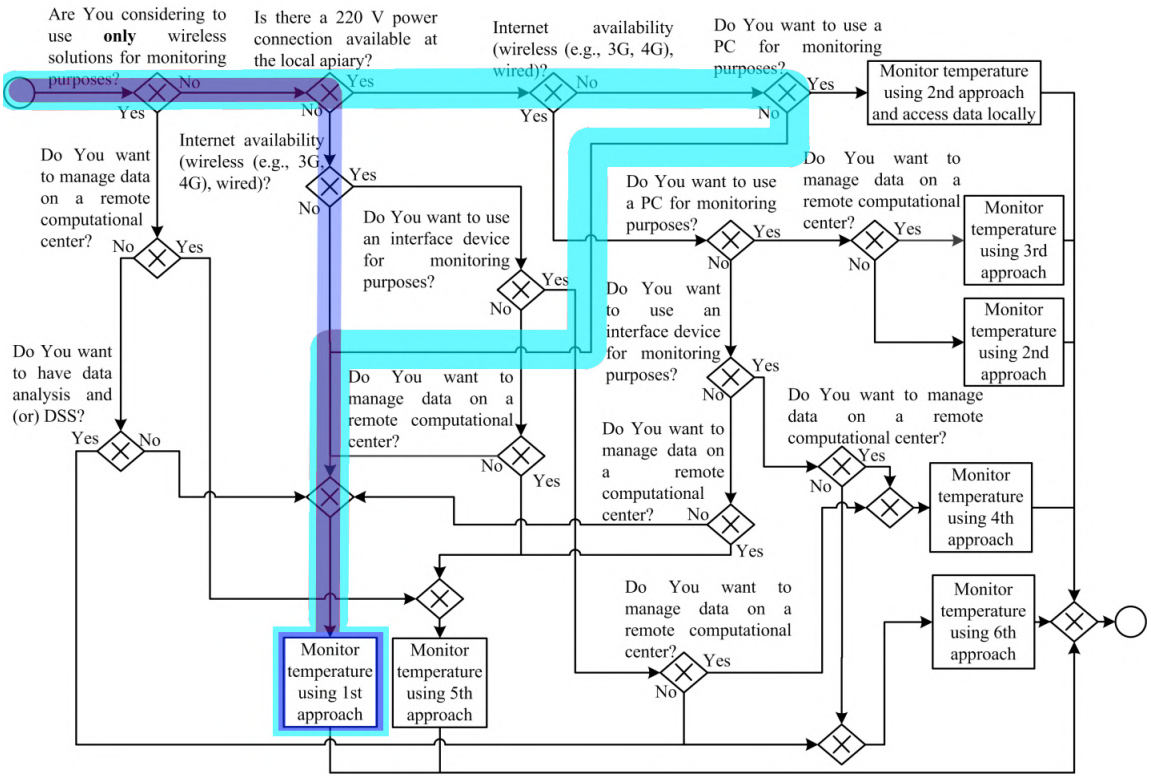
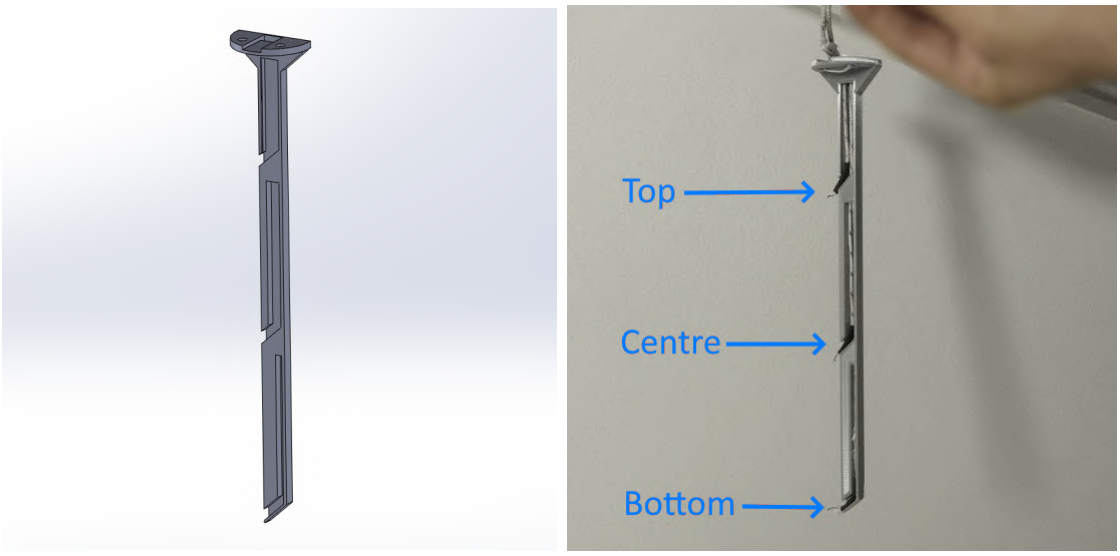


Figure 5.4: Selection algorithm for system architectures (extracted from [138]) followed for Bunny Park apiary (red) and Risley apiary (blue).

5.2.1 Instrumentation

Temperature was measured Type J fine wire thermocouples. These temperature sensors should be carefully inserted into the brood box before the testing. For that, a 3D printable probe was designed to hold the sensors and facilitate their introduction to the beehive without disturbing the bees. The probe is shown in Figure 5.5. The arrows in the Figure 5.5 show the slots through which the sensors cables enter and exit.



(a) (b)

Figure 5.5: (a) Sensor probe CAD. (b)Sensor probe 3D printed assembled with thermocouples.

The distribution of the sensors inside the brood box were as shown in Figure 5.6. The blue lines are the positions of the probes that will have 3 temperature sensors (bottom, centre and top). In addition, temperature sensors were added to the heat source and a sensor placed outside the box will record the ambient temperature.

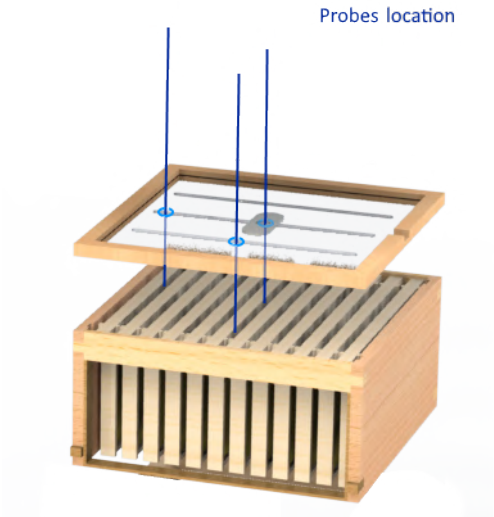


Figure 5.6: Probes positions inside the brood box.

Temperature measurements were taken and saved using a Grant Squirrel 2020 series data logger (Figure 5.7). This eight-input datalogger can operate for many hours on batteries and is suitable for outdoor use. It was set up to read and store data at a rate of once per second. The readings are saved in the device's internal

memory in a .csv file that can be transferred to a computer using the provider's software.



Figure 5.7: Datalogger used.

5.3 Experimental methodology

5.3.1 Overall aim

The laboratory studies were conducted with the overall purpose of evaluating the various PCM packs in an empty beehive. They were evaluated with varying concentrations of SAT, various encapsulating materials, and locations.

These tests were consistent with the simulation and validated the mathematical model. However, it was assumed that experimental tests could provide information that the simulations could not, since in these perhaps some factor was being overlooked.

The aim was to optimise the PCM packs while achieving the desired thermal performance, which was to attain a minimum temperature of 40 °C in the centre region of the beehive and a maximum temperature of 47 °C and maintain that temperature for at least 1.5 hours. The majority of the studies were conducted over a longer period of time in order to determine the maximum duration of the heat delivered by the PCM packs.

These testing also aided in the refinement of the drawer floor design. Several alternative concepts were also tested, including the usage of external and interior insulation, staged activation, etc.

5.3.2 Hypothesis

Placing 3.4 kilograms of PCM in the base may raise the temperature of the beehive to 40 °C. The new floor, in conjunction with the additional insulation at the top, will aid in the retention of the produced interior warmth.

As previously stated, the brood box's temperature should be approximately 33 °C. So if the pack is warmer than 50 °C, it will be essential to wait for the temperature to rise to 40 °C before introducing the activated PCM pack. For the

experiments without bees, it is expected that the temperature would be greater than in the tests without bees, as suggested by the simulations. On the other hand, in test with bees, they may respond by preventing the interior temperature of the beehive from increasing, the waiting period will be increased.

5.3.3 Experiment setup

Every experiment follows a similar operating procedure. As previously stated, all experiments were conducted inside a conventional or modified National Standard beehive.

The thermocouples were always connected to the datalogger's inputs. Sensor tips were affixed to the 3D-printed plastic probes. Following that, the probes were installed in the corresponding places between the frames through the crownboard, carefully inserted to avoid crushing or disturbing the bees. Additionally, a sensor was installed near the beehive to measure the ambient temperature. The PCM containers had to be put on the floor of the beehive or in some cases, the modified floor drawer in each experiment. Then, a temperature sensor was put on the surface of the PCM facing the interior of the brood box just before the packages were completely inserted. The data recording was then initiated, and the PCM packs' activation coins were clicked. Finally, the PCM packs were inserted completely. Thermal insulation was added to the tests that required it once the preceding process was done.

The majority of these trials lasted at least 3.5 hours. After that, all instruments were withdrawn in the reverse sequence of their installation.

5.4 Data processing program

As indicated before, the datalogger captured and stored data from each sensor once every second, which adds up to a massive quantity of data over the course of a test. Due to the volume of data gathered and the number of tests conducted, a data collection and graphing program was developed to standardise the presentation of results and to facilitate analysis. MatLab was used to create the software, and the source code is included in Appendix 2.

The application reads the Comma Separated Values (.csv) file containing the datalogger's raw data. Additionally, a diagram that details the test's physical properties is taken. Following execution, the software outputs a graph depicting the PCM's temperature line, the ambient temperature, and the temperature in the beehive's centre. Furthermore, it displays a diagram constructed from the temperatures recorded by the many sensors positioned throughout the beehive and interpolates the data to display them visually as a colour graph. On the other hand, a quick summary of the test is given on the screen through the display of the overall duration of the test, the average room temperature, whether or not the thermotherapy temperature was achieved in the central sensor, its maximum temperature, and the time required to attain it. Finally, an animation is generated with jumps every ten minutes that depicts the transitory changes in temperature within the brood box.

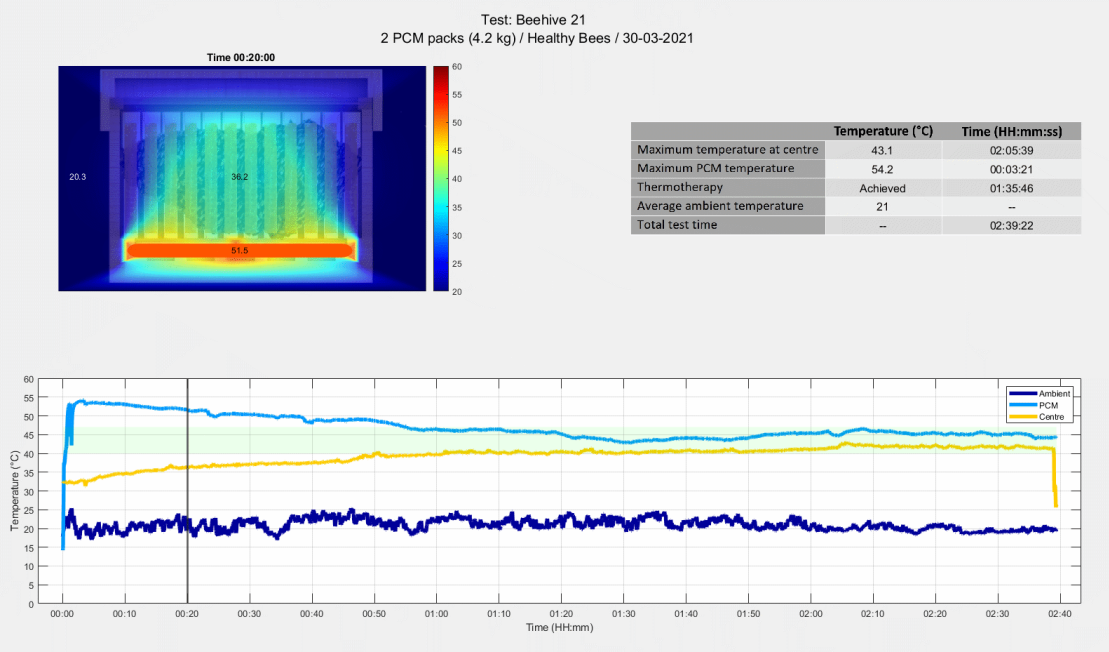


Figure 5.8: Example of the results displayed by the program after its execution.

5.5 Chapter conclusions

It was planned and constructed an experimental apparatus named "observation beehive" that was used to observe several laboratory and field investigations. Similarly, an unique floor was created for use with the PCM pack. Initially, no increase was contemplated to accommodate the PCM pack, however it was determined that additional room was necessary owing to the mass required. Furthermore, heat was lost from the PCM pack to the exterior beneath the floor of the common beehive. That is why it was decided to utilise a drawer compatible with the National Standard beehive to facilitate the introduction of the PCM pack quickly and without disturbing the bees. The drawer's design was developed during the testing. The final version included an insulating board bottom with ridges that elevated the PCM packs and increased heat transfer.

Additionally, sensors and equipment were chosen to capture temperature variations within the beehive throughout each test. The procedures for conducting the tests in the laboratory and on-site were defined.

Chapter 6

Laboratory experiments

This chapter explains the variations that were made in the different tests. The experiments' methodology and analysis of the findings are then described.

6.1 Experiments in laboratory

The laboratory experiments were done on the University of Nottingham's city campus on the laboratory of the Sustainable Research Building. The laboratory is equipped with a temperature control, which is typically set at 20 °C. The beehive was set 30 cm above the ground, as is customary in an apiary. Additionally, draughts were avoided throughout the testing.

Naturally, these tests are unaffected by climatic or biological conditions. Due to the strict regulations governing testing and laboratory safety, no bees were employed in this set of trials. The only tests with bees were conducted on-site, not in the laboratory.

Laboratory trials were largely used to optimise and adjust the design of the PCM packs and, more broadly, the thermotherapy implementation method. These testing resulted in the final design of the thermotherapy-specific floor mentioned at the beginning of this chapter. Additionally, they provided as a backup for mathematical models and simulations. Finally, they acted as a practice run for some of the tests conducted on-site.

6.2 Different variations

Both in the laboratory and in apiaries, trials with varying parameters were conducted. A matrix of experiments was created to keep track of the many variables that were varied throughout the various testing. Naturally, more tests were conducted in the laboratory owing to the apiary's availability and in order to avoid potential risks and therefore prevent bees casualties.

Variations were tested in the following six categories.

- **Mesh floor:** According to the bibliography, it is conceivable that Varroa mites attempt to re-enter the brood box after their detachment from the bees due to heat stroke. This is why it was proposed to use a physical barrier

in the shape of a mesh to isolate the bees from the falling mites during the treatment. Various mesh sizes and materials were experimented with.

- **Number of frames:** This determines the hive's size for on-site testing. When the colony is insufficiently big, the beekeepers remove some frames from the brood box to concentrate the bees in the centre. In laboratory testing, the greater the number of frames, the more air space there is within the brood box.

- **Mass of the PCM:** Although mathematical modelling and simulations aided in establishing the PCM's mass, laboratory experiments were conducted to verify it. In addition, the manufacture of PCM packs was facilitated when each package made was 2 kg. As a result, tests were conducted with 2, 4, and up to 6 kg. In a few instances, thermal mats were used instead of PCM.

- **Position:** As previously stated, the packs may be vertical or horizontal in orientation. Preliminary simulations indicate that both have favourable qualities and are likely to provide positive outcomes. This was mostly accomplished via laboratory experiments.

- **Insulation:** Given that the simulations assumed constant temperatures and considering the results of the first laboratory and field testing, the idea of utilising thermal insulation to ease the job of PCM or to undertake a thermal treatment in climates with temperatures below 20 °C was investigated. Numerous materials were evaluated, including polyisocyanurate foam, natural cork, and others.

- **Other variables:** All the other strategies that suggested anything distinct than the preceding groupings were placed together in this section. For instance, preheating the PCM packs, staggered activation, the use of fans, and sandwiching the PCM packs in the top and bottom regions of the brood box were all tried.

6.3 Laboratory experiment results

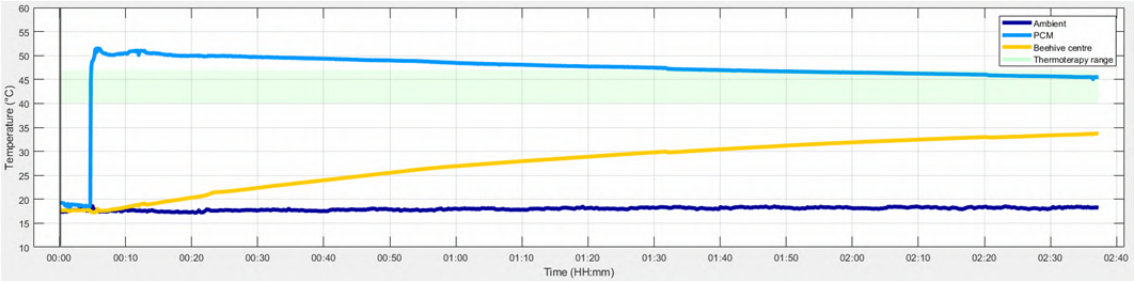
Appendix 3 Part 1 provides a thorough overview of all the tests conducted as well as their outcomes. A total of 74 variations were proposed, and each variation was tested at least once, but in some instances many times, with the most significant findings being recorded in Table 6.1. The Table illustrates the combination of factors to be varied and the outcomes that determined the route for the improvements.

6.3.1 Mesh floor

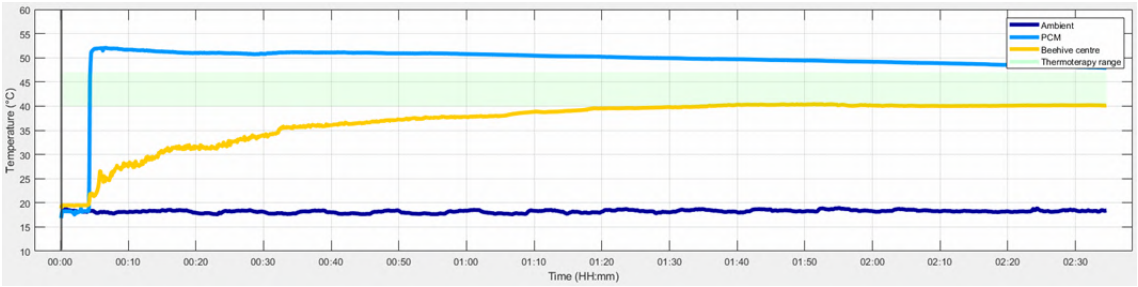
The first factor was the incorporation of a metal mesh. As previously stated, it was suggested in order to prevent mites from crawling back into the brood box.

The first 24 experiments employed a metal mesh. It was observed that the mesh could have lateral heat conduction, obstructing optimum heat transmission. Later, it would be tried with a plastic mesh, but this was abandoned due to the fact that heat transmission was improved when there was no physical barriers between the PCM pack and the beehive's interior.

The findings from trials 24 and 25 are displayed in Figure 6.1 to further highlight these insights. In both instances, 4 kg of PCM was utilised, 7 frames were inside, and the beehive's outside was thermally insulated. The sole difference between tests 24 and 25 was that test 24 involved placing a metal mesh on the floor whereas test 25 did not.



(a) Test 24: Beehive with metal mesh floor.



(b) Test 25: Beehive without metal mesh floor.

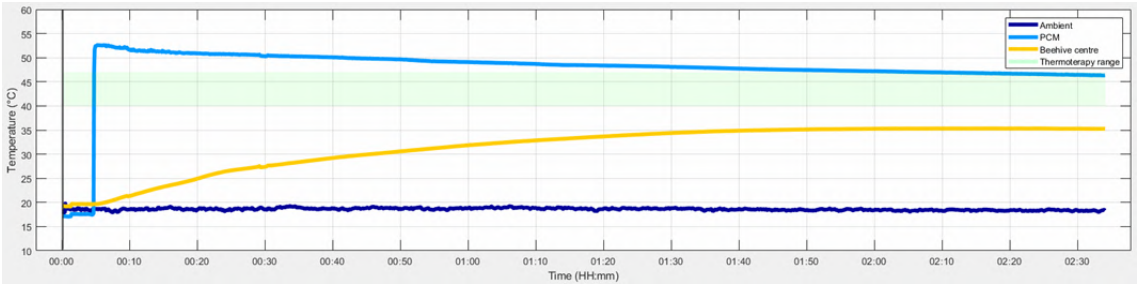
Figure 6.1: Comparison between tests with and without metal mesh floor.

The first experiment (Figure 6.1a) demonstrates how, despite the PCM's performance being fairly comparable, the temperature in the centre of the beehive takes some time to rise and does not reach the thermotherapy temperature range. In contrast, the necessary temperature is easily obtained in the second case (Figure 6.1b).

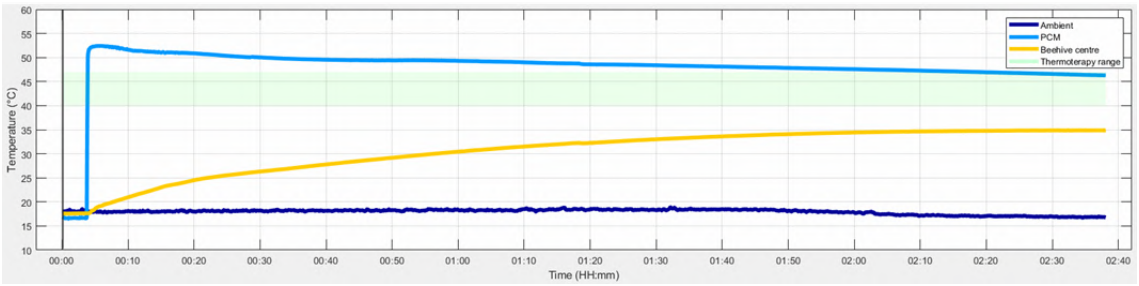
6.3.2 Number of frames

The second variable that differed among experiments was the number of frames. It was first tried without frames inside the beehive, from test 1 to 7 . Although this is a unrealistic situation, these experiments served as a means of calibrating and adjusting the formula, mass, and materials used in the manufacture of PCM and its packaging. The frames in the laboratory could not have contained bees. However, experiments were conducted using wax frames, and wax frames with honey in order to assimilate as closely as possible to the real scenario.

The temperature variations for two distinct scenarios are shown in tests 34 and 37 under identical settings. 7 frames were inserted in test 34, and 11 frames with wax base were placed in test 37. Figure 6.2 presents the test results.



(a) Test 34: Beehive with 7 frames.



(b) Test 37: Beehive with 11 frames.

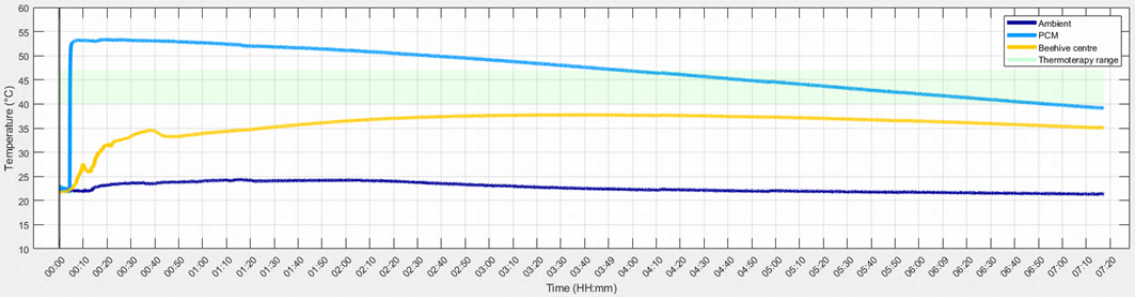
Figure 6.2: Comparison between tests using 7 and 11 frames.

It is obvious that the outcomes are very similar. It has been shown that the number of frames does not significantly alter the interior temperature on its own. However, it is conceivable that bees might increase convection in a real setting.

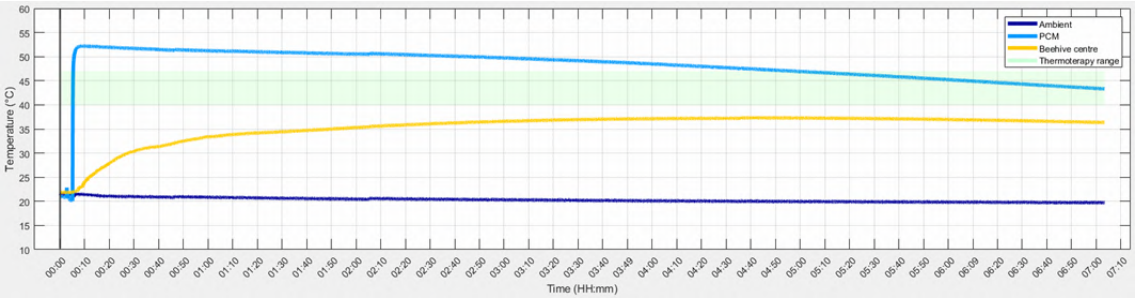
6.3.3 Mass of the PCM

Simultaneously with the previous tests, it was evaluated with packages weighing 2, 4, and up to 6 kg. Materials for the packaging were switched throughout these testing until the best one was identified. Additionally, these tests were used to determine the size of the drawer that was put on the beehive's floor. As explained by the simulation findings, mass has no effect on the PCM's maximum temperature, but it does influence the duration it can sustain a high temperature. That is why, despite the mathematical study indicating that the required mass should be 3.5 kg, it was determined that 4 kg was a more appropriate mass for the packets, which, in addition to delivering heat for more than 3 hours, were simpler to manufacture.

Figure 6.3, which contrasts the outcomes of tests 12 and 13, provides an illustration of these tests in action. The only variation between the two tests was the amount of PCM used—in test 12 it was 4 kg and in test 13 it was 6 kg.



(a) Test 12: Beehive with PCM pack of 4 kg.



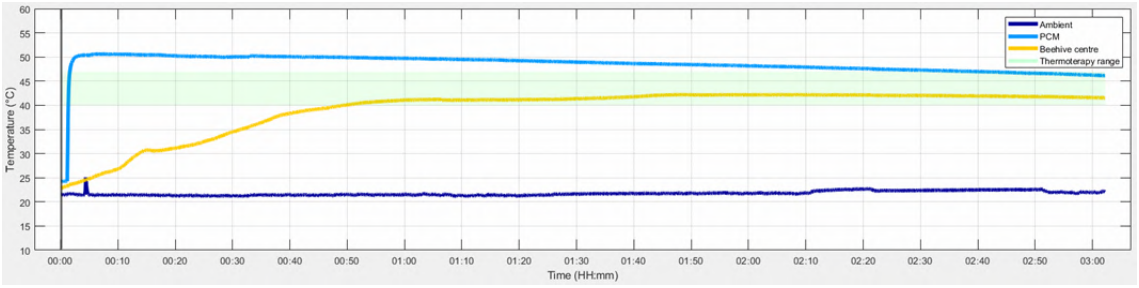
(b) Test 13: Beehive with PCM pack of 6 kg.

Figure 6.3: Comparison between tests using PCM packs of 4 and 6 kg.

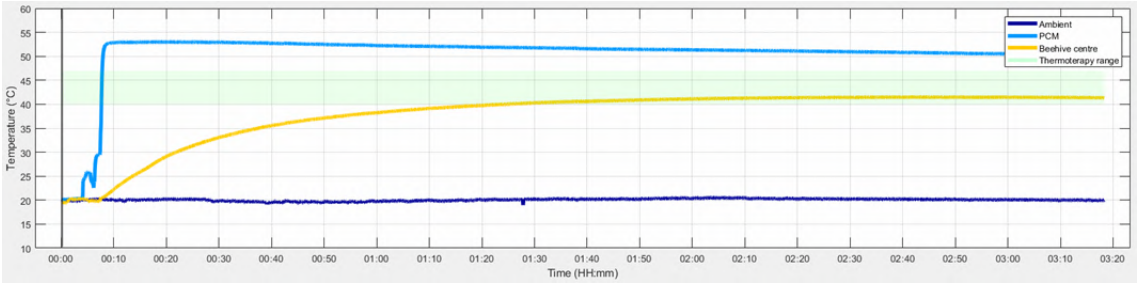
Figure 6.3's comparison of the two plots reveals that the difference in core temperature is not particularly pronounced. The maximum temperature is maintained for a longer period of time in test 13 (the one with the largest amount of PCM), as can be observed. This supports the theory that the PCM's chemical properties, not its mass, control the maximum temperature.

6.3.4 Position

Similarly, starting from the preliminary simulations, the position of the PCM packs was experimented with. They were tested arranged horizontally and vertically. Tests 21 and 22 provide as examples of the impact a vertical position as opposed to a horizontal one has. In test 21, the PCM packs were positioned horizontally, but in test 22, they were positioned vertically, all other factors being equivalent.



(a) Test 21: Beehive with PCM packs positioned horizontally.



(b) Test 22: Beehive with PCM packs positioned vertically.

Figure 6.4: Comparison between tests using PCM packs positioned horizontally and vertically.

Figure 6.4 shows that vertical placement increases temperature more effectively than horizontal positioning, which is consistent with early simulations. However, it is difficult to stack the packages vertically due to their size. Additionally, it was mentioned that a lot of handling of the bees would be required to replicate a test like 21 in a real beehive with bees, which would stress them out. Finally, it was thought that it may be harmful to have the heat sources so near to the bees. The vertical position is therefore operationally impractical even if it is thermally more efficient.

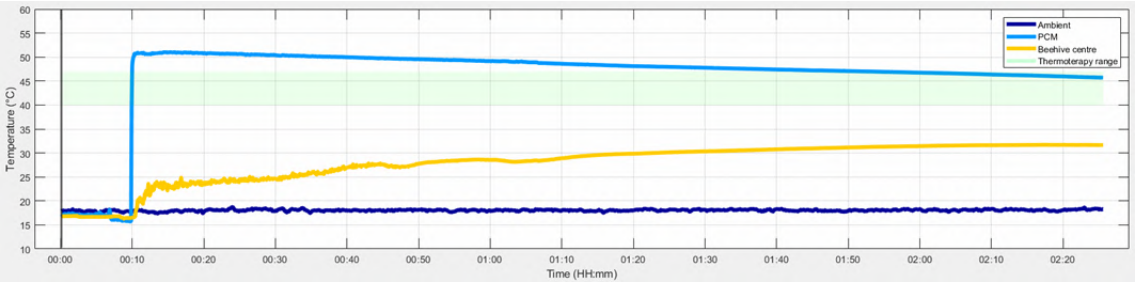
Vertical placement was found to be more laborious, and the space inside a beehive with 11 frames was insufficient to accommodate the PCM packs, even though less mass would be needed since the packages would be closer to the region where thermotherapy should be administered. Finally, these tests showed that the horizontal position was easier to use and less obtrusive for the bees.

6.3.5 Insulation

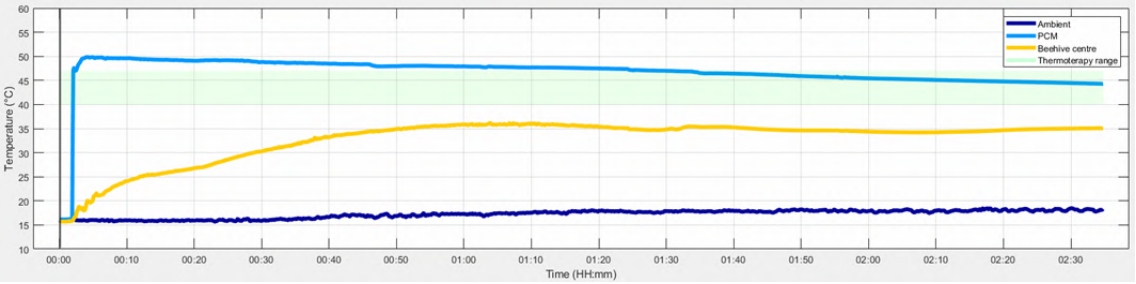
Both in case 2 of the simulations and in the majority of the trials conducted without insulation, temperatures barely reached 40 °C. Given that this temperature is the bare minimum for thermotherapy, a method for increasing the temperature was sought, primarily to prevent relying on weather circumstances while administering the treatment. This is why the option of adding thermal insulation was considered. Numerous ideas and materials were evaluated, among which stand out, an aluminum multi-layer insulating jacket and insulation foam panels (polyisocyanurate).

To exemplify the disparity between adding isolation and not adding it, Figure

6.5 shows experiments 33 and 27. Same amount of PCM was used on each, horizontally and under the same number of frames. In test 33, no insulation of any kind was used, but in test 27, 20 mm foam panel insulation was positioned on top of the brood box and beneath the PCM packets.



(a) Test 33: Beehive with no insulation.



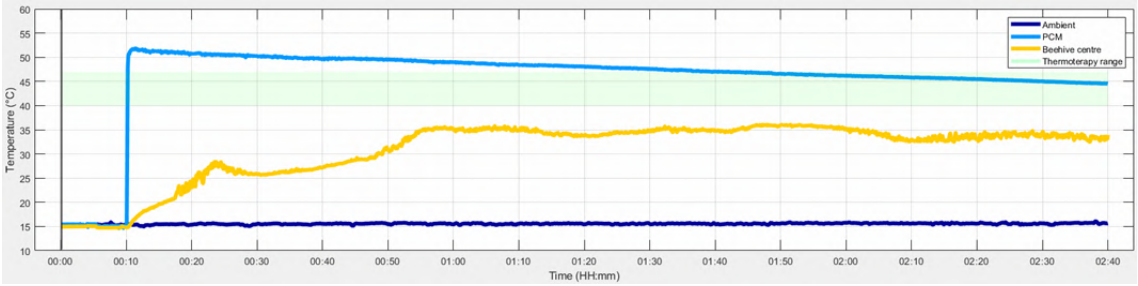
(b) Test 27: Beehive with foam panel insulation on top and bottom.

Figure 6.5: Comparison between tests with and without thermal insulation.

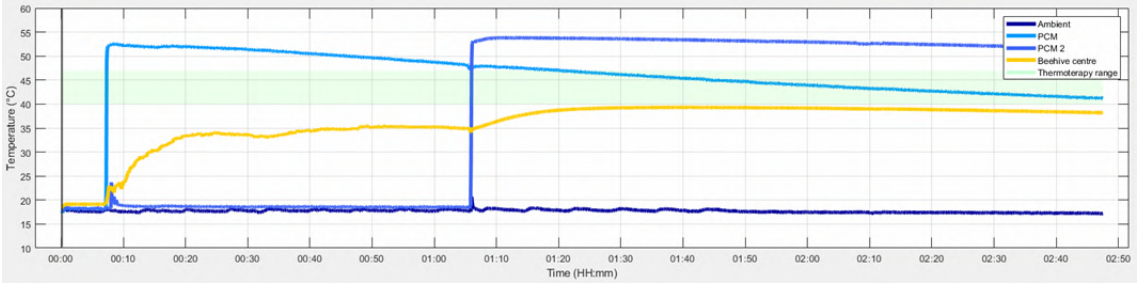
It was found that simply adding an insulating board on the beehive's top lid and one on the bottom, where the PCM packets would be deposited, was enough to speed up the temperature rise and prevent losses.

6.3.6 Other variations

Lastly, some other somewhat more radical ideas and concepts were tested. Examples of this alternative techniques were a staggered activation, in experiment 30 (Figure 6.6a), or the use of internal fans in experiment 32 (Figure 6.6b).



(a) Test 30: Beehive with internal mini fans.



(b) Test 32: Beehive with PCM packs activated by stages.

Figure 6.6: Results of tests using alternative variations.

However, the results around these were not promising so, these concepts were discarded.

Table 6.1: Laboratory experimental matrix with main results data.

Test #	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*
Mesh floor																									
Metal mesh floor	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Plastic mesh floor																									X
No mesh floor																									
Frames																									
No frames	X	X	X	X	X	X	X							X											
with foundation								X									X								
with waxcombs									X	X	X	X	X		X	X		X	X	X	X	X	X	X	X
with waxcombs and honey																									
with waxcombs and honey (filled)																									
Heat source																									
SAT 2 kg	X	X	X		X	X	X	X	X	X	X								X	X					
SAT 4kg				X								X									X	X	X	X	X
SAT 6 kg													X	X	X	X	X	X							
Heater mats																									
Position																									
Horizontal	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		X	X	X
Vertical															X	X	X	X				X	X		
Insulation																									
Box										X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Insulation crown board						X	X	X	X															X	X
Insulation bottom	X	X		X		X		X	X						X		X	X	X					X	X
Other		X	X	X	X		X				X														
Variations																									
Sandwich																							X		
Preheated																									
Staggered																									
Results																									
Duration (hours)	3.5	3	3	3	3	2.5	3	2.5	2.5	5	2.5	7	7	7	7	7	3.5	8	3	3	3	3	3	2.5	2.5
Average ambient temperature (°C)	21	25	23	25	23	21	24	22	21	21	20	21	21	21	21	21	21	21	21	21	21	21	20	18	18
Max surface temperature (PCM) (°C)	52	52	50	52	53	46	45	53	54	52	36	52	52	52	52	51	52	52	50	47	50	52	50	51	52
Max temperature at centre (°C)	31	35	37	35	38	34	37	34	35	36	30	38	38	45	42	41	44	49	35	35	41	41	41	35	40

Test #	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*	*35*	*36*	*37*	*38*	*39*	*40*	*41*	*42*	*43*	*44*	*45*	*46*	*47*	*48*	*49*	*50*
Mesh floor																									
Metal mesh floor																									
Plastic mesh floor														X	X										
No mesh floor	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X
Frames																									
No frames																									
with foundation																									
with waxcombs	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
with waxcombs and honey																									X
with waxcombs and honey (filled)																									
Heat source																									
SAT 2 kg																									X
SAT 4kg	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
SAT 6 kg																									
Heater mats																				X	X	X	X	X	
Position																									
Horizontal	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Vertical																									
Insulation																									
Box	X																								
Insulation crown board	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Insulation bottom	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Cork panels on walls						X																			
Variations																									
Preheated																									
Staggered	X						X																		
Folded				X			X						X												
Fans					X																				
Results																									
Duration (hours)	2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	3.5	6	7	4	5	2.5
Average ambient temperature (°C)	18	17	17	20	15	18	18	18	19	19	19	18	18	19	17	19	19	17	19	20	20	20	17	20	25
Max surface temperature (PCM) (°C)	54	50	52	52	52	52	52	51	52	52	52	52	50	52	52	50	52	54	51	NA	NA	NA	NA	NA	50
Max temperature at centre (°C)	40	36	38	39	35	36	39	31	35	35	37	35	38	32	31	36	36	39	39	43	45	47	43	40	40

Test #	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
Mesh floor																								
Metal mesh floor																								
Plastic mesh floor																								
No mesh floor	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Frames																								
No frames																								
with wax foundation																								
with waxcombs																								
with waxcombs and honey	X	X	X								X	X	X	X	X	X	X	X	X	X	X	X	X	X
with waxcombs and honey (filled)				X	X	X	X	X	X	X														
Heat source																								
SAT 2 kg						X								X							X	X		
SAT 3 kg											X	X	X										X	
SAT 4kg	X	X	X	X	X		X	X	X	X					X	X	X	X	X	X				X
SAT 6 kg																								
Heater mats																								
Position																								
Horizontal	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				
Vertical																					X	X	X	X
Insulation																								
Box													X	X	X									
Jacket																								
Insulation crown board	X	X	X	X	X	X	X	X	X	X		X				X	X				X	X	X	X
Insulation bottom	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Vacuum insulation panels on walls												X	X	X	X	X	X	X	X	X				
Cork																		X	X	X				
Variations																								
Preheated																								
Staggered			X				X	X																
Results																								
Duration (hours)	2.5	3	3.5	4.5	4.5	4.5	4.5	8	9.5	7	1.5	1.5	1.5	1.5	4.5	2.5	2.5	1.5	4	4.5	3	3.5	3	5.5
Average ambient temperature (°C)	25	25	24	22	23	23	23	22	25	27	6	9	9	9	10	5	14	9	7	14	7	14	18	11
Max surface temperature (PCM) (°C)	55	54	54	53	54	50	53	54	54	55	56	56	54	56	55	50	54	55	54	50	44	50	52	52
Max temperature at centre (°C)	41	42	43	42	41	35	38	40	40	43	35	39	35	37	42	34	35	36	40	36	42	38	41	41

6.4 Chapter conclusions

The laboratory studies were critical in rectifying the prototype and fine-tuning the thermal treatment application procedure prior to the on-site testing. As previously stated, bee testing is a highly sensitive procedure that must be conducted with extreme caution. That is why any variation of the experiments was carried out in the laboratory before doing it in the apiary.

It was mainly successful results that were examined, and the parameters that led to them were compared. From this observation, it was revealed that the inclusion of any form of mesh in the brood box's lowest section obstructed the free flow of heat. Secondly, as expected, it was demonstrated that a thermal insulation top cover is required to prevent heat from leaking. Also, it was noted that the mass of PCM in the packages had an impact only on how long they can retain their maximum temperature. Finally, it was observed that preheated PCM achieved higher temperatures in the laboratory; while this is not required for the treatment to be successful, it is recommended.

The findings of these tests suggested improvements to the prototype design. Some of these combinations of parameters were tested on-site to compare the results. Laboratory work reduced the number of on-site tests.

Chapter 7

On-site experiments

This chapter describes the methods used for the on-site testing and the supplementary tests that were conducted. The experiment's findings are displayed and discussed.

7.1 Experiments on-site

The on-site experiments were carried out at three locations. One of these is located in Nottingham's Bunny Park. It is managed by Tom Ryder, a subcontractor to the University of Nottingham. Tom is a bee farmer with over two decades of expertise. He has an arrangement with the University to maintain bees at King's Meadow and at Bunny Park Farm, where his workshop is located. Tom has participated in University of Nebraska research studies on beehives and bee health. He was gracious enough to designate three colonies for the trials that were conducted.

Another apiary where work was done was one at Risley in Derby. This apiary is a division of the Healthy Bees Ltd. company, which was founded and is led by Tony Maggs, a highly experienced beekeeper. The apiary is home to more than 40 colonies, five of which were leased for research purposes.

Finally, the third location was the headquarters of E.H.Thorne (Beehives) Ltd., a company which is the largest manufacturer and supplier of beekeeping products and accessories in the UK. They also provide help to over 40,000 beekeepers with almost a century of expertise building beehives. Thorne operates a multi-disciplinary firm on a property in Market Rasen, Lincolnshire, employing approximately 100 employees. Five more colonies were prepared for testing in this location.

In each apiary, it was attempted to work with average-sized colonies and to always deal with the same assigned colonies in order to do a more thorough follow-up. Bunny Park, was the only apiary of the three that had access to electricity. The other two, as is common, were away from human traffic and close to large natural areas. All experiments were conducted during daylight hours and were always conducted with the assistance and supervision of expert beekeepers. Their directions were always followed and they were well instructed on the thermotherapy operating technique. At each of the three locations, the colonies allocated to the tests were normal colonies, meaning they did not have a specific Varroa infestation.

On-site experiments are critical because they validate the bees' response to the

suggested treatment and quantify its efficacy. To ensure that the heat treatment did not have any adverse effects on the bees, brood or honey, several samples were gathered throughout these trials and sent to the laboratory for analysis.

The following material was gathered: live Varroa mites, honey encapsulated within the brood box, and photographs of the frames of some chosen beehives. The procedures for collecting these three kinds of samples are detailed below, and findings derived from them are addressed in the next chapter.

7.1.1 CO_2 test

Overall aim

The purpose of this operation is to catch live Varroa found clinging to worker bees inside the beehive. They will be taken to a laboratory after capture, where they will be subjected to crucial thermotherapy temperatures and their response would be visually evaluated. A quantitative reverse transcription PCR (RT-qPCR) approach will be attempted later, if feasible.

Hypothesis

According to bibliographical sources, the Varroa mite cannot tolerate temperatures between 42 and 45 °C. This test tries to confirm it and determine whether their death occurs instantly or whether they can withstand the temperature for an extended amount of time. It is predicted that they can survive for only a few minutes, with reduced mobility. The length of the heat treatment, which exceeds three hours, is believed to be sufficient to kill any Varroa mite exposed to the thermotherapy temperature.

Equipment

A CO_2 Varroa tester device was used to determine the amount of Varroa mite infection in the colony. This device (Figure 7.1) consists of a transparent cylindrical container with removable lids, a metal mesh in the middle, and a minuscule hole for injecting CO_2. Along with the container, the instrument is equipped with a CO_2 injector.



Figure 7.1: CO_2 Varroa tester kit.

Methodology

The sampling included collecting roughly 200 bees and putting them in the container. CO_2 is then injected into the container to temporarily numb bees and mites [139]. Being in this state, the mites are not firmly attached to their hosts, so they are released and fall though a fine metal mesh into a compartment within the same jar. Once there, the mites that fell can be counted and in this way estimate the percentage of infestation of the colony.



Figure 7.2: Sample taken using CO_2 Varroa tester device.

7.1.2 Honey sampling

Overall aim

The objective of this activity was to collect two samples of honey from two beehives, one treated with heat and another one without any treatment (control). Standard microbiological tests would determine changes in bacterial and fungal composition of honey from heat treated (HT) and non heat treated (NHT) hives.

Hypothesis

The honey samples will indicate if there is any alteration at the biological level of the honey after thermotherapy. The heat from the PCMs is expected not to affect the honey encapsulated in the wax comb. According to the literature, honey is susceptible to temperatures much higher than the thermotherapy ranges (40 - 47 °C). In fact, honey can spoil more easily if there is a considerable increase in humidity.

Equipment

For this stage, two pieces were used, a sterilized scalpel blade and a 50 ml sterile specimen container as shown in Figure 7.3. It is important that both are sterilized to prevent the samples from being contaminated. To handle the sampling equipment, the tester wore medical grade gloves to avoid contaminating the honey samples.



(a) (b)

Figure 7.3: Equipment used to take honey samples. (a)Specimen container. (b)Scalpel blade.

Methodology

The sample was taken from the middle frame, the fifth one, counting from the left facing the entrance, in order to get the sample that represents the part that undergoes the treatment. The scalpel was used to carefully cut a piece of the honeycomb in an area with honey. Enough honeycomb with honey was taken to fill at least one third of the container tube (Figure 7.4). These samples were immediately taken to the laboratory where they were properly stored for analysis.



Figure 7.4: Honey sample taking.

7.1.3 Photography

Overall aim

The objective of this operation was to photograph on both sides, each of the frames of two of the beehives of the apiary. Changes in the health of the brood will be monitored, as well as its growth and expansion inside the HT and NHT beehives. It was planned to measure this using the OECD guidelines (2007) for testing brood health. This can be done by photographing frames from HT and NHT hives throughout the season, and using the computer software HoneybeeComplete from WSC-regexperts Ltd. and machine learning to determine the effect on brood quality and quantity.

Hypothesis

It is predicted that photographic analysis will reveal normal activity inside the HT beehives and that the generations of bees produced by these larvae will be healthy regardless the heat treatment.

Equipment

Photographic equipment was used to meet the imaging requirements necessary to use the software HoneybeeComplete to analyze the honey quality and brood health after the heat treatment.

Show Case This piece of equipment is a stand manufactured by E.H.Thorne Ltd. to hold and display frames usually for honey exhibitions. In this case it was used to keep the frames to be photographed in the correct position.



Figure 7.5: "Show case" stand for beehive frames.

Camera The camera used was a Canon model EOS M50. It is a compact mirrorless interchangeable lens camera with a 24.1 Megapixel (APS-C) CMOS sensor. A 70-300mm lens was also used to achieve the best focus of the brood according to the recommendations of the software provider. Both are shown in the Figure 7.6.



(a) (b)

Figure 7.6: Photography equipment used. (a)Camera Canon EOS M50. (b)Canon EF 70-300 mm f/4-5.6 IS II USM Lens.

Lighting In order to have a clear image of the brood inside the wax combs, it is suggested by the software provider to use a separate light source. In this case, we opted to use a battery powered 18-inch LED ring light. A portable studio was also used to achieve a homogeneous and bright background. Both are shown in the Figure 7.7



(a) (b)

Figure 7.7: Illumination devices. (a) Light ring. (b)Portable photo studio.

Methodology

First it was necessary to locate a table near the beehive to be photographed, in this way it was avoided to move the frames long distances. Later, the portable photographic studio was set on that table and the show case was placed inside. The ring lamp was also placed close at 45°. It was adjusted to its maximum luminosity, that is 100% and a cold light, that is 5600K. Finally, the camera was placed on a tripod approximately 4 meters away from the target. The 300mm lens was set to autofocus. The camera was in manual mode with an automatic white balance and an aperture of f8, also set for autofocus, automatic ISO, and the exposure selected was 0. The WiFi connection of the camera was used to shoot remotely and thus avoid moving the camera. Being in an isolated apiary, all the equipment was operated with batteries. All the setup can be seen in Figure 7.8.



Figure 7.8: Photography setup.

After having placed all the photographic equipment in its position, we proceeded to extract each one of the frames, starting from the extreme left. Each frame was smoked and cleaned of bees so that the photographs captured the brood caped. The frames were moved one by one to the photography area, photographs were taken from both sides and once finished, they were returned to their position inside the brood box. One of the taken photographs is shown in Figure 7.9.

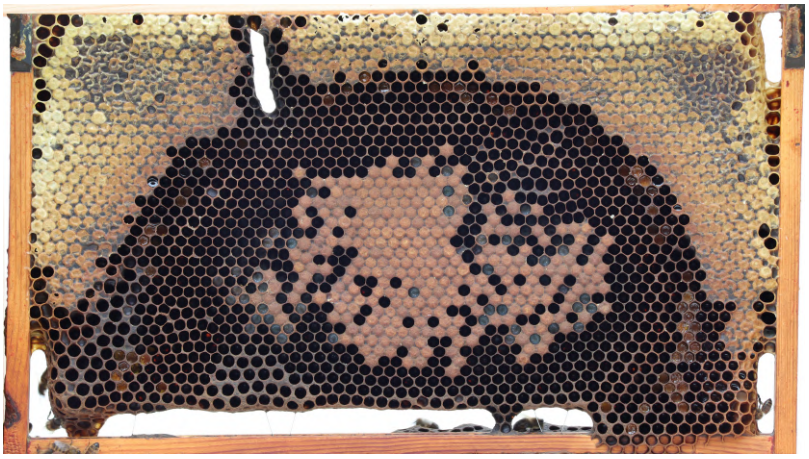


Figure 7.9: Example of a photograph taken.

7.2 On-site experiment results

The identical experiment matrix design was used for the experiments across all apiaries. For reasons of availability of the apiraries and unsatisfactory results, not all of the laboratory experiments were repeated on site. However, the variants that were considered key were tested. Table 7.1 summarises all of the tests conducted at the various apiaries and provides a crossed reference to the relevant corresponding laboratory experiment. Appendix 3 part 2 offers a more complete description and graph of each experiment conducted in the laboratory and on-site, and for the latter, photographs and the main findings are also provided.

Table 7.1: On-site experimental matrix with main results data.

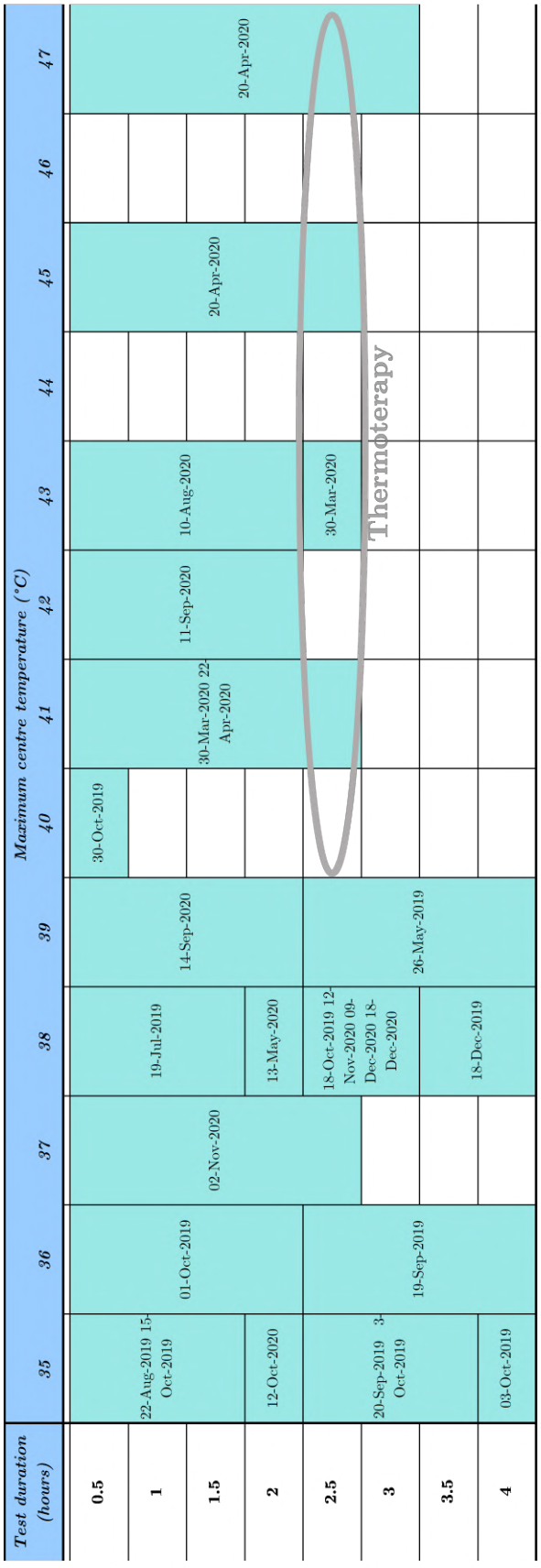
Date	19-Jul-2019	22-Aug-2019	17-Sep-2019	19-Sep-2019	20-Sep-2019	20-Sep-2019	01-Oct-2019	03-Oct-2019	03-Oct-2019	15-Oct-2019
Location	Derbyshire	Derbyshire	Nottinghamshire	Nottinghamshire	Nottinghamshire	Nottinghamshire	Derbyshire	Nottinghamshire	Nottinghamshire	Derbyshire
Frames										
Number of frames	11	11	12	12	12	12	11	12	12	5
Mesh floor										
Metal mesh floor			X	X	X	X		X	X	
Plastic mesh floor										
No mesh floor	X	X					X			X
Heat source										
SAT 2 kg	X	X	X	X			X	X	X	
SAT 3kg										
SAT 4kg					X	X				
SAT 6 kg										X
Heater mats										
Position										
Horizontal	X	X	X	X	X	X	X	X	X	X
Vertical										X
Insulation										
Box										X
Jacket								X		
Insulation crown board										
Insulation bottom										
Cork panels on walls									X	
Other				X					X	
Variations										
Preheated										
Staggered										
Sandwich						X				
Metal boxes	X									
Fan										
Results										
Duration (hours)	1.5	1.5	3.5	4	3.5	3.5	2	3.5	4	1.5
Average ambient temperature (°C)	24	21	17	-	-	-	19	-	-	13
Max surface temperature (PCM) (°C)	47	45	-	-	-	-	45	-	-	-
Max temperature at centre (°C)	38	35	33	36	35	35	36	35	35	35
Lab test related	50	56	56	19	60	23	56	56	31	15,16

Date	18-Oct-2019	30-Oct-2019	26-May-2020	10-Aug-2020	11-Sep-2020	14-Sep-2020	12-Oct-2020	02-Nov-2020	12-Nov-2020	09-Dec-2020
Location	Nottinghamshire	Nottinghamshire	Derbyshire	Derbyshire	Derbyshire	Derbyshire	Derbyshire	Derbyshire	Nottinghamshire	Lincolnshire
Frames										
	7	11	11	11	11	11	11	11	11	9
Mesh floor										
Metal mesh floor										
Plastic mesh floor										
No mesh floor	X	X	X	X	X	X	X	X	X	X
Heat source										
SAT 2 kg						X				
SAT 3kg				X			X	X	X	
SAT 4kg			X		X					X
SAT 6 kg	X									
Heater mats		X								
Position										
Horizontal	X	X	X	X	X	X	X	X	X	X
Vertical	X									
Insulation										
Box	X	X						X	X	
Jacket										
Insulation crown board			X	X	X	X	X	X	X	X
Insulation bottom	X		X	X	X	X	X	X	X	X
Cork panels on walls										X
Other										
Variations										
Preheated				X	X		X			
Staggered										
Sandwich										
Metal boxes										
Fan										
Results										
Duration (hours)	3	0.5	5	2	2	2	2	2.5	3	3
Average ambient temperature (°C)	12	10	18	25	18	22	10	13	12	8
Max surface temperature (PCM) (°C)	50	NA	57	55.2	55.7	55.7	55.4	55.9	55.1	53.2
Max temperature at centre (°C)	38	40	39	43	42.6	39.8	35.4	37.4	38.3	38.6
Lab test related	17,22	45-49	54,55,59	51,52	51,52	50,56	41-44	36, 61	36,61	5, 7, 68

Date / *Location*	*09-Dec-2020* *Lincolnshire*	*18-Dec-2020* *Lincolnshire*	*18-Dec-2020* *Lincolnshire*	*30-Mar-2020* *Derbyshire*	*30-Mar-2020* *Derbyshire*	*20-Apr-2020* *Lincolnshire*	*20-Apr-2020* *Lincolnshire*	*22-Apr-2020* *Derbyshire*	*13-May-2020* *Derbyshire*
Frames									
	11	9	11	11	11	11	11	11	11
Mesh floor									
Metal mesh floor									
Plastic mesh floor									
No mesh floor	X	X	X	X	X	X	X	X	X
Heat source									
SAT 2 kg									
SAT 3kg									
SAT 4kg	X	X	X	X	X	X	X	X	X
SAT 6 kg									
Heater mats									
Position									
Horizontal	X	X	X	X	X	X	X	X	X
Vertical									
Insulation									
Box									
Jacket									
Insulation crown board	X	X	X	X	X	X	X	X	X
Insulation bottom	X	X	X	X	X	X	X	X	X
Cork panels on walls	X	X	X						
Other						X			
Variations									
Preheated								X	
Staggered									
Sandwich									
Metal boxes									
Fan	X		X						
Results									
Duration (hours)	2.7	4	3	2.5	2.5	2.5	3	2.5	2
Average ambient temperature (°C)	8	13	12	21	20	19	18	12	15
Max surface temperature (PCM) (°C)	54	50.3	54.4	54.2	57.2	54.7	56	53.8	55.6
Max temperature at centre (°C)	38.6	38.1	38.7	43.1	41.7	45.2	47.9	41.7	38.6
Lab test related	68-70	5,31, 68-70	68-70	51,52,54,55,59,60	51,52,54,55,59,60	65	51,52,54,55,59,60	51,52	51,52,54,55,59,60

To avoid overheating the bees, the initial experiments were conducted for a brief duration. As improvements in the performance of the prototypes were achieved, the duration of the experiments was extended. In Table 7.2, a graphic summary of the highest temperature achieved in the brood chamber's centre and the time period during which the studies were conducted is depicted. The objective was for the tests to fall inside the thermotherapy zone, denoted by an oval in the Table. It was revealed that exposing the beehive to a temperature of 47 °C for around three hours is still tolerable for the bees. It is uncertain if they could withstand a greater temperature or a longer duration at thermotherapy temperatures. After identifying the experiments that reached the thermotherapy zone, the settings under which they were conducted and the factors with which they coincided were studied.

Table 7.2: Summary of the experiments done in the apiary.



The graph shown in Figure 7.10 shows the results of one of the most outstanding tests. It is the one identified as 20-Mar-2020 in the Table 7.2 above. The parameters that proved to be the most efficient and least laborious in laboratory testing and certain on-site tests were employed in this test. The parameters were 4.2 kg of PCM, top and bottom insulation, no metal mesh, and an average ambient temperature of 21 °C.

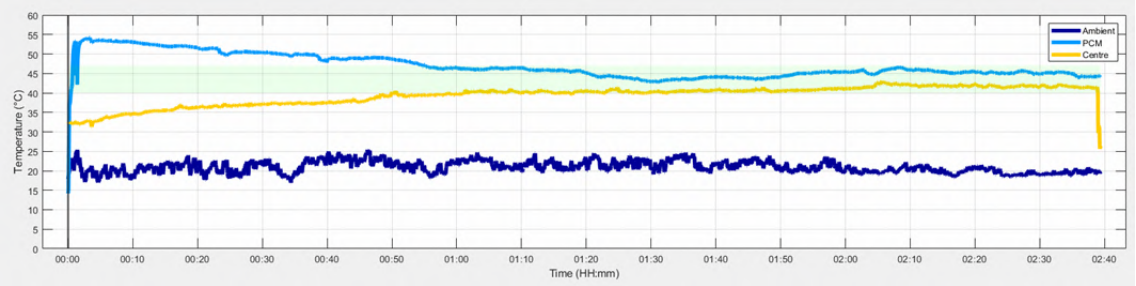


Figure 7.10: Results of test performed on site (20-Mar-2020).

The results confirmed that the beehive's interior typically has a temperature of 33 °C. That was the starting temperature in this instance. It is important to note that even though the PCM activated achieved a peak temperature of around 55 °C, its temperature curve is erratic and degrades more quickly than it did in lab tests. This is probably a result of the contact with the bees, either by active thermal dissipation, such flapping or other actions to attempt to lower the temperature, or through passive action, like heat absorption. A 45 °C decrease in PCM surface temperature is seen. The beehive center's temperature, however, progressively rises until it reaches the green band, which denotes the thermotherapy range, after 50 minutes.

The temperature in the beehive's centre was within the appropriate range for at least 1 hour and 30 minutes at the conclusion of the 2 hours and 30 minutes, which is the amount of time advised by the literature. The objectives of this experiment are satisfied since it collects all the factors that have been selected by earlier laboratory and on-site testing. Additionally, the identical settings were used multiple times with comparable results.

7.3 Treatment results

After refining the PCM prototype, defining the PCM formula, designing the floor with insulation, and manufacturing the packages with the best material selected, more tests were conducted. CO_2 testing, honey sampling, and photography were all done throughout these trials.

This last round of tests was designed to assess the thermotherapy itself. Regrettably, due to factors unrelated to this project, the quantity of testing required could not be particularly extensive. The tests were conducted over a three-month period. In two of the apiaries, a total of five beehives (HT) were evaluated and compared to five control beehives (NHT). Four visits, one every seven days, were

conducted to each beehive, and the Varroa count was recorded in a sample of 200 bees prior to treatment. The record of Varroa mites recorded using CO_2 sampling during these studies is shown in Table 7.3. Appendix 4 includes the visit and count record format.

Although the beehives used in the experiment were not previously treated, they were not highly infected with Varroa mite, as shown by the mite count of the control beehives. In most instances, the therapy seems to be beneficial, since a progressive decline in the number of Varroa is observed. However, a longer follow-up period and increased thermotherapy administration would have given firmer evidence of its efficacy.

Unfortunately, 5 trials on-site were insufficient to assess the efficacy of the therapy in this situation. Although the literature claims that applying the temperatures reached with the PCM (40-47 °C) for around 2.5 hours is enough to kill the Varroa mite, regardless of the nature of the heat source.

Table 7.3: Record of treated and control beehives and Varroa count through CO2 sampling.

Location	*Beehive*	*Type*	*Date*	*Visit*	*Varroa mites*
Healthy Bees	6	Control	30-Mar	1st	--
			22-Apr	2nd	0
			29-Apr	3rd	0
			06-May	4th	1
	21	Treated	30-Mar	1st	0
			22-Apr	2nd	2
			29-Apr	3rd	1
			06-May	4th	1
	12	Control	30-Mar	1st	--
			22-Apr	2nd	16
			29-Apr	3rd	5
			06-May	4th	3
	22	Treated	30-Mar	1st	2
			22-Apr	2nd	5
			29-Apr	3rd	3
			06-May	4th	3
	45	Control	22-Apr	1st	1
			29-Apr	2nd	0
			06-May	3rd	1
			13-May	4th	1
	25	Treated	22-Apr	1st	1
			29-Apr	2nd	0
			06-May	3rd	1
			13-May	4th	0
Thorne	2	Control	20-Apr	1st	1
			27-Apr	2nd	0
			04-May	3rd	0
			11-May	4th	0
	1	Treated	20-Apr	1st	2
			27-Apr	2nd	0
			04-May	3rd	0
			11-May	4th	0
	C4	Control	20-Apr	1st	3
			27-Apr	2nd	0
			04-May	3rd	0
			11-May	4th	0
	A3	Treated	20-Apr	1st	2
			27-Apr	2nd	0
			04-May	3rd	0
			11-May	4th	0

7.3.1 Effects of heat treatment

Based on the above-described CO_2 testing, honey sampling, and photography, research were conducted on the effects of heat treatment on varroa mites, honey quality, and larvae health, respectively. The outcomes are listed below.

On Varroa mites and worker honeybees

A total of about 100 live Varroa mites were collected during visits to Risley's apiary in October and November 2020. A CO_2–based Varroa collection device was used to temporarily anesthetise worker bees. If worker bees carry mites, the mites fall off and can subsequently be separated from the bees. Roughly 200 bees are treated per CO_2 exposure.

Mites were split into two groups and transferred to two Petri Dishes. Petri Dish #A was incubated at 35 °C during 1 hour, while Petri Dish #B was incubated at 42 °C - 45 °C during 1 hour. The incubators contained H_2O-baths, to provide some humidity, simulating conditions within the beehive. Independent of the two temperature exposures, all mites survived the heat-shock treatment. Survival was assessed visually, observing the mobility of the mites. The higher temperature range (42 °C - 45 °C) supposed to reflect the heat-pack treatment. Exposure to 42 °C - 45 °C over a 60 minute period of time does not kill the mites, nor does it impair their motility.

On the other hand, worker honeybees were split into two groups with 10 bees each, and transferred to glass jars, covered with a fine metal mesh. Jar #A was incubated at 35 °C during 1 hour, while jar #B was incubated at 42 °C - 45 °C during 1 hour. The incubators included H_2O-baths to simulate beehive conditions. Regardless of the temperature exposures, all bees survived, as expected.

Initially, it was planned to analyse the expression of a specified set of heat-shock genes in honeybees and Varroa mites after exposure to the two temperatures relevant to the project, i.e. 35 °C and 42 °C - 45 °C. A large number of mites is needed to isolate sufficient mRNA to monitor potential changes in gene expression. As this sort of study has not been performed before with Varroa mites, there are no known genes that could be used as controls, which are those whose expression is unaffected by temperature changes. Given the time of year and the restricted availability of live Varroa mites, the technique of quantitative reverse transcription PCR (RT-qPCR) initially intended would be unable to provide useful data.

On honey microbiology

Samples of honey were collected from control and heat-treated hives on four separate apiary visits in October and November 2020. One control and one heat-treated hive were sampled on each occasion. Each sample was diluted 1:9 in Maximum Recovery Diluent (MRD, CM0733, Oxoid, UK) and decimally diluted in the same medium to 10-3. Volumes of each diluent were spread-plated onto three different types of agar medium:

Nutrient Agar (CM0003B, Oxoid, UK): to detect aerobic micro-organisms.

Sabouraud Dextrose Agar (PO0394, Oxoid, UK): to detect dermatophytes, other fungi and yeasts.

MacConkey Agar (CM0007, Oxoid, UK): a differential medium for the isolation of intestinal pathogens which can contaminate honey.

All inoculated media were incubated aerobically at 37 °C for up to 72 h, with inspection at 24 h intervals. None of the inoculated plates showed growth of micro-organisms after 72 h suggesting that bacteria and fungi were either absent or below the limit of detection using this method.

Growth was recorded for positive control plates, media inoculated with cultures of bacteria or fungi which should grow on the agar. The plates were inoculated with cultures of *E.coli K12* for Nutrient Agar and MacConkey Agar; and *Saccharomyces cerevisiae* for Sabouraud Dextrose Agar. As the number of honey samples assessed was very small, larger scale sampling may result in some positive samples. However, it was not possible to determine if there was an effect of heat treatment on the micro-organisms in the honey with the samples tested.

On brood health

Four visits were made to the test apiary (October 12th and 19th and November 2nd and 10th). At each of the Oct 12th and Nov 2nd visits, two hives were selected, one control and one test.

With two photographs taken of each frame of both beehives, a total of 44 photographs were taken. Photographs from the control and test colonies were taken on the first visit, and then the test colonies were photographed in the same way one week later. Measurements of capped brood and larvae were determined using HoneyBeeComplete software (Figure 7.11), initially with automatic detection, then manual confirmation of the results .

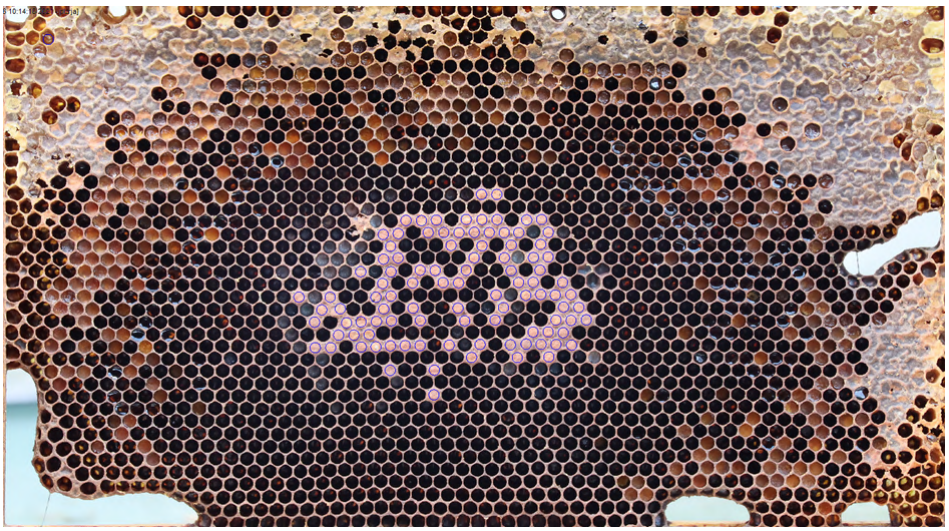
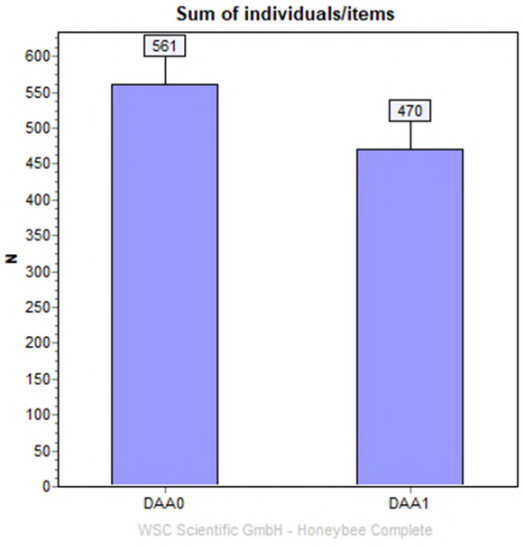


Figure 7.11: Example of auto-detection of capped cells on a sample frame using HoneyBeeComplete software.

Automated detection of larvae was hampered because the frames from these colonies were old and so the contrast was not sufficient for the software to make the

correct calls on all occasions. Capped cells were largely identified accurately, but larvae less so and many of them had to be manually added to the counts following confirmation screening.

The number of capped cells fell slightly, one week after heat treatment, as shown in Figure 7.12 generated as a result by the software. This is to be expected given the time of year the sampling was taking place, and many of the larvae in these cells may have emerged as adults, considering egg to adult development time for workers is approximately 21 days.

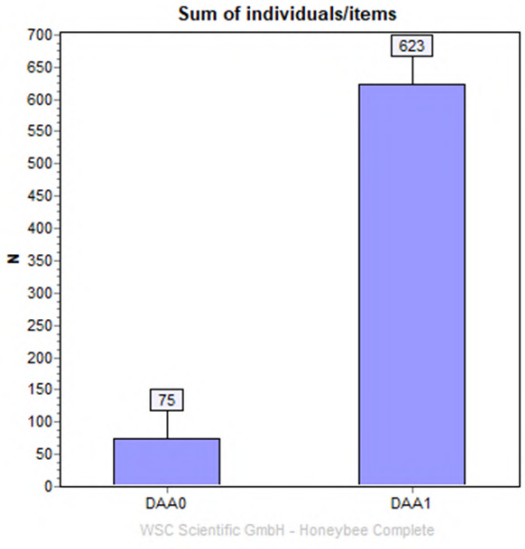


	DAA0	DAA1
Comb 1:	0	0
Comb 2:	0	0
Comb 3:	0	0
Comb 4:	0	0
Comb 5:	0	0
Comb 6:	0	0
Comb 7:	0	0
Comb 8:	0	0
Comb 9:	100	98
Comb 10:	204	318
Comb 11:	257	54
Comb 12:	0	0
Comb 13:	0	0
Comb 14:	0	0
Comb 15:	0	0
Comb 16:	0	0
Comb 17:	0	0
Comb 18:	0	0
Comb 19:	0	0
Comb 20:	0	0

	DAA0	DAA1
Sum:	561	470
Mean:	28.05	23.5
Min:	0	0
Max:	257	318

Figure 7.12: Capped cells in colony before and 1 week after heat treatment.

Figure 7.13 shows how the counts of larvae increased appreciably one week after heat treatment. This suggests that heat treatment did not prevent a significant number of eggs from developing into larvae. Future trials would need to focus on a greater number of hives, both from control and heat treated colonies, in order to determine if there are any statistically significant differences between the two groups.



	DAA0	DAA1
Comb 1:	0	0
Comb 2:	0	0
Comb 3:	0	0
Comb 4:	0	0
Comb 5:	0	0
Comb 6:	0	0
Comb 7:	0	0
Comb 8:	0	0
Comb 9:	55	249
Comb 10:	9	106
Comb 11:	11	268
Comb 12:	0	0
Comb 13:	0	0
Comb 14:	0	0
Comb 15:	0	0
Comb 16:	0	0
Comb 17:	0	0
Comb 18:	0	0
Comb 19:	0	0
Comb 20:	0	0

	DAA0	DAA1
Sum:	75	623
Mean:	3.75	31.15
Min:	0	0
Max:	55	268

Figure 7.13: Larvae counts in colony before and 1 week after heat treatment.

7.4 Chapter conclusions

All experiments that were to be conducted were scheduled. The tests were differentiated by a set of parameters that were varied for each test. This experiments aimed to further determine the most effective method of applying heat treatment. Adjustments were made to parameters like as the mass of the PCM, the insulation, etc., and some upcoming ideas were also tried, such as the usage of fans or preheating the PCM packs.

The on-site experiments revealed that the external ambient temperature has a significant influence on the PCM pack's performance. An ambient temperature of at least 15 °C is necessary to achieve the thermotherapy temperature. Additionally, by altering the amount of PCM, it was confirmed that, as anticipated by the theoretical model, a mass of at least 3.4 kg, preferably 4 kg, is necessary to sustain the thermotherapy temperature for the 150 minutes required to perform the treatment.

Although different configurations and some pack prototypes were tested in the initial experiments, the final tests used the parameters recommended by the most successful laboratory and on-site tests. Therefore, the best parameters found were: no mesh floor, bottom and top insulation, 3 to 4 kg of PCM, and a minimum ambient temperature of 15 °C.

Finally, CO_2 testing, honey sampling, and frame photography were used to conduct a more extensive laboratory examination of the treated colonies. Regrettably, the CO_2 tests were inconclusive since the treated beehives were not severely infested and thorough follow-up was not feasible. However, it has been demonstrated that these treatments are successful in eliminating the Varroa mite while having no adverse effect on worker bees. No evidence of alteration to the honey's microbiology or brood health was detected.

Chapter 8

Conclusion

This chapter presents the study project's overall and ultimate conclusion. The circumstances identified as essential for the proper execution of the thermotherapy treatment are promptly mentioned. Future works are discussed.

8.1 Achievements, key findings and conclusions

In conclusion, it was demonstrated that by utilising sustainable energy technologies such as PCMs, it is feasible to eradicate the Varroa mite, the primary pest that threatens bees in the United Kingdom and around the world. Supercooled SAT was employed. A functional prototype was created that was not only straightforward to use but also simple to manufacture. It was proven that the treatment had no adverse effect on bees or their products.

In order to understand the existing situation of bees in the habitat chosen for this study, we conducted a thorough assessment of the literature. This review also provided us with an idea of the possible scope of this project. Several characteristics of commercial beehives were determined, and these characteristics served as the basis for the heat treatment approach. The physical dimensions and constraints of beehives were recognised. Additionally, by understanding the materials that were utilised in their construction, it is possible to ascertain their thermal qualities.

On the other hand, we are well-aware of the obstacles bees face, particularly when it comes to extreme weather conditions such as heat. Understanding bees' heat regulation behaviour processes enabled us to anticipate these activities before to applying the thermal treatment in an experimental setting.

After conducting an extensive investigation into the life cycle of the Varroa mite, it was possible to select the thermotherapy (also known as hyperthermia) as the most sustainable strategy for mite elimination.

Studying the state of the art in heat treatment devices was beneficial in terms of understanding what has been accomplished over time and also identifying opportunities where other devices have demonstrated deficiencies or obstacles, which distinguish the solution proposed in this thesis from those used by others. For example, it was pointed out that the vast majority of operations need the use of on-site electrical power and that many are time-consuming processes that are

incompatible with commercial beehives and necessitate the relocation of bees for treatment. As part of the ongoing search for a more ecologically and user-friendly technology, efforts have been made to prevent the inconveniences associated with previous technologies.

A phase change material (PCM) was chosen following a selection criteria that prioritised, among other factors, high volumetric heat capacity and thermal conductivity, rapid and reversible crystallisation and consistent freezing and melting. Due to its thermal, physical, and chemical characteristics, Sodium Acetate Trihydrate (SAT) was found to be the best PCM for use in thermal treatment applications. There are several applications for this material, including thermal energy storage. It presents low risk usage, affordable cost and the ability to be encapsulated and triggered in a variety of ways. This versatility allowed for the exploration of various methods of producing the prototypes, which were developed until some viable options for thermotherapy application were discovered. Plastic materials were discovered to be less expensive and easier to deal with than other materials. The prototypes made of Nylon, EVOH, and biodegradable plastic were the most successful. In order to maximise the amount of surface area exposed to heat transfer while also increasing the efficiency of heat exchange, grooved pouches were developed. The technique for preparing the SAT supercooled has been enhanced; the appropriate water content is 8 wt% (weight percent). It was also decided that the use of thickeners would be discarded in order to reach the highest possible temperature in the PCM pack's surface.

Comparatively, the cost of any of these non-mass-produced prototypes was far lower than the cost of any of the devices detailed in the state of the at summary. The cost of producing a PCM pack was roughly £ 20. Depending on the design, the time necessary to make the packs ranged between 2 and 6 hours on an average. Although it should be mentioned that this process was completed totally by hand and without the use of any specialised equipment.

Developing a basic mathematical model that approximates the thermal interaction that happens within a brood box when an active PCM pack is inserted proved to be feasible in this study. The absence of air currents within the brood chamber results in natural convection transferring heat upward from the base to the top of the chamber. The research was carried out at four nodes that were strategically placed in the midst of the beehive's key regions: the PCM, the bottom, the centre, and the top of the hive. This analysis contributed in the size of the PCM pack, which resulted in the determination that around 3.4 kg is necessary to achieve the thermotherapy temperature in the brood chamber's centre.

To aid in visualising the heat transfer inside the beehive and determining if, given the temperature of the PCM pack, a thermotherapy temperature in the desired range (40 - 47 °C) would be achieved, preliminary simulations were also carried out. Results showed that the PCM pack is incapable of overheating the beehive's interior, even under the most ideal of conditions for operation. Due to the fact that the temperatures reached were extremely close to the bees' maximum tolerated range, there is a true risk of overheating in a real-world scenario. It is necessary to take into account additional factors such as humidity and bee density.

In order to forecast the behaviour of the PCM pack, as well as to determine

the temperature distribution and to estimate the time necessary to reach the thermotherapy temperature, the main simulations were used. There are various precedents for mathematical modelling of thermal interactions within a beehive; however, because this application is unique, there are no precedents for computational fluid dynamics (CFD) analysis of a beehive utilising a heat source (as in this application). This simulation may be useful as a starting point for potential thermotherapy research in the future. The results of the prediction made by the simulation will be compared to those obtained in the laboratory and in the apiary.

This project involved designing and building an experimental rig, the "observation beehive," which was later used to watch a number of laboratory and outdoor trials. In a similar way, a special floor was designed specifically for use with the PCM pack. Initially, there was no consideration for expanding the space to accommodate the PCM pack; however, it was discovered that extra room was required due to the mass of the PCM packs. Aside from that, heat was lost from the PCM pack to an external surface beneath the floor of the common beehive. As a result, it was decided to use a drawer that was compatible with the National Standard beehive in order to ease the entrance of the PCM pack as rapidly as possible while minimising disruption to the bees. During the testing process, the design of the drawer was refined. It was decided to use an insulating board bottom with ridges, which raised the PCM packs and enhanced heat transmission.

Additionally, sensors and equipment were used in order to record temperature differences within the beehive throughout each of the experiments. The protocols for conducting the tests in the laboratory and on-site were detailed in this thesis. A more in-depth laboratory analysis of the treated colonies was carried out in the latter case through the use of CO_2 testing, honey sampling, and frame photography.

All of the tests that were to be done were planned in advance. Several factors were changed from one test to the next. The purpose of these tests was to find the most effective way of performing heat treatment in greater detail. Adjustments were made to characteristics like the mass of the PCM, the insulation, and so on, and some novel concepts, such as the use of fans or preheating the PCM packs, were also tested.

The results of the intended simulations have been acquired and analysed. In spite of the fact that some assumptions were made in order to simplify the calculations, it was discovered that temperature changes within the brood chamber were relatively similar to those seen in laboratory tests and comparable to those reported in apiary investigations.

In order to improve the prototype and fine-tune the thermal treatment application technique prior to the on-site testing, it was necessary to conduct preliminary laboratory tests. It has already been mentioned that honeybee testing is a highly delicate technique that should be carried out with considerable caution. As a result, any variations of the trials were carried out in the laboratory before being carried out in the apiary.

The results of the on-site studies demonstrated that the temperature of the surrounding environment has a considerable impact on the performance of the PCM pack. The findings gathered throughout the studies led the conclusion that five

key requirements must be addressed in order for thermotherapy to be performed correctly by inserting PCM packs with SAT horizontally. The requirements are the following:

1. There should be no metal or plastic mesh, or any other obstacle between the PCM pack and the interior of the brood box. The use of any type of mesh in the lowest area of the brood box, according to laboratory research, interfered with the free movement of heat in the enclosure.

2. The mass of PCM must be at least 3 kg. As predicted by the mathematical model, a mass of at least 3 kg, preferably 4 kg, is required to maintain the thermotherapy temperature for the 150 minutes required to complete the treatment.

3. The brood box should have thermal insulation on both the top and bottom. It is necessary in order to prevent heat from leaking out of the beehive.

4. The temperature in the ambient should be higher than 15 °C by the time of applying the treatment in order to attain the thermotherapy temperature inside the brood box. It should be avoided to perform the treatment during the winter or while the colony is clustering.

5. The PCM pack (or any other heat source) put on the brood chamber floor must attain a temperature of at least 53 °C.

Preheated PCM achieves higher temperatures in the laboratory, and while this is not essential for the treatment to be effective, it is highly advised to attain the highest temperatures possible.

Regrettably, the CO_2 tests were found to be inconclusive since the treated beehives were not seriously infected and because a complete follow-up was not possible. However, it has been established that these treatments are effective in eradicating the Varroa mite while having no negative impact on worker bee populations. There was no indication of a change in the honey's microbiology or the health of the brood that could be discovered.

The standardised procedure by which all of the aforementioned tests were carried out was documented in the document shown in Appendix 4, which was sent to beekeepers in order to explain how the testing and sampling would be conducted.

As the study progressed, communication of the discoveries and approaches that were produced in a continual manner was made, both throughout the academic community and within the professional beekeeping environment. Publications such as press releases and websites have also been created to provide information about this project to the general audience. These dissemination activities contributed in raising awareness of the Varroa mite problem and the loss of bees on a regional and worldwide scale. And, on the other hand, to explain to the beekeeping community why thermotherapy is the optimal method for solving this issue.

Finally, the prototype developed is only a few steps away from being a commercially viable product that will aid in the reduction or elimination of Varroa mite infestations in UK apiaries. This will improve bees' living circumstances,

will not hurt other species with harmful chemical substances, and will be reusable and thus environmentally friendly. It is also reasonably priced, which not only attracts potential purchasers but also benefits their economy. As a result, bee losses will be reduced, Varroa mites will cease developing resistance to pesticides, and pollination of agricultural products that are critical for human sustenance and a cornerstone of the UK economy will improve.

8.2 Research outcomes dissemination

The development of this research project achieved a wide impact. The findings of this study were intended to be widely disseminated, since the Varroa mite issue continues to be a major concern for British beekeepers. It spanned a broad range, from the academic to the most accessible to the general public.

Academically, two papers have been published, conferences have been attended, and instructive posters have been created. In the commercial sector, beekeeping showcases were visited to communicate the outcomes and get in touch with the beekeeper community. Finally, for the benefit of the general public, a press release was issued and a website was constructed to describe and explain the new technology in broad strokes. All work published as a result of this project is shown in appendices 5 to 8.

8.3 Future work

Much future work could derive from this research. On the one hand, it was discovered that the prototype might be improved. Secondly, an in-depth assessment methodology is required to corroborate that this technology effectively eliminates the Varroa mite from the brood box. Finally, after these steps are completed, this prototype has the potential to swiftly become a marketable product, and therefore a route to market is proposed in Appendix 10.

8.3.1 Improvements on CFD simulation

The concept of porous media was applied in the bee simulation to simplify the software's computations. It was assumed that the bees would be spread uniformly inside the beehive. The equation (9) may be used for a more specific simulation or one designed to be compared to a real beehive whose number of bees is known or can be estimated.

$$\varepsilon = 1 - \frac{N_{bc} V_{bee}}{V_{bc}} \tag{1}$$

In this equation, N_{bc} is the number of bees, V_{bee} denotes the volume of each individual, and V_{bc} is the total volume covered by the bees, including the air voids. This equation lets calculate the individual volume of bees more freely, for instance as cylinders or as a spheroid body, and is adaptable to various bee species.

Despite the fact that the 3D model of the brood box had a slot for air flow, the temperature differential in the simulation did not result in a considerable escape

of air to the outside due to natural convection. In addition, any cooling technique from the bees such as fanning, was neglected. However, it was decided throughout the trials that this slot should stay closed in order to perform thermotherapy and only open or partly open to manage the temperature and avoid overheating. As a result, it was a correct assumption to disregard it.

Another factor that was overlooked was the amount of heat generated by the bees per unit volume. It was assumed that the bees would give more heat in any scenario, which would benefit the beehive's thermotherapy temperature. If it had been included in the simulation, Thompson's [140] technique would have been used, in which the metabolic heat generating rate per unit volume of honeybee is calculated through oxygen and glucose consumption.

8.3.2 Improvements on prototype

Stability and performance Throughout the trials, it was observed that the PCM in liquid state can be triggered unintentionally. This is because the formula is highly sensitive to certain circumstances, such as abrupt temperature fluctuations. Stabilizing or thickening agents might be applied to aid in this process. During this investigation, some of those agents were tried to be added without success. Additionally, materials are currently being investigated that, when included into the SAT mixture, have the potential to increase its thermal conductivity.

Heat transfer area The larger the contact area between the PCM pack's surface and the brood box's air, the better the thermal performance. Additional study could be conducted to determine alternative ways to improve the surface area of the gaskets. An example of how the heat transfer area can be increased is shown in Figure 8.1 Here is shown a concept of a hard plastic container, with a bumpy surface that could improve the thermal performance of the PCM.

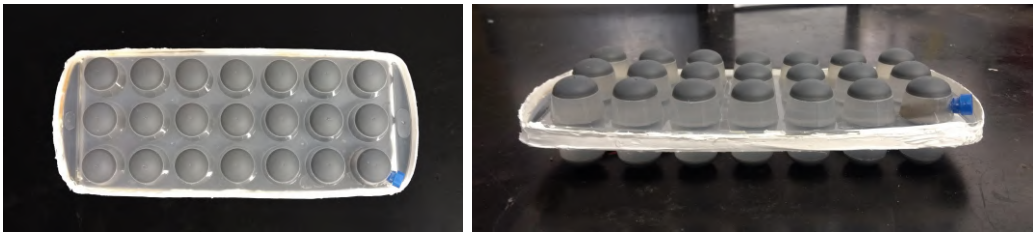


Figure 8.1: Rigid plastic pack concept.

Encapsulation Another disadvantage noticed was that when thin and flexible polymers were used, they posed potential handling and transportation issues. Exploratory research might be conducted on rigid materials with similar thermal properties to those employed. If a hard material could be employed, it would be relatively simple to increase the PCM's surface area and therefore its heat transmission.

Near the conclusion of this project, the possibility of utilising a hard material was explored. The SAT was contained using an "icepack". Figure 8.2 displays an

early version of this prototype. The sturdy container enables the PCM pack to be vertically positioned between the beehive frames. Only a few laboratory tests were conducted using this container, but they were insufficient.

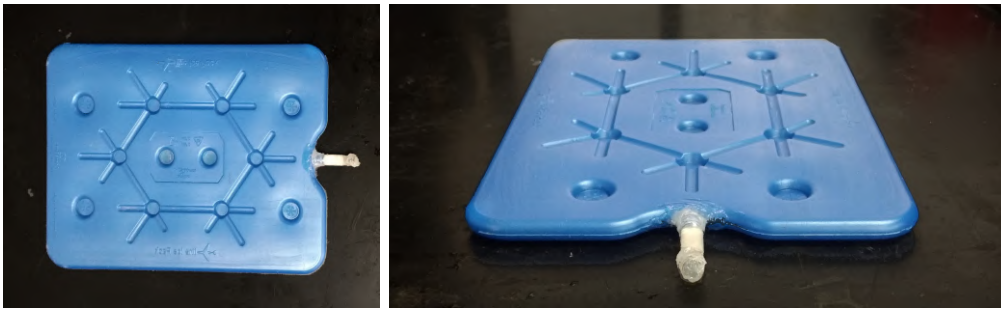


Figure 8.2: Hard plastic PCM pack.

Heat transfer performance New techniques were tried and found to be beneficial, such as preheating or staged activation. Subsequent research could examine the potential of adopting other new techniques or components to enhance the treatment's efficiency.

8.3.3 Treatment evaluation

Due to the biological cycle of bees being inextricably linked to the seasons of the year and the project's time constraints, adequate evaluations of the thermal treatment could not be conducted. However, the work of other researchers was evaluated, and two viable experimental approaches for determining the efficacy of heat therapy with PCM packs were proposed. Appendix 9 contains this report.

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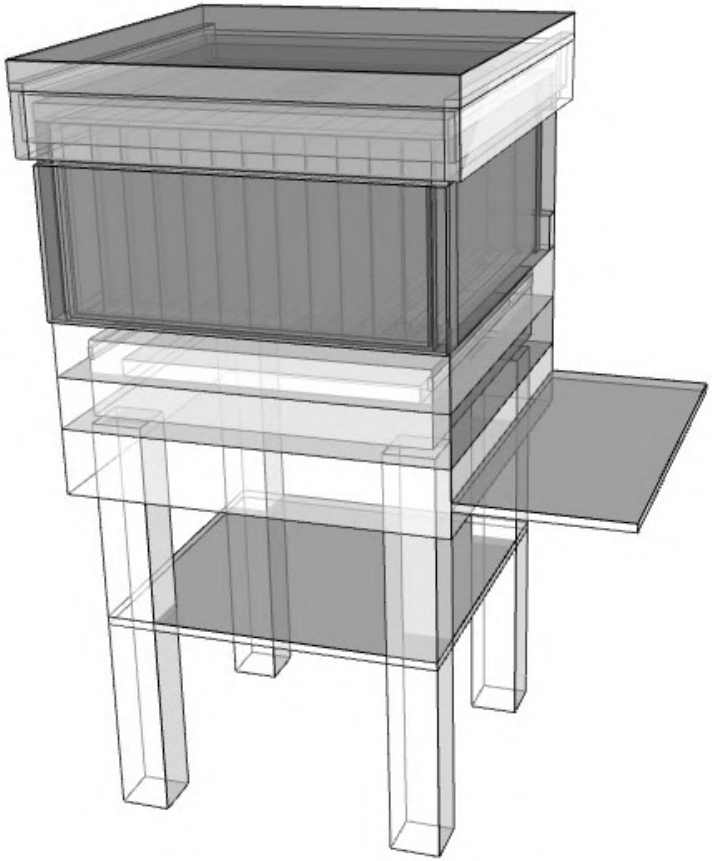
Appendix

Appendix 1

3D blueprints of the observation beehive

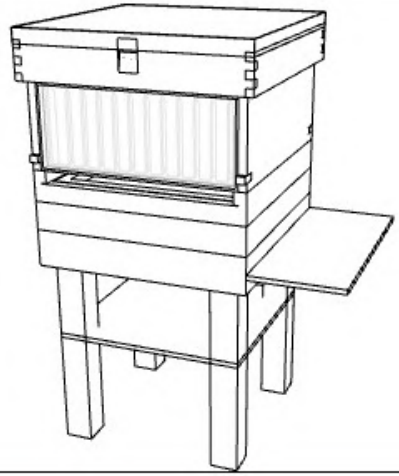
Part Number: Observation Beehive
Comments:

Date: 19/12/2019
Revision:
Material: Cedar
Designed by: Emmanuel Tapia



Notes:

- The windows material would be Polycarbonate
- The side panels shold be easily removable
- The drawer should have a handle




Current Model View


*Front


*Back


*Left


*Right


*Top


*Bottom

Appendix 2

Data processing code

```
%%DATA PROCESSOR AND PLOT GENERATOR - Emmanuel Tapia %%

%Plot layout
Test = readtable('Beehive_12.csv','TreatAsEmpty',{'Calibration','O/C','#N/A'});
Beehive = imread('New_beehive.png');
filename = 'Results_Beehive12.gif';
Test_name = 'Beehive 12' ;
Test_description= '2 PCM packs (4.2 kg) / Healthy Bees / 13-05-2021';
Step_size = 10; %Graph every X minutes
Sample_size = 1; %Seconds between samples on the datalogger
step = (60*Step_size)/Sample_size;
sample = 1;
Tmin=20;
Tmax=60;
h = figure;
%Maximized window
set(groot, 'defaultFigureWindowState', 'maximized');
%Title of the window
sgtitle(sprintf('Test: %s \n %s',Test_name,Test_description));
%Data aquisition
Ambient_data = table2array(Test(:,3));
PCM_data = table2array(Test(:,4));
Top_data = table2array(Test(:,5));
Centre_data = table2array(Test(:,6));
Bottom_data = table2array(Test(:,7));
Top2_data = table2array(Test(:,8));
Centre2_data = table2array(Test(:,9));
Bottom2_data = table2array(Test(:,10));
Left_data = table2array(Test(:,8));
Down_data = table2array(Test(:,10));
Test_time = duration(0,0,sample:size(Test,1));

while sample < size(Test,1)
%Gathering the data
Ambient = Test{sample,3};
PCM = Test{sample,4};
Top = Test{sample,5};
Centre = Test{sample,6};
Bottom = Test{sample,7};
Top2 = Test{sample,8};
Centre2 = Test{sample,9};
Bottom2 = Test{sample,10};
Left = Test{sample,9};
Right = Test{sample,6};
strength = [Ambient Ambient Ambient Ambient Ambient Ambient Ambient Ambient Ambient
Ambient Top2 Top Top2 Left Centre2 Centre Centre2 Right Bottom2 Bottom Bottom2 PCM
PCM PCM PCM PCM PCM]';
%Position of the sensors
X = [0 930 0 930 155 765 155 765 155 765 405 460 510 300 400 460 510 610 400 460 510
175 450 750 175 450 750]';
Y = [0 0 570 570 115 115 430 430 500 500 150 150 150 280 280 280 280 280 420 420 420
450 450 450 490 490 490]';
%Background image
[height,width,depth] = size(Beehive);
OverlayImage=[];
F = scatteredInterpolant(Y, X, strength,'natural');
for i = 1:height-1
   for j = 1:width-1
          OverlayImage(i,j) = F(i,j);
   end
end

%SECTION 1: Color plot
subplot(2,2,1);
alpha = (~isnan(OverlayImage))*0.7;
imshow(Beehive);
hold on
OverlayImage = imshow( OverlayImage );
set( OverlayImage, 'AlphaData', alpha );
%Color the PCM pack
PCM_color =((PCM-Tmin)/(Tmax-Tmin))*(256);%Interpolate between defined scale and rgb
scale(0-256)
PCM_rgb = ind2rgb(int16(PCM_color),colormap(jet(256))); %Convert color vaule to r g
```

```
    b values from the jet color scale
69  rectangle('Position',[175,450,570,35],'Curvature',[0.1,1],'LineStyle','none','FaceColo
    r',PCM_rgb)
70  %Title of the subplot
71  Date_string = datestr(((sample-1)*Sample_size)/(24*60*60),'HH:MM:SS');
72  title(sprintf("Time %s ",Date_string));
73  %Indicate the temperature
74  text(460,280,num2str(Centre,3),'HorizontalAlignment','center','Color','black','Fontsiz
    e',9);
75  text(460,465,
    num2str(PCM,3),'HorizontalAlignment','center','Color','black','Fontsize',9);
76  text(50,280,
    num2str(Ambient,3),'HorizontalAlignment','center','Color','white','Fontsize',9);
77  %Show Color Map and bar
78  colormap( OverlayImage.Parent, jet);
79  colorbar( OverlayImage.Parent );
80  caxis([Tmin Tmax]);
81
82  %SECTION 2: Analysis summary
83  subplot(2,2,2);
84  title(sprintf("Results"));
85  imshow('Table.jpg');
86
87  %Temperature analisys
88  Terapy_time = 0;
89  for i=1:size(Centre_data)
90      if Centre_data(i) == max(Centre_data)
91          Max_centre_time = Test_time(i)*Sample_size;
92          if max(Centre_data) >= 40
93              Thermoterapy = 'Achieved';
94          else
95              Thermoterapy = 'Not achieved';
96          end
97      end
98      if PCM_data(i) == max(PCM_data)
99          Max_pcm_time = Test_time(i)*Sample_size;
100     end
101     if Centre_data(i) >= 40
102         Terapy_time = (Terapy_time + 1) * Sample_size;
103     end
104 end
105 Total_terapy = duration(0,0,Terapy_time);
106 %Answers Temp
107 text(860,95,num2str(max(Centre_data)),'HorizontalAlignment','center','Fontsize',12);
108 text(860,160,num2str(max(PCM_data)),'HorizontalAlignment','center','Fontsize',12);
109 text(860,225,Thermoterapy,'HorizontalAlignment','center','Fontsize',12);
110 text(860,285,num2str(round(mean(Ambient_data,'omitnan'),1)),'HorizontalAlignment','cen
    ter','Fontsize',12);
111 text(860,350,'--','HorizontalAlignment','center','Fontsize',12);
112 %Answers Time
113 text(1300,95,datestr(Max_centre_time,'HH:MM:SS'),'HorizontalAlignment','center','Fonts
    ize',12);
114 text(1300,160,datestr(Max_pcm_time,'HH:MM:SS'),'HorizontalAlignment','center','Fontsiz
    e',12);
115 text(1300,225,datestr(Total_terapy,'HH:MM:SS'),'HorizontalAlignment','center','Fontsiz
    e',12);
116 text(1300,285,'--','HorizontalAlignment','center','Fontsize',12);
117 text(1300,350,datestr(Test_time(end),'HH:MM:SS'),'HorizontalAlignment','center','Fonts
    ize',12);
118
119
120 %SECTION 3: Graph
121 subplot(2,2,[3,4]);
122 plot(Test_time*Sample_size,Ambient_data,'LineWidth',4,'Color','#000099')
123 xticks(minutes(0:10:size(Test)));
124 xtickformat('hh:mm');
125 hold on
126 plot(Test_time*Sample_size,PCM_data,'LineWidth',4,'Color','#0099ff')
127 plot(Test_time*Sample_size,Centre_data,'LineWidth',4,'Color','#ffcc00')
128 %plot(Test_time*Sample_size,Centre2_data,'LineWidth',4,'Color','#da7900')
129 %plot(Test_time*Sample_size,Top_data,'LineWidth',4,'Color','#22ffa0')
130 %plot(Test_time*Sample_size,Bottom_data,'LineWidth',4,'Color','#ff2d22')
131 %area(Test_time*Sample_size,Centre_data,40)
```

```
xline(duration(0,0,sample*Sample_size),'LineWidth',2);
grid on
ylim([0 60]),xlabel('Time (HH:mm)'),ylabel('Temperature (°C)'),set(gca,'FontSize',10)
yticks(0:5:60)
%Thermoterapy temperature
x_points = [0, 0, Test_time(end), Test_time(end)];
y_points = [40, 47, 47, 40];
a = fill(x_points, y_points, 'g','EdgeColor','none');
a.FaceAlpha = 0.08;
%Legend
legend({'Ambient','PCM','Centre'})


% Capture the plot as an image
      frame = getframe(h);
      im = frame2im(frame);
      [imind,cm] = rgb2ind(im,256);
% Write to the GIF File
      if sample == 1
          imwrite(imind,cm,filename,'gif', 'Loopcount',inf);
      else
          imwrite(imind,cm,filename,'gif','WriteMode','append');
      end
sample = sample + step;
end
```

Appendix 3

Detailed experiment results

Experimental work summary (Part 1)

The aim of the experiments was to evaluate and analyse the heat flow of the BeeSave prototype pack (PCM pack). Different configurations were tested in order to see which one could get the temperature for the thermotherapy (40-47°C) in the centre of the beehive. A secondary objective was to have results that allow us to contrast the experiments that will be carried out on site in the apiaries.

In total, 74 experiments were carried out in laboratory and 29 in field. This appendix contains the results for all the experiments carried in laboratory and the most relevant results of experiments carried on site.



Figure A1 Setup of the experiments in laboratory (left) and in Bunny Park apiary (right)

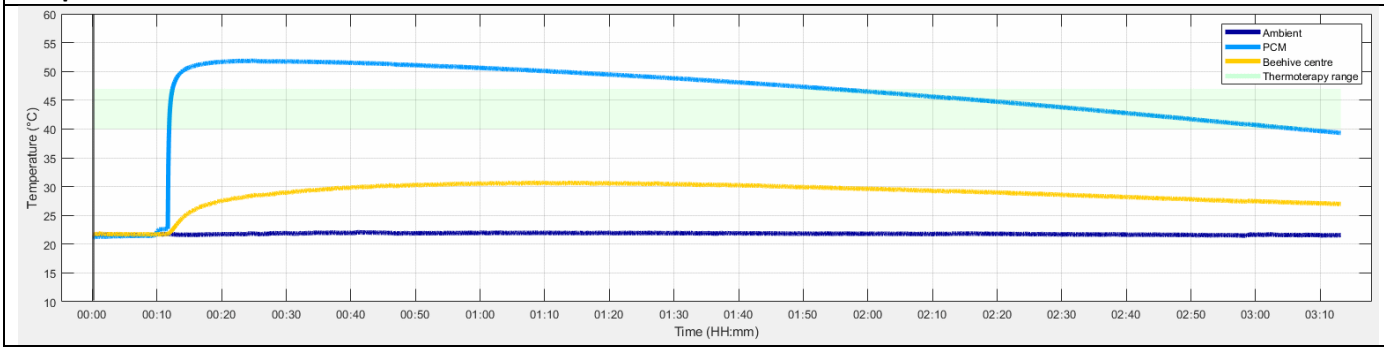
Laboratory experiments with PCMP produced packs (first production)

Test 1

Setup	Visual Key	Results
• 2 kg PCM • No insulation on top • 0 frames (empty box) • Metal mesh floor • Insulation bottom		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	30.6	01:09:50
Maximum PCM temperature	51.8	00:25:15
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	21.8	--
Total test time	--	03:13:10

Graph



Comments

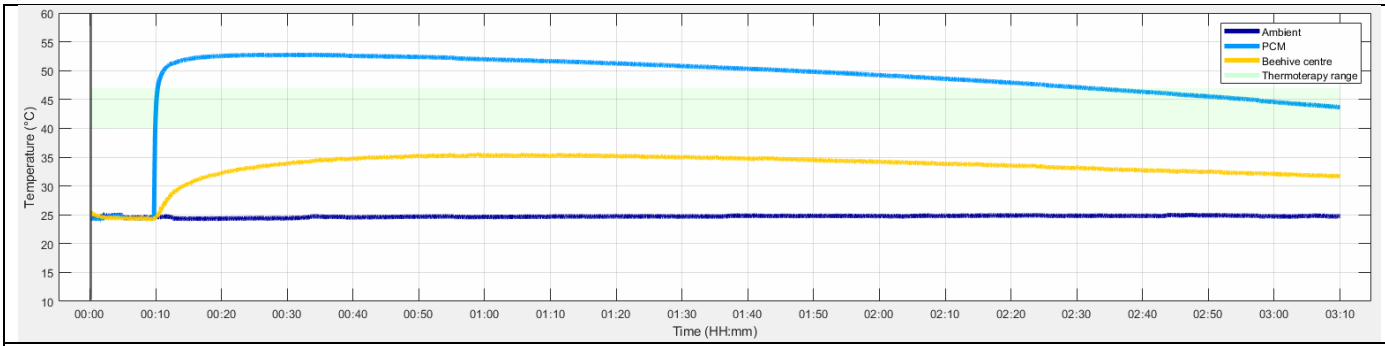
This simple experiment tested the proposed implementation of the PCM pack. With the empty box the maximum temperature was about 30°C at the centre.

Test 2

Setup	Visual Key	Results
• 2 kg PCM • Aluminium insulation on top • 0 frames (empty box) • Metal mesh floor • Insulation bottom		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35.5	00:57:50
Maximum PCM temperature	52.7	00:33:45
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	24.7	--
Total test time	--	03:10:00

Graph



Comments

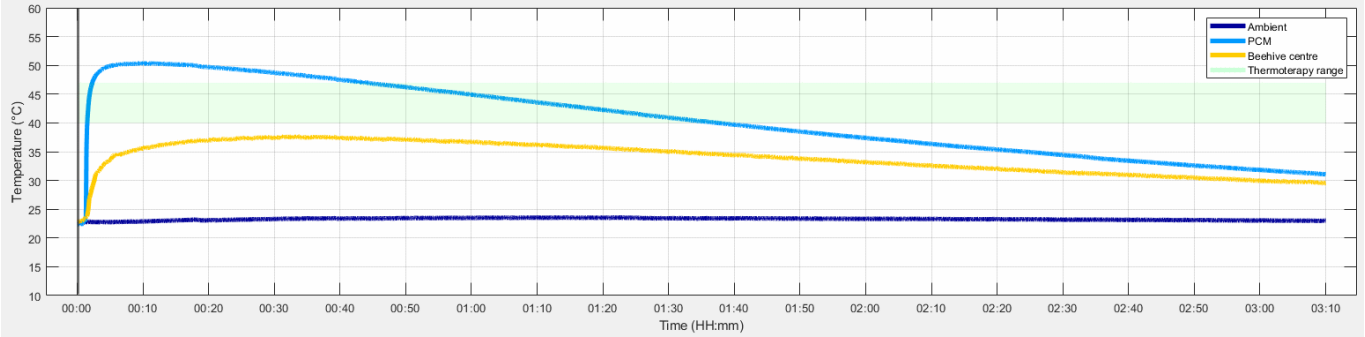
In order to reduce thermal losses, insulation was added at the top of the hive. The maximum temperature was about 35°C, which is considerably higher.

Test 3

Setup	Visual Key	Results
• 2 kg PCM • Aluminium insulation on top • 0 frames (empty box) • Pack over metal mesh floor • Insulation bottom		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	37.6	00:33:25
Maximum PCM temperature	50.3	00:09:40
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	23.3	--
Total test time	--	03:10:00

Graph



Comments

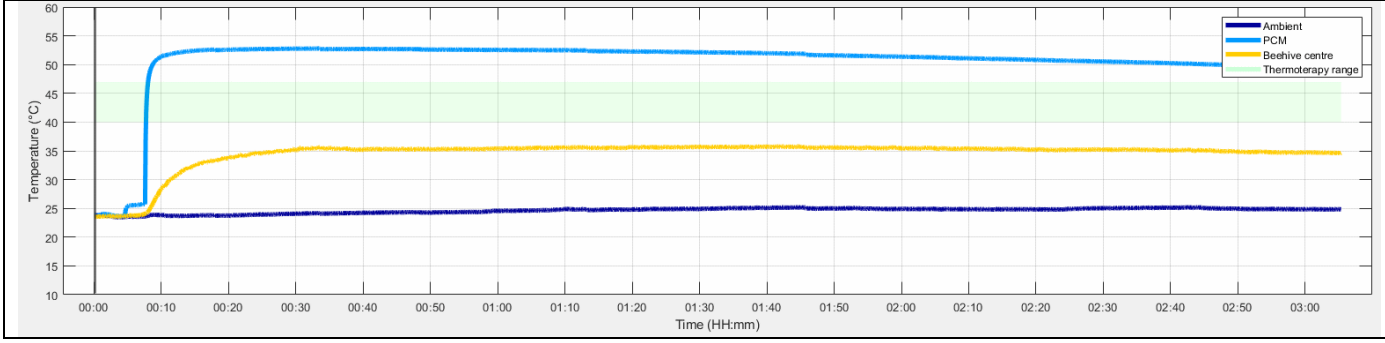
This test located the PCM pack closer to the centre. The maximum temperature was about 37°C at the centre and reached faster than the last two experiments.

Test 4

Setup	Visual Key	Results
• 4 kg PCM • Aluminium insulation on top • 0 frames (empty box) • Metal mesh floor • Insulation bottom		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35.7	01:42:15
Maximum PCM temperature	52.8	00:33:20
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	24.6	--
Total test time	--	03:05:20

Graph



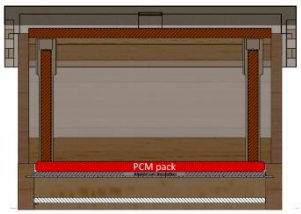
Comments
This test shows that increasing the mass of PCM does not represent higher temperature inside the beehive, but a higher rise and a longer time keeping that temperature.

Test 5

Setup

- 2 kg PCM
- SHINS insulation on sides and top
- 0 frames (empty box)
- Pack over aluminium insulation over metal mesh floor

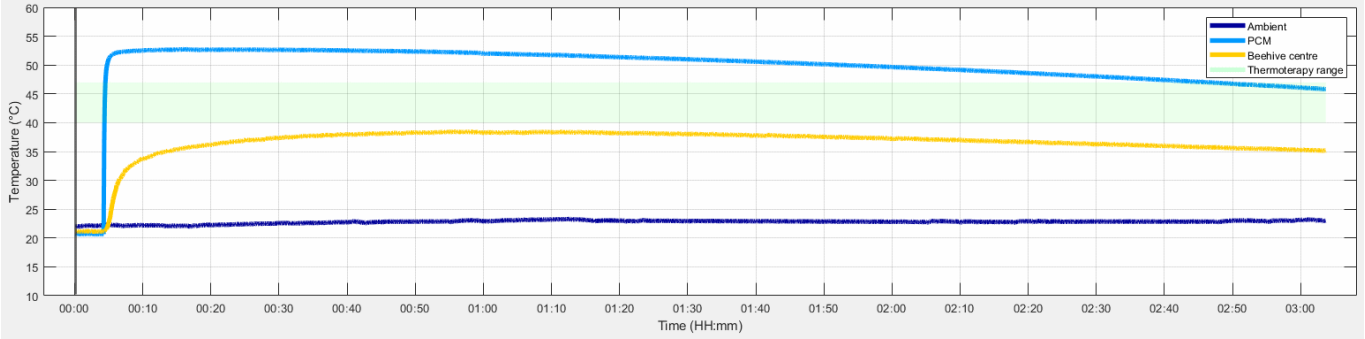
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	38.4	00:58:05
Maximum PCM temperature	52.7	00:16:25
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	22.8	--
Total test time	--	03:03:40

Graph



Comments

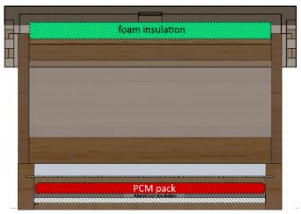
SHINS is a type of insulation made out of cork, the use of it prevented losses on the walls. Besides that, the PCM pack was located closer to the centre and it was avoided direct contact with the metal mesh floor. The maximum temperature was about 38°C and during the whole test it was over 35°C.

Test 6

Setup

- 2 kg PCM
- Foam insulation top
- 0 frames (empty box)
- Metal mesh floor
- Aluminium insulation on bottom

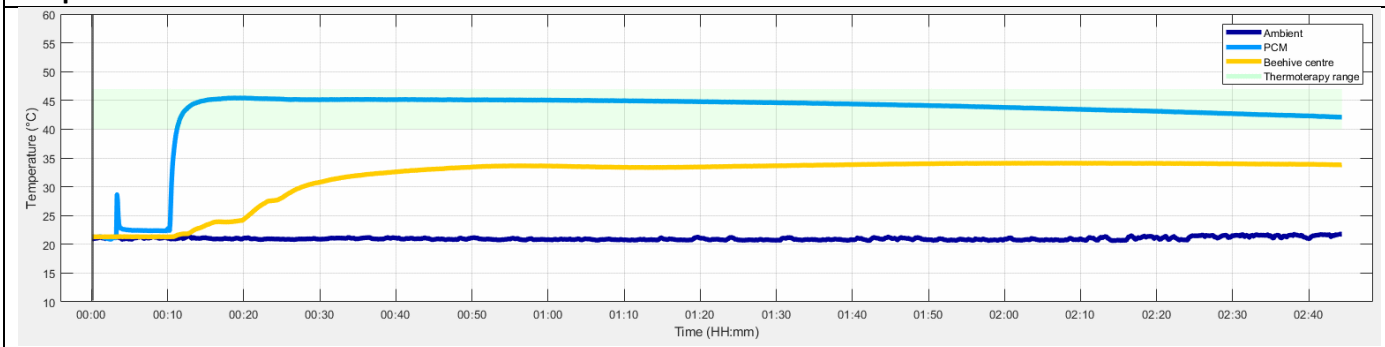
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	34.1	02:05:00
Maximum PCM temperature	45.4	00:20:05
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	21	--
Total test time	--	02:44:20

Graph



Comments

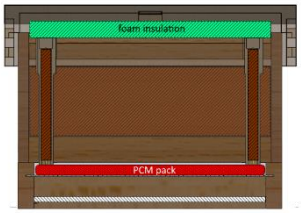
The performance of the PCM on this test was poor. Nevertheless, the foam insulation was testes. This test demonstrates that the insulation helps to maintain the maximum temperature during the treatment time.

Test 7

Setup

- 2 kg PCM
- Foam insulation top
- SHINS insulation on sides
- 0 frames (empty box)
- Pack over metal mesh floor

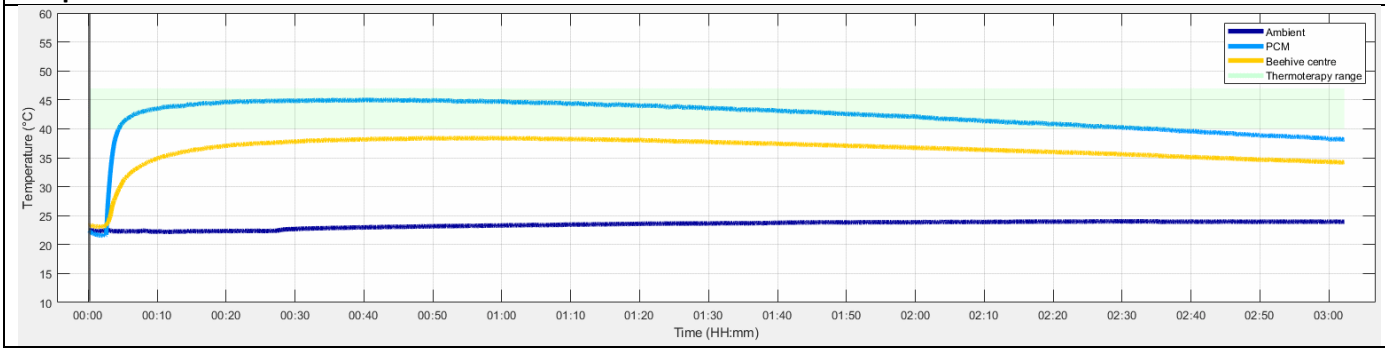
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	38.4	00:58:25
Maximum PCM temperature	45	00:40:05
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	23.4	--
Total test time	--	03:02:15

Graph



Comments

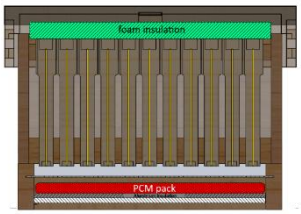
This test combined foam insulation on top and SHINES for the sides. The maximum temperature was closer to the PCM temperature and above 35°C most of time.

Test 8

Setup

- 2 kg PCM
- Foam insulation top
- 11 frames (wax foundation)
- Metal mesh floor
- Aluminium insulation on bottom

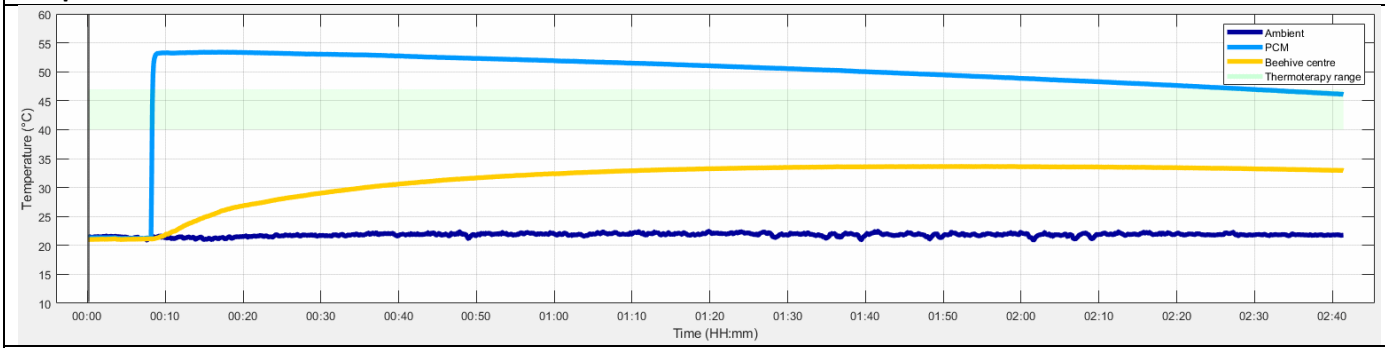
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	33.7	01:55:20
Maximum PCM temperature	53.4	00:17:05
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	21.8	--
Total test time	--	02:41:25

Graph



Comments

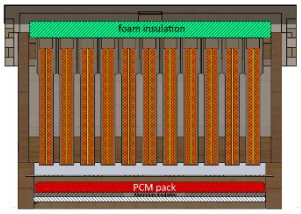
This test shows that the heat absorption of the internal components, reduce significantly the maximum temperature inside. A temperature of 35°C was never reached.

Test 9

Setup

- 2 kg PCM
- Foam insulation top
- 11 frames (wax combs)
- Metal mesh floor
- Aluminium insulation on bottom

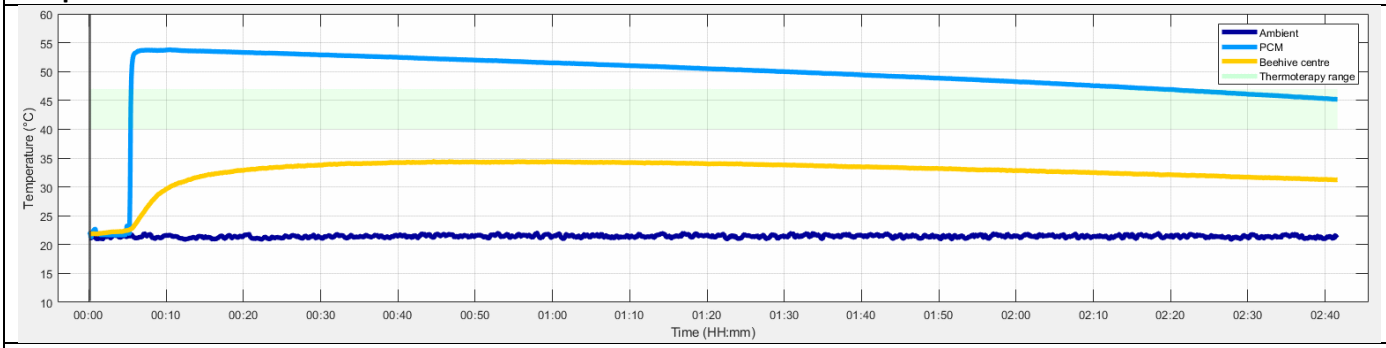
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	34.4	00:44:35
Maximum PCM temperature	53.8	00:10:30
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	21.4	--
Total test time	--	02:41:35

Graph



Comments

This experiment seems to indicate that the presence of wax does not negatively impact the temperature raise.

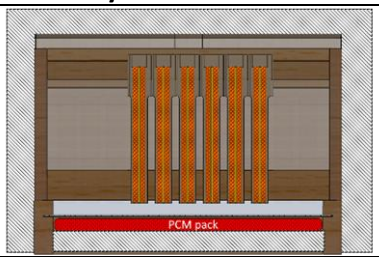
Laboratory experiments with PCMP produced packs (first production) with insulation box

Test 10

Setup

- 2 kg PCM
- Insulation box (50mm)
- 6 frames (wax combs)
- Metal mesh floor
- Insulation on bottom (50mm)

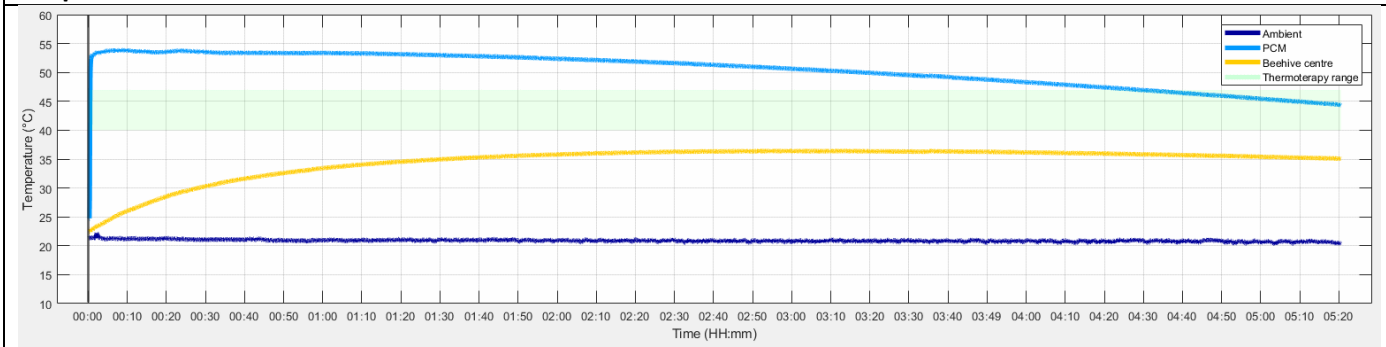
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	36.4	03:35:05
Maximum PCM temperature	53.9	00:09:35
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	20.9	--
Total test time	--	05:20:30

Graph



Comments

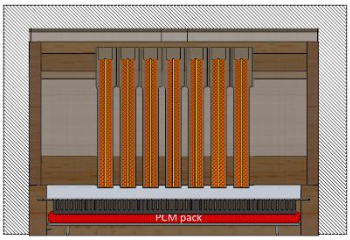
This new set of tests were carried with an insulation box to prevent losses from sides and top. The maximum temperature was close to 38°C.

Test 11

Setup

- 2 kg PCM
- Insulation box (50mm)
- 6 frames (wax combs)
- Metal mesh floor
- Metallic fins over pack
- Pack over metal grill

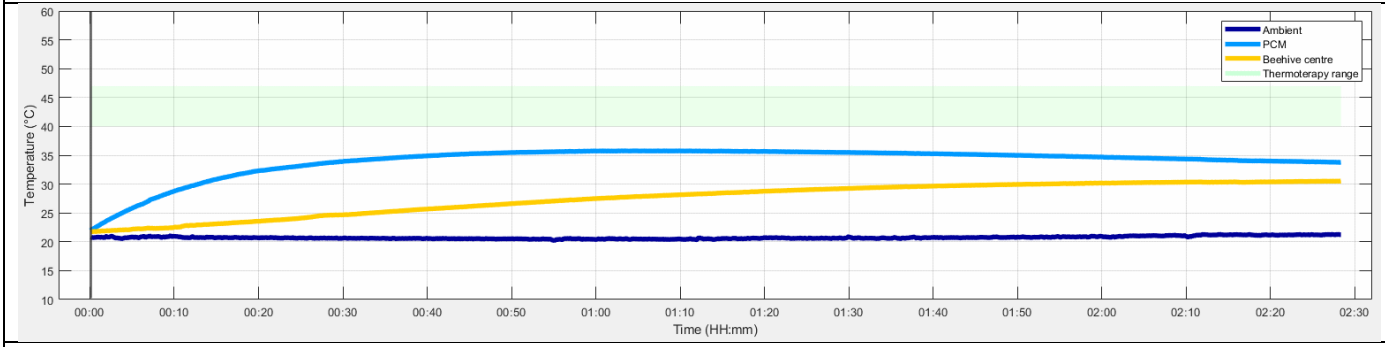
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	30.5	02:28:20
Maximum PCM temperature	35.8	01:09:30
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	20.7	--
Total test time	--	02:28:20

Graph



Comments

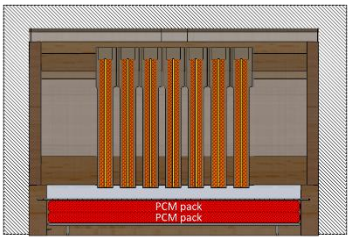
In this experiment, metallic dissipators were tested to see if they could increase the heat transfer. The results indicate that the fins dissipate the heat from the PCM not allowing it to overpass the dissipator.

Test 12

Setup

- 4 kg PCM
- Insulation box (50mm)
- 6 frames (wax combs)
- Metal mesh floor
- Packs over metal grill

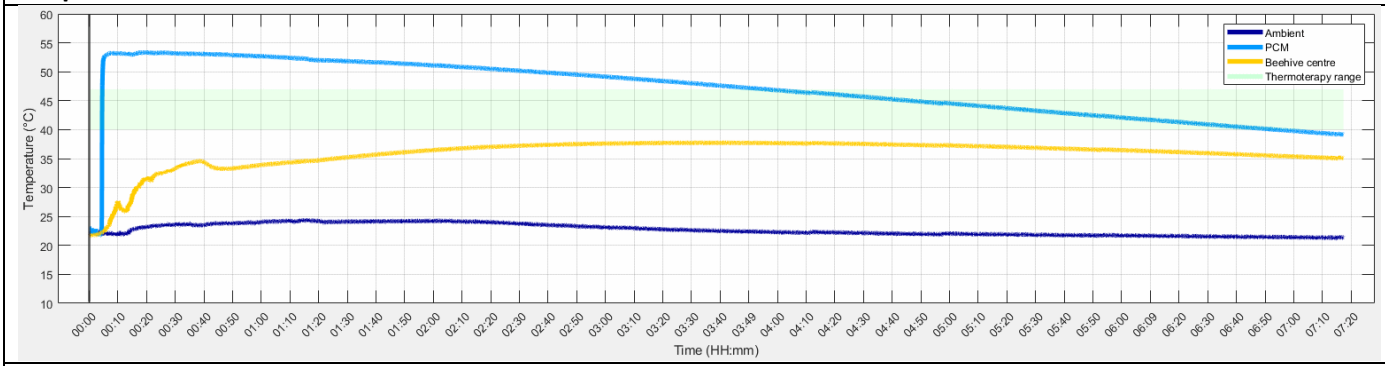
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	37.8	04:11:45
Maximum PCM temperature	53.3	00:19:10
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	22.7	--
Total test time	--	07:17:20

Graph



Comments

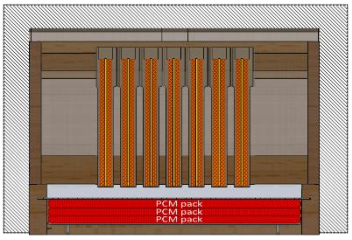
For this test a metal grill was used in order to facilitate convection. The temperature almost reached 40°C.

Test 13

Setup

- 6 kg PCM
- Insulation box (50mm)
- 6 frames (wax combs)
- Metal mesh floor
- Packs over metal grill

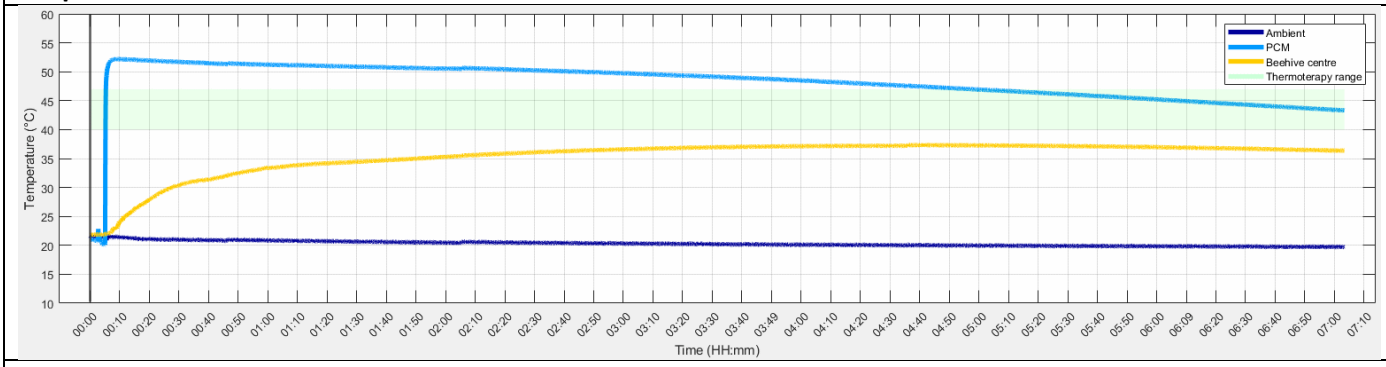
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	37.4	04:36:00
Maximum PCM temperature	52.2	00:08:55
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	20.3	--
Total test time	--	07:03:20

Graph



Comments

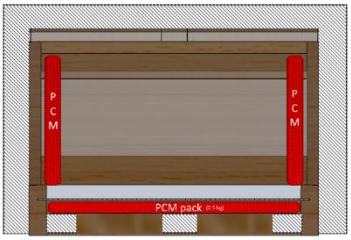
This test showed that even 6 kgs of PCM are not enough to reach 40°C at the centre.

Test 14

Setup

- 6.5 kg PCM
- Insulation box (50mm)
- 0 frames (empty box)
- Metal mesh floor
- 2 packs hanging on sides
- 1 pack over insulation pieces

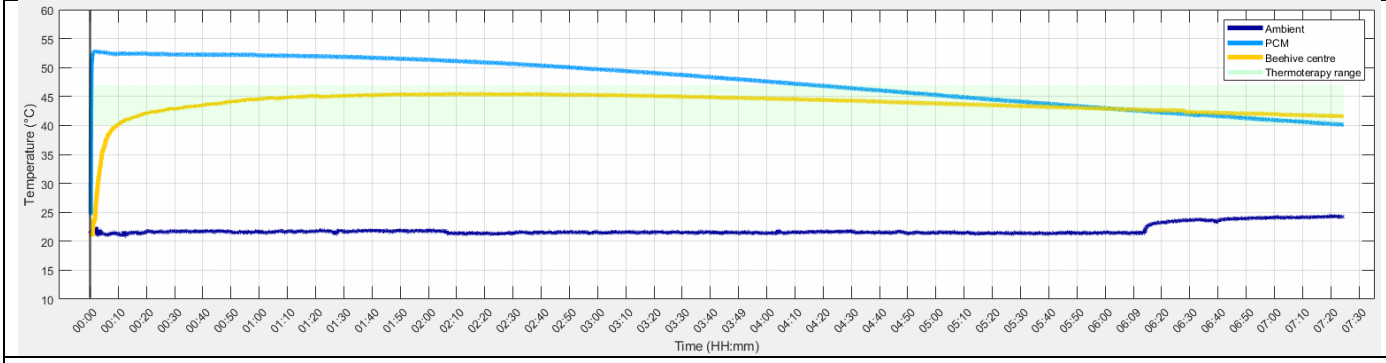
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	45.5	02:12:00
Maximum PCM temperature	52.9	00:01:55
Thermotherapy	Achieved	07:15:05
Average ambient temperature	21.9	--
Total test time	--	07:24:30

Graph



Comments

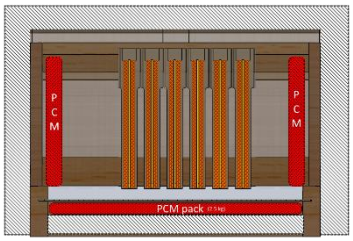
This experiment demonstrates that with 6 kg and a better distribution of the packs, a temperature of 45°C was reached and kept for several hours due to the insulation.

Test 15

Setup

- 6.5 kg PCM
- Insulation box (50mm)
- 6 frames (wax combs)
- Metal mesh floor
- 2 packs hanging on sides
- 1 pack over insulation board

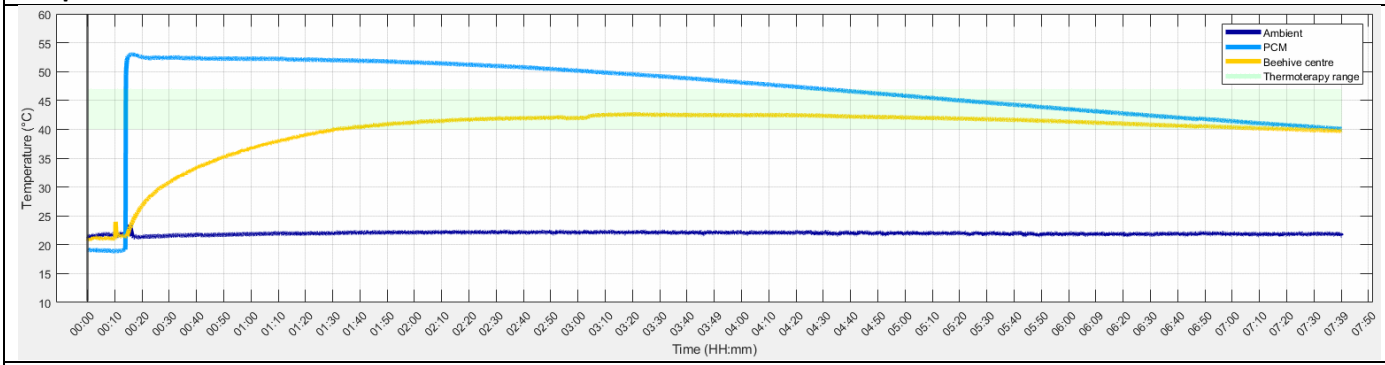
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	42.6	03:21:10
Maximum PCM temperature	53	00:16:35
Thermotherapy	Achieved	05:50:40
Average ambient temperature	22	--
Total test time	--	07:40:10

Graph



Comments

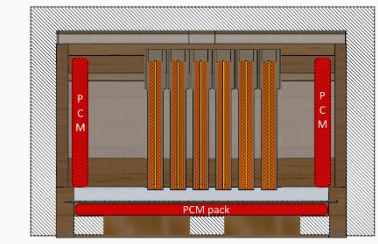
This is a similar experiment to the previous but this time integrating the wax frames. Once again it was reached a temperature above 40 °C.

Test 16

Setup

- 6 kg PCM
- Insulation box (50mm)
- 6 frames (wax combs)
- Metal mesh floor
- 2 packs hanging on sides
- 1 pack over insulation pieces

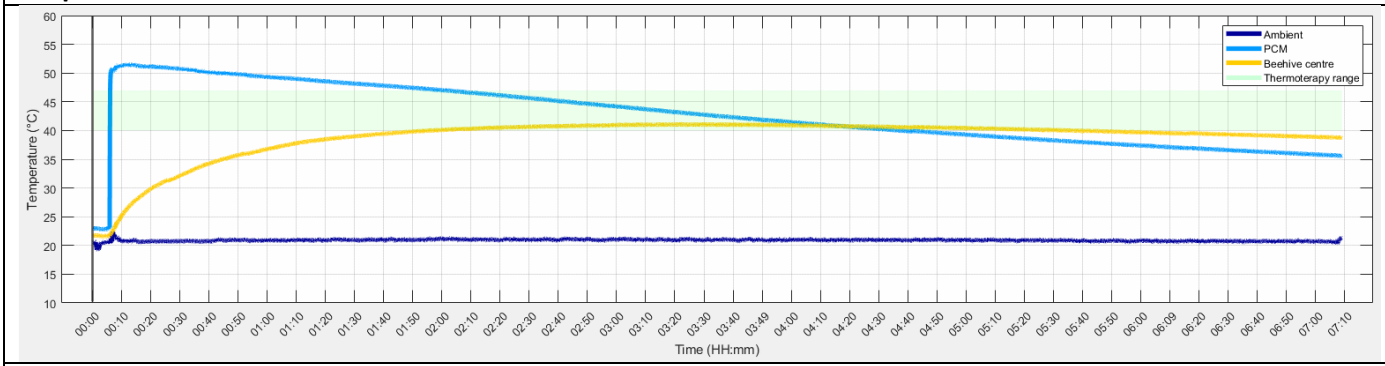
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.1	03:32:50
Maximum PCM temperature	51.5	00:13:20
Thermotherapy	Achieved	03:40:15
Average ambient temperature	20.9	--
Total test time	--	07:09:05

Graph



Comments

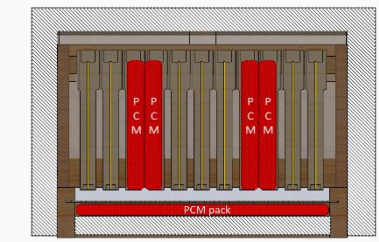
In this test, the flat board was compared with the non-flat. The results show that allowing convection is desirable.

Test 17

Setup

- 6 kg PCM
- Insulation box (50mm)
- 7 frames (wax foundation)
- Metal mesh floor
- 2 packs hanging
- 1 pack over insulation board

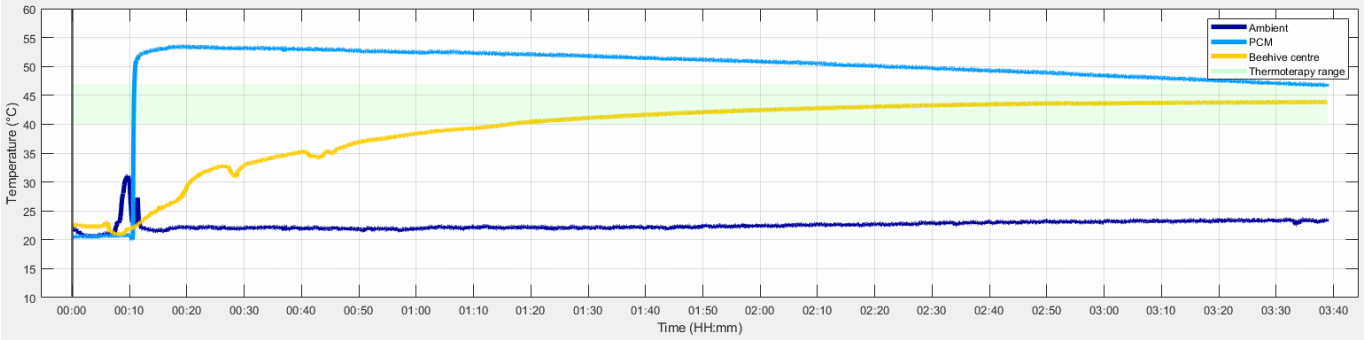
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	43.9	03:37:55
Maximum PCM temperature	53.4	00:18:30
Thermotherapy	Achieved	02:22:55
Average ambient temperature	22.5	--
Total test time	--	03:38:55

Graph



Comments

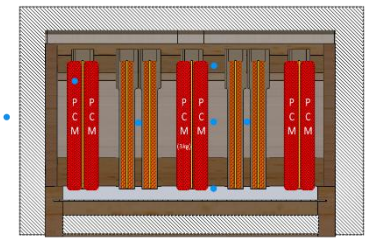
This test showed that locating the packs close to the centre increase the central temperature despite being in vertical position.

Test 18

Setup

- 6.5 kg PCM
- Insulation box (50mm)
- 4 frames (wax foundation)
- Metal mesh floor
- 3 packs hanging
- Insulation bottom

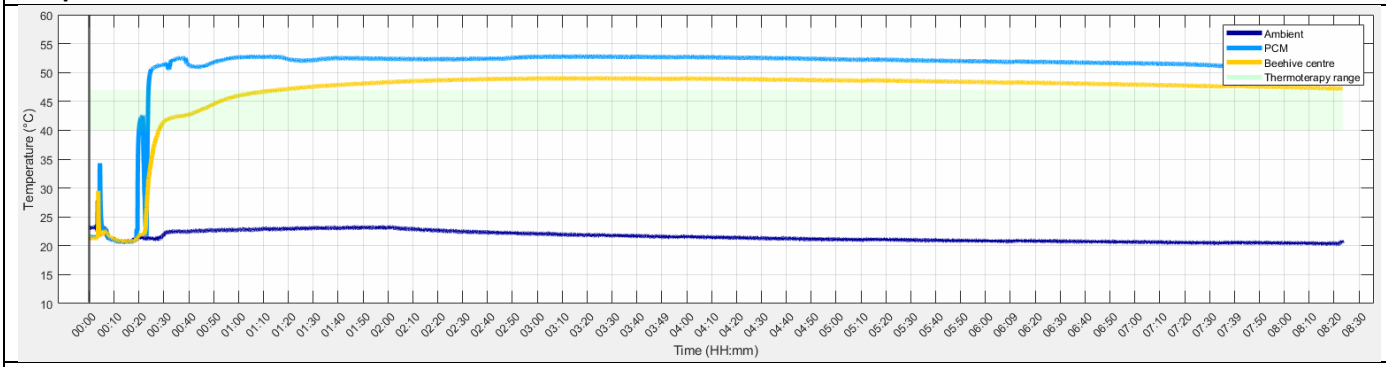
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	49	03:13:55
Maximum PCM temperature	52.8	03:11:20
Thermotherapy	Achieved	07:55:25
Average ambient temperature	21.6	--
Total test time	--	08:23:25

Graph

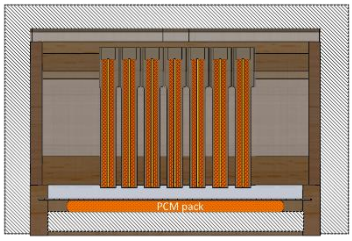


Comments

In this experiment 6 kg were used vertically, showing the maximum temperatures.

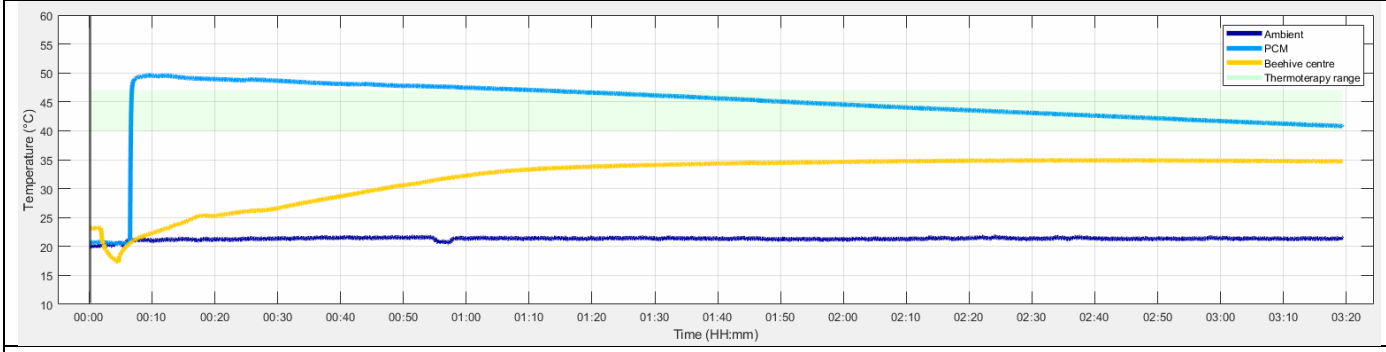
Laboratory experiments with commercial PCM packs

Test 19

Setup	Visual Key	Results
• 2 kg PCM • Insulation box (50mm) • 7 frames (wax combs) • Metal mesh floor Pack over insulation board		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	34.9	02:44:10
Maximum PCM temperature	49.6	00:12:20
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	21.3	--
Total test time	--	03:19:25

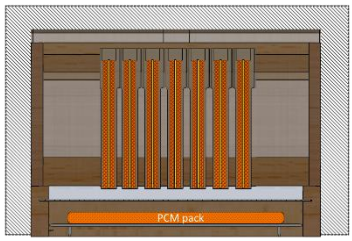
Graph



Comments

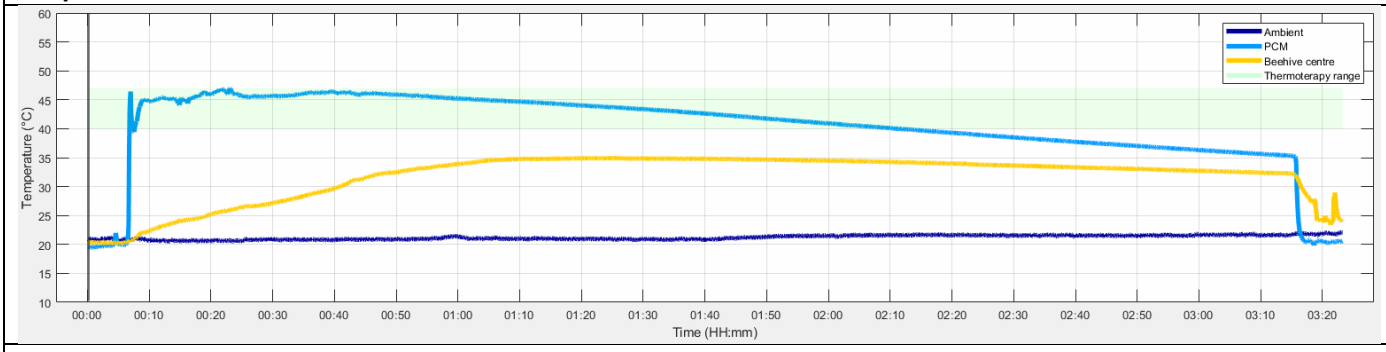
For this set of tests, commercial PCM pack were tested, to compare with the produced by the partner company. On this test, the results were very similar.

Test 20

Setup	Visual Key	Results
• 2 kg PCM • Insulation box (50mm) • 7 frames (wax combs) • Metal mesh floor • Pack over metal grill		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	34.9	01:23:10
Maximum PCM temperature	47	00:23:05
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	21.2	--
Total test time	--	03:23:15

Graph



Comments

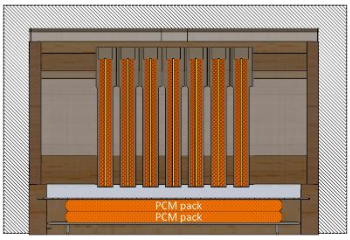
This test showed once again that the grill helps to have a better convection, therefore a better heat transfer.

Test 21

Setup

- 4 kg PCM
- Insulation box (50mm)
- 7 frames (wax combs)
- Metal mesh floor
- Pack over metal grill

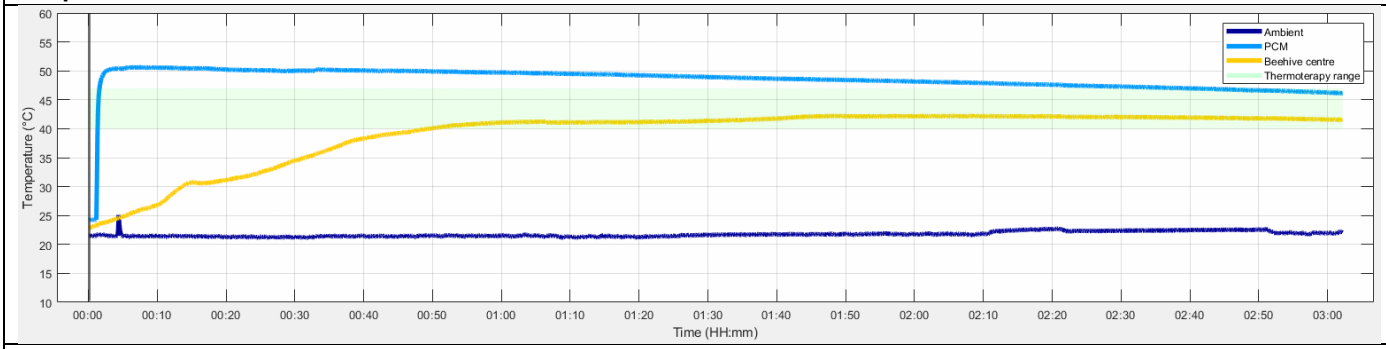
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	42.2	01:48:25
Maximum PCM temperature	50.6	00:07:40
Thermotherapy	Achieved	02:12:40
Average ambient temperature	21.8	--
Total test time	--	03:02:10

Graph



Comments

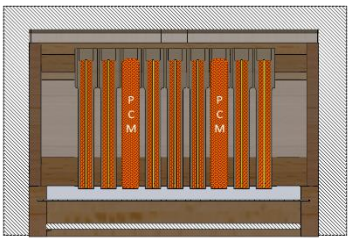
On this test, two packs raised the internal temperature up to 40 °C.

Test 22

Setup

- 4 kg PCM
- Insulation box (50mm)
- 7 frames (wax combs)
- Metal mesh floor
- 2 packs hanging

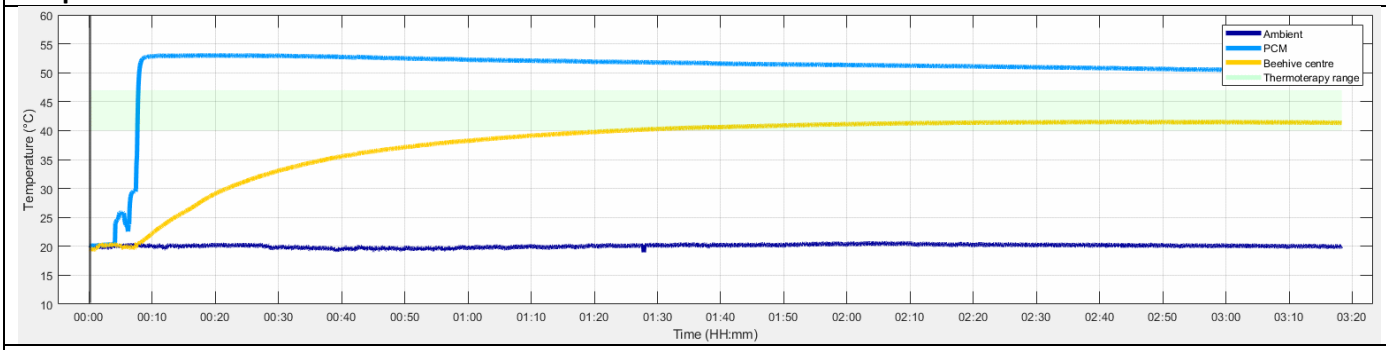
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.5	02:47:40
Maximum PCM temperature	53	00:19:40
Thermotherapy	Achieved	01:54:15
Average ambient temperature	20.1	--
Total test time	--	03:18:20

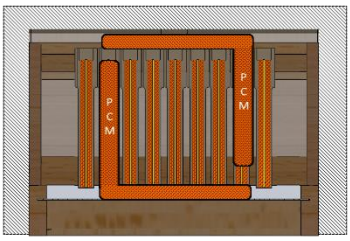
Graph



Comments

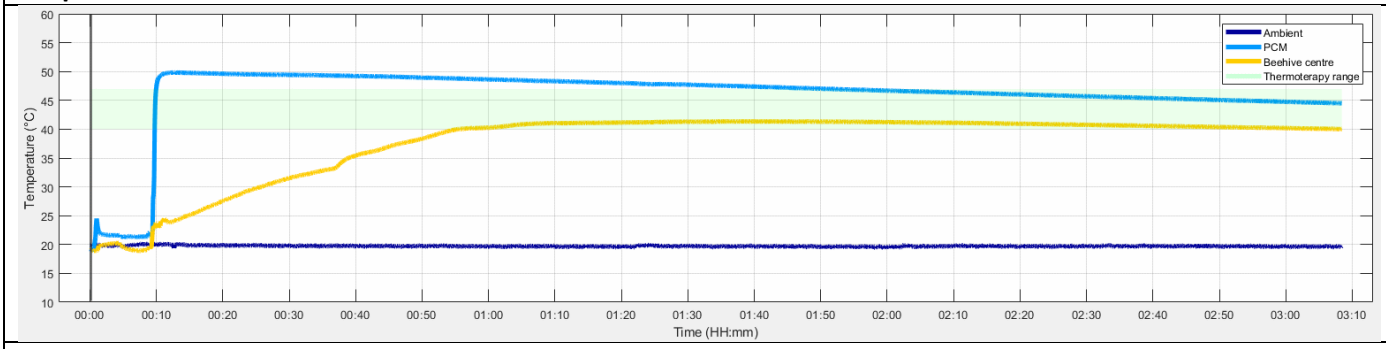
This experiment showed similar results to the previous one, demonstrating that the location can be compensated with better convection.

Test 23

Setup	Visual Key	Results
• 4 kg PCM • Insulation box (50mm) • 7 frames (wax combs) • Metal mesh floor • 2 packs forming a square		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.4	01:39:05
Maximum PCM temperature	49.8	00:12:55
Thermotherapy	Achieved	02:12:55
Average ambient temperature	19.7	--
Total test time	--	03:08:25

Graph

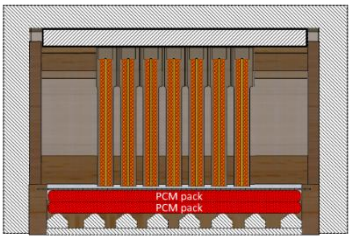


Comments

This test tried to cover more area. Despite the temperature reached was the highest with 2 kgs of PCM, this distribution was discarded for future tests as it was very laborious and with unrealistic application.

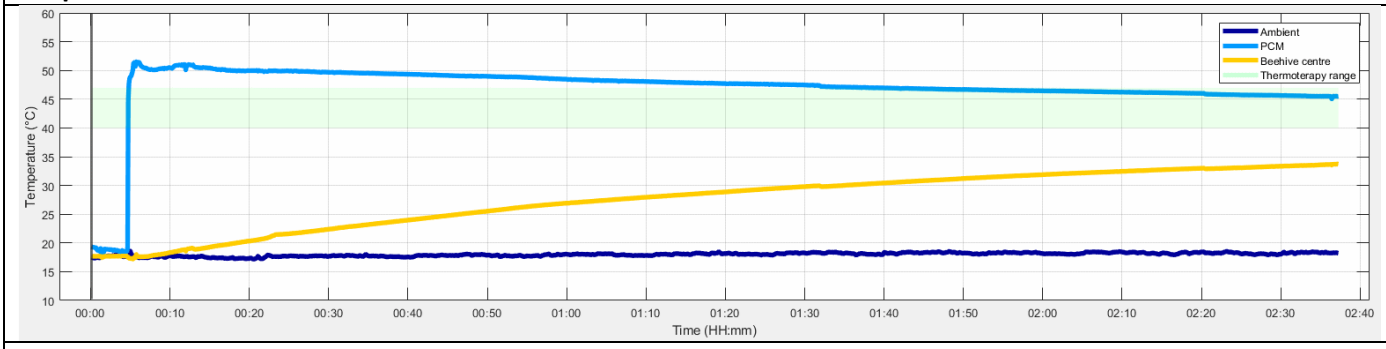
Laboratory experiments with PCMP produced packs (second production)

Test 24

Setup	Visual Key	Results
• 4 kg PCM • Insulation box (50mm) • 7 frames (wax combs) • Metal mesh floor • Pack over insulation fins		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	33.7	02:37:10
Maximum PCM temperature	51.5	00:05:50
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	18	--
Total test time	--	02:37:15

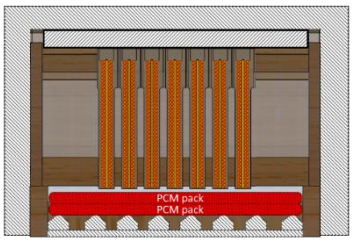
Graph



Comments

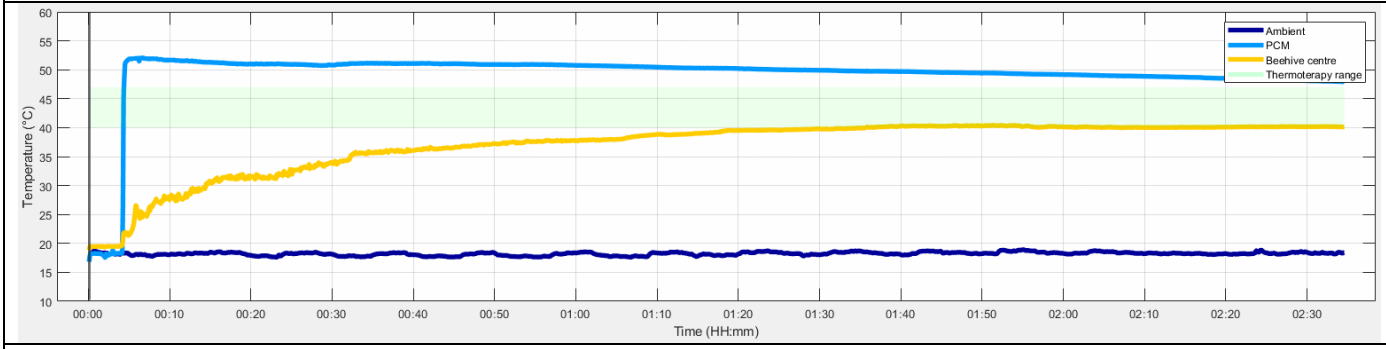
This experiment incorporates insulation fins on the bottom, combining the convection techniques with the insulation. The results show a slow rise of temperature, being the highest at the end with a trend of rise. The maximum temperature was 35 °C.

Test 25

Setup	Visual Key	Results
• 4 kg PCM • Insulation box (50mm) • 7 frames (wax combs) • No metal mesh floor • Pack over insulation fins		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	40.4	01:51:35
Maximum PCM temperature	52.1	00:06:40
Thermotherapy	Achieved	00:58:10
Average ambient temperature	18.2	--
Total test time	--	02:34:35

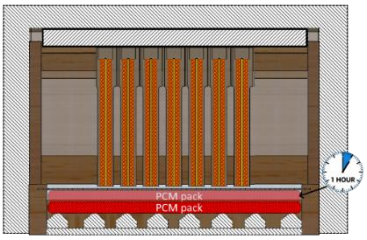
Graph



Comments

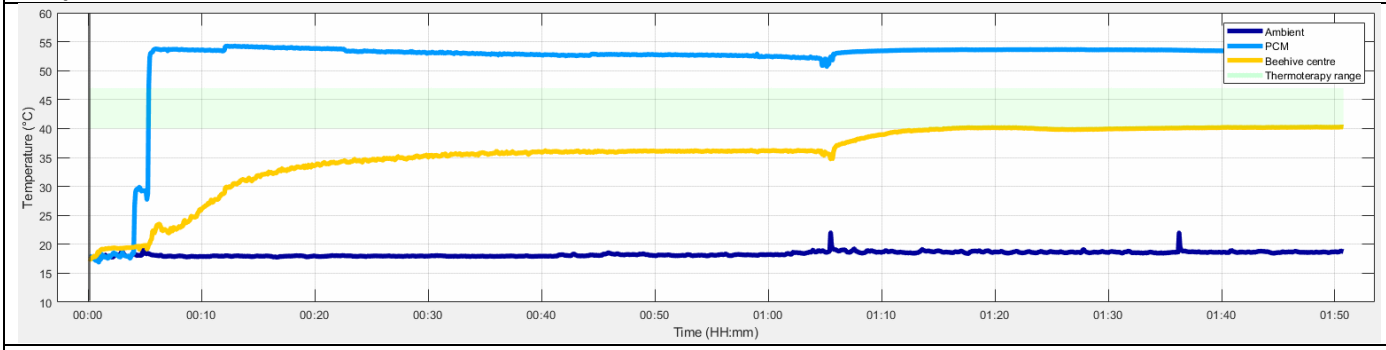
For this test, the metal mesh floor was removed from the beehive. In previous tests it was observed that the mesh floor dissipates heat impeding the central temperature to get high. The temperature surpassed 40 °C.

Test 26

Setup	Visual Key	Results
• 4 kg PCM • Insulation box (50mm) • 7 frames (wax combs) • No metal mesh floor • Pack over insulation fins		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	40.3	01:50:40
Maximum PCM temperature	54.3	00:12:20
Thermotherapy	Achieved	00:25:20
Average ambient temperature	18.3	--
Total test time	--	01:50:45

Graph



Comments

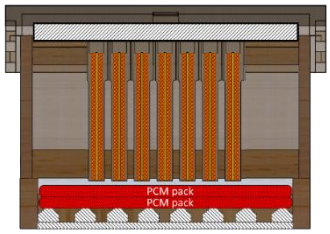
This experiment tested the addition of the second PCM pack after 1 hour, as it was observed that preheating the beehive eases a sudden rise of temperature.

Test 27

Setup

- 4 kg PCM
- Insulation top
- 7 frames (wax combs)
- No metal mesh floor
- Pack over insulation fins

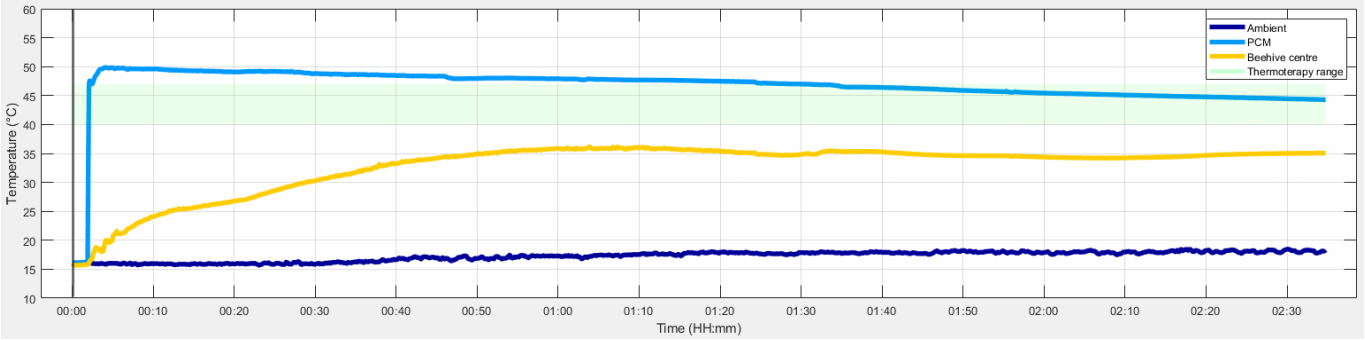
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	36.2	01:03:55
Maximum PCM temperature	49.9	00:04:05
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	17.3	--
Total test time	--	02:34:45

Graph



Comments

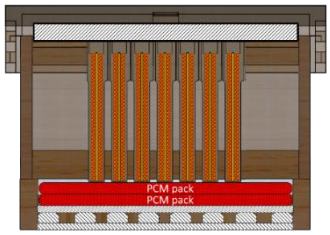
For this test the insulation box was removed to avoid dependence on it. The results proved that 35 °C were reached with 4 kg of PCM.

Test 28

Setup

- 4 kg PCM
- Insulation top
- 7 frames (wax combs)
- No metal mesh floor
- Pack over flat insulation

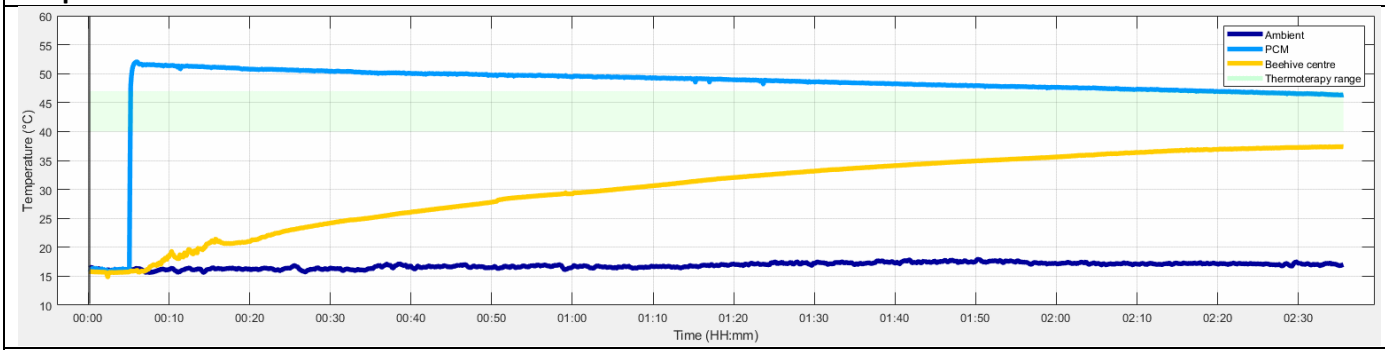
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	37.4	02:35:25
Maximum PCM temperature	52.1	00:06:00
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	16.8	--
Total test time	--	02:35:35

Graph



Comments

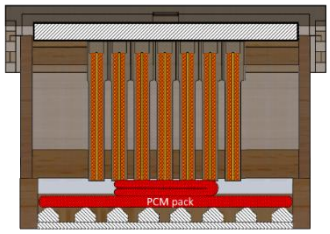
This test shows that a flat surface brings no better performance than the fins.

Test 29

Setup

- 4 kg PCM
- Insulation top
- 7 frames (wax combs)
- No metal mesh floor
- Pack over insulation fins

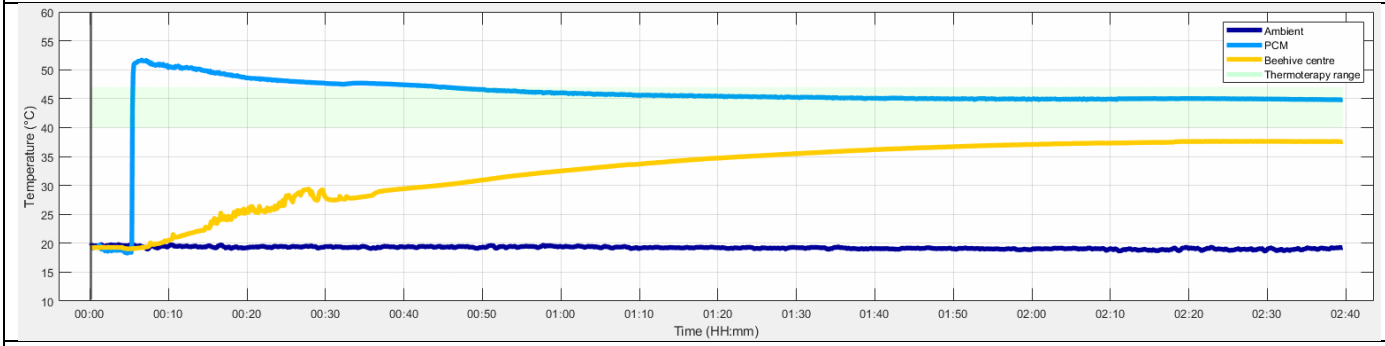
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	37.6	02:31:10
Maximum PCM temperature	51.7	00:06:35
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	19.2	--
Total test time	--	02:39:35

Graph



Comments

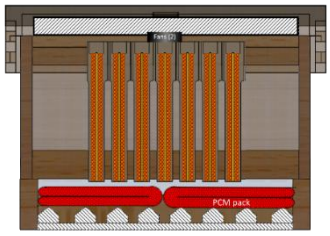
A better PCM distribution was seek on this test, concentrating most of the mass in the centre, which is the most relevant part of the beehive.

Test 30

Setup

- 4 kg PCM
- Insulation top
- 2 mini fans
- 7 frames (wax combs)
- No metal mesh floor
- Pack over insulation fins

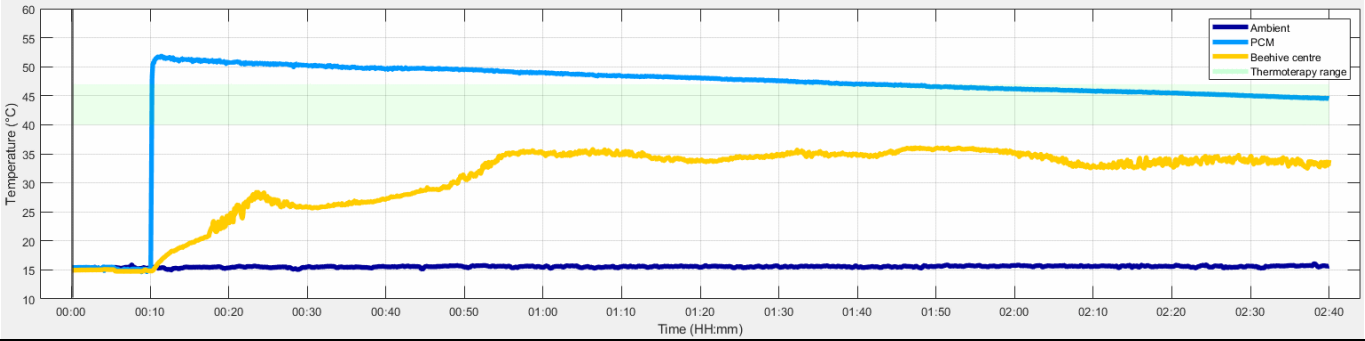
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	36.1	01:51:25
Maximum PCM temperature	51.8	00:11:25
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	15.6	--
Total test time	--	02:40:00

Graph



Comments

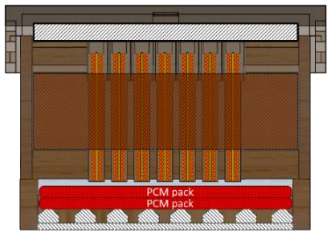
This test tried the use of mini fans to help the internal circulation of heat. The results were not very different that those without using the fans.

Test 31

Setup

- 4 kg PCM
- Insulation top
- 2 SHINS on sides
- 7 frames (wax combs)
- No metal mesh floor
- Pack over insulation fins

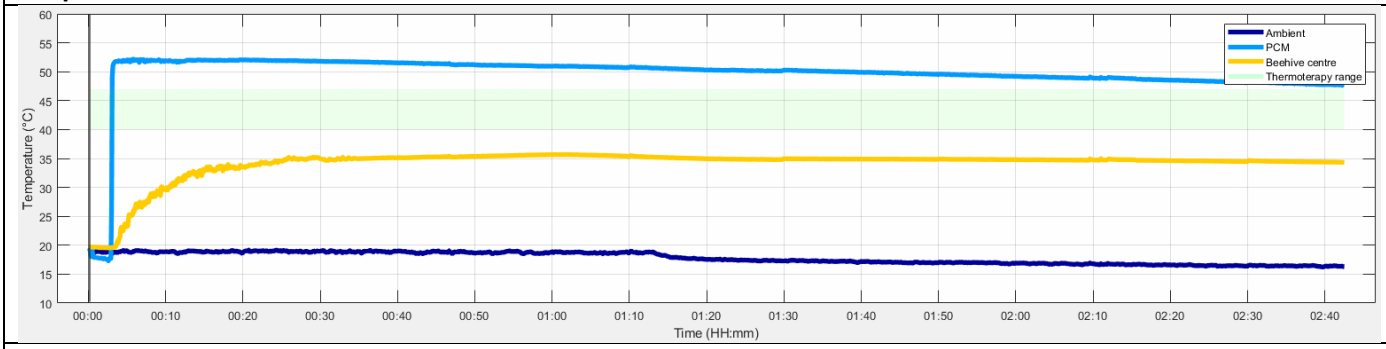
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35.7	01:01:55
Maximum PCM temperature	52.2	00:05:45
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	17.8	--
Total test time	--	02:42:30

Graph



Comments

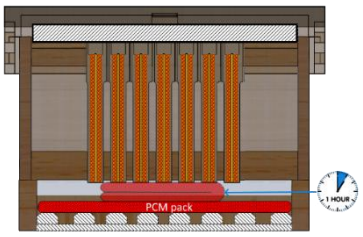
This experiment tried to reduce the losses thought the use of SHINS on two of the external walls. The internal temperature was above 35 °C but below 40 °C.

Test 32

Setup

- 4 kg PCM
- Insulation top
- 7 frames (wax combs)
- No metal mesh floor
- Pack over insulation fins

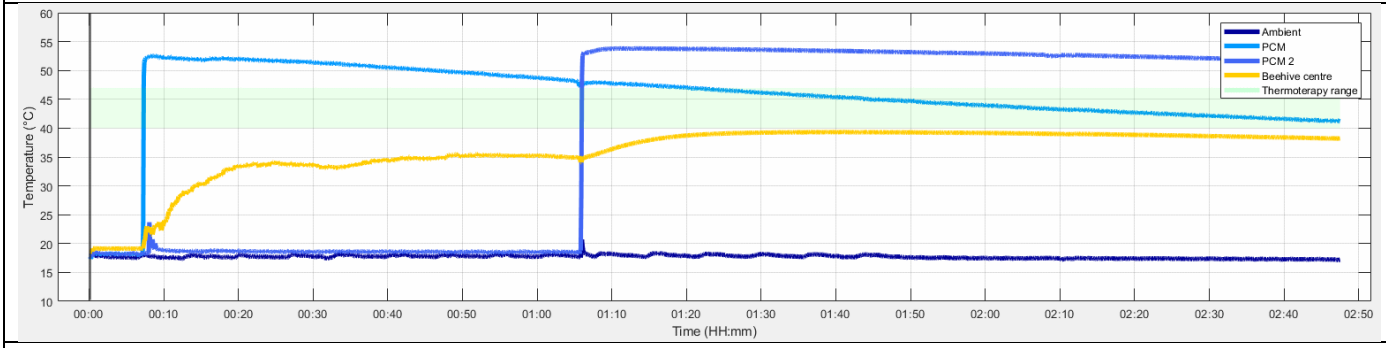
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	39.3	01:38:45
Maximum PCM temperature	52.5	00:08:35
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	17.7	--
Total test time	--	02:47:30

Graph



Comments

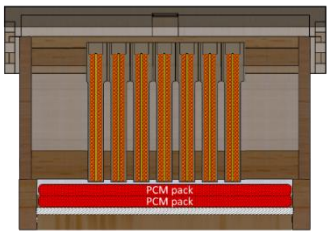
This was a second test of a stepped triggering of the packs, combined with the central concentration of one of the packs. The internal temperature was close to 40 °C.

Test 33

Setup

- 4 kg PCM
- 7 frames (wax combs)
- No metal mesh floor
- Pack over flat insulation

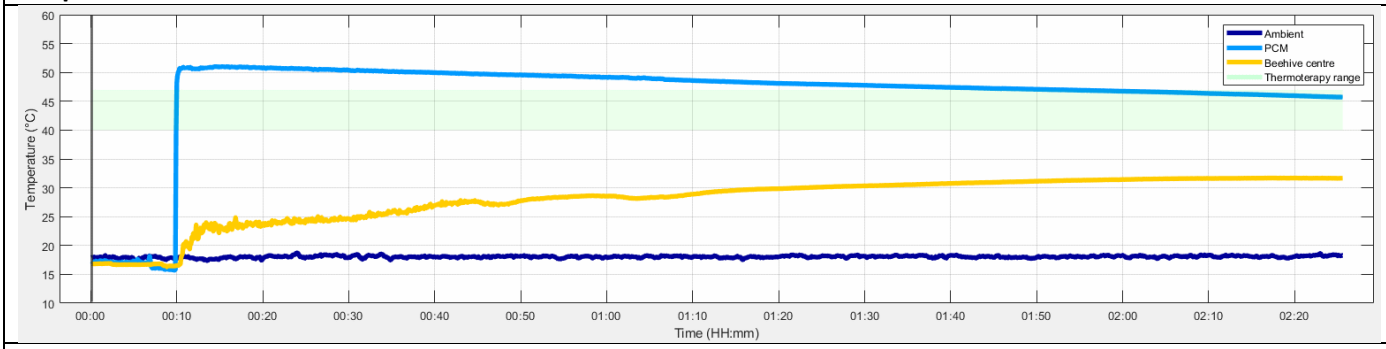
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	31.7	02:17:25
Maximum PCM temperature	51	00:14:45
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	18.1	--
Total test time	--	02:25:35

Graph



Comments

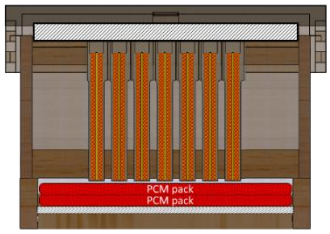
This was a test to measure the heat capabilities of the new PCM packs.

Test 34

Setup

- 4 kg PCM
- Insulation top
- 7 frames (wax combs)
- No metal mesh floor
- Pack over flat insulation

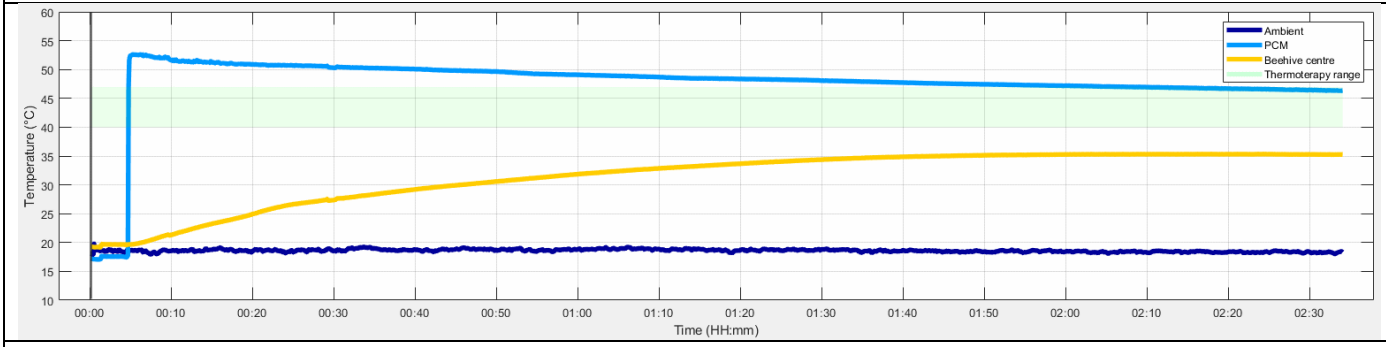
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35.3	02:24:20
Maximum PCM temperature	52.6	00:05:20
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	18.6	--
Total test time	--	02:34:05

Graph



Comments

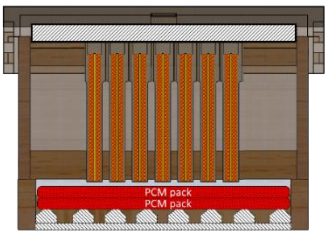
This test demonstrates once more the effectiveness of insulation at the top of the beehive.

Test 35

Setup

- 4 kg PCM
- Insulation top
- 7 frames (wax combs)
- No metal mesh floor
- Pack over insulation fins

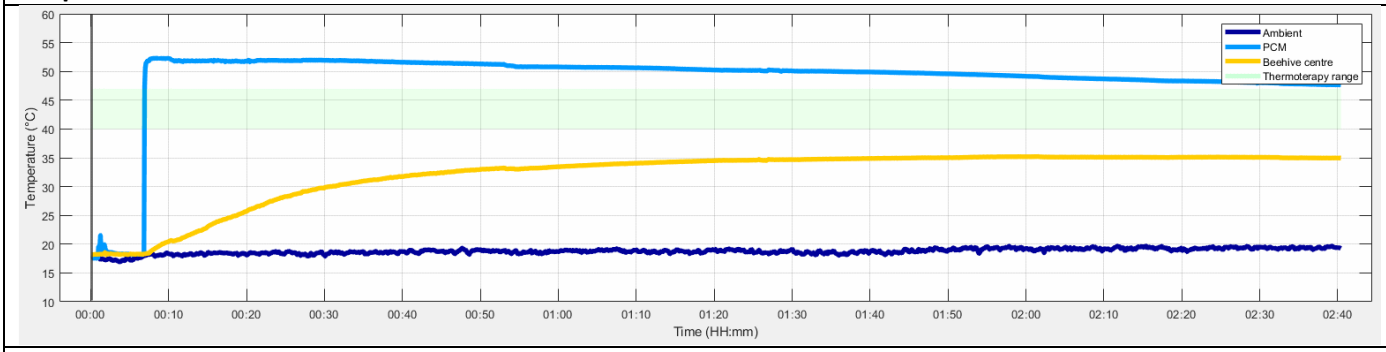
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35.2	02:01:30
Maximum PCM temperature	52.3	00:09:45
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	18.8	--
Total test time	--	02:40:25

Graph



Comments

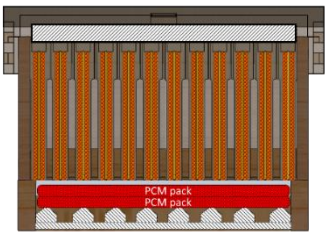
This test is a repetition of a previous experiment.

Test 36

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs)
- No metal mesh floor
- Pack over insulation fins

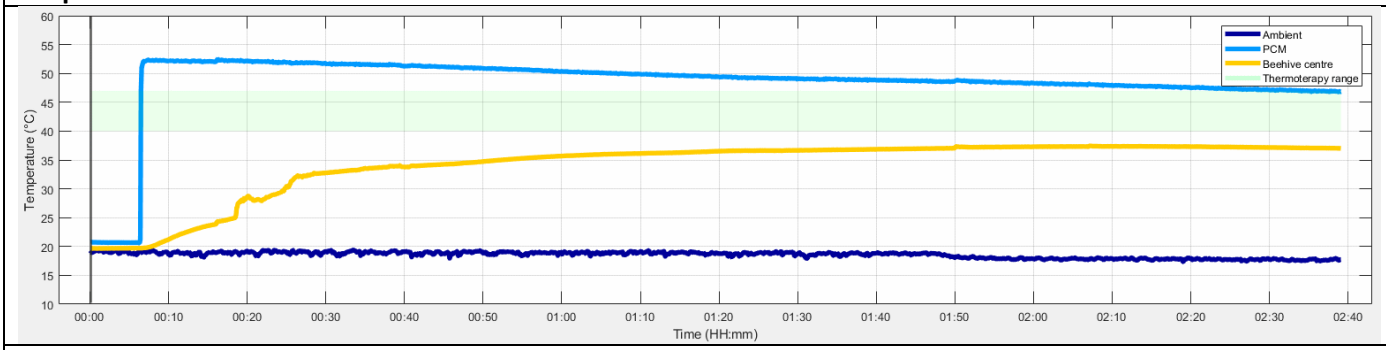
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	37.4	02:07:05
Maximum PCM temperature	52.4	00:16:20
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	18.5	--
Total test time	--	02:39:05

Graph



Comments

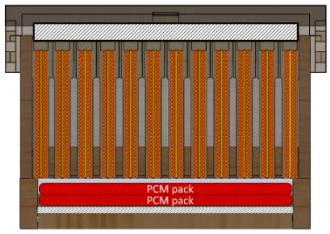
This test adds more frames, to replicate conditions closer to reality. The results showed once again that the presence of more wax does not affect the rise of temperature. Apparently, the wax prevents losses on the sides.

Test 37

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs)
- No metal mesh floor
- Pack over flat insulation

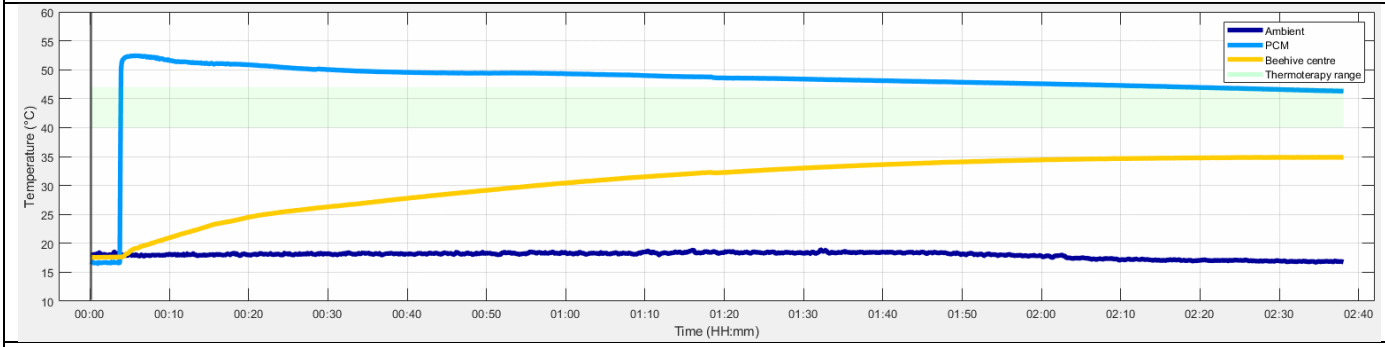
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	34.9	02:34:50
Maximum PCM temperature	52.5	00:05:30
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	18	--
Total test time	--	02:38:05

Graph



Comments

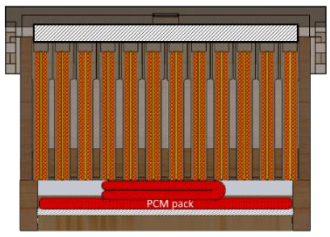
This test was to compare the flat bottom with the bottom with fins. Again, the fins resulted a better choice.

Test 38

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs)
- No metal mesh floor
- Pack over flat insulation

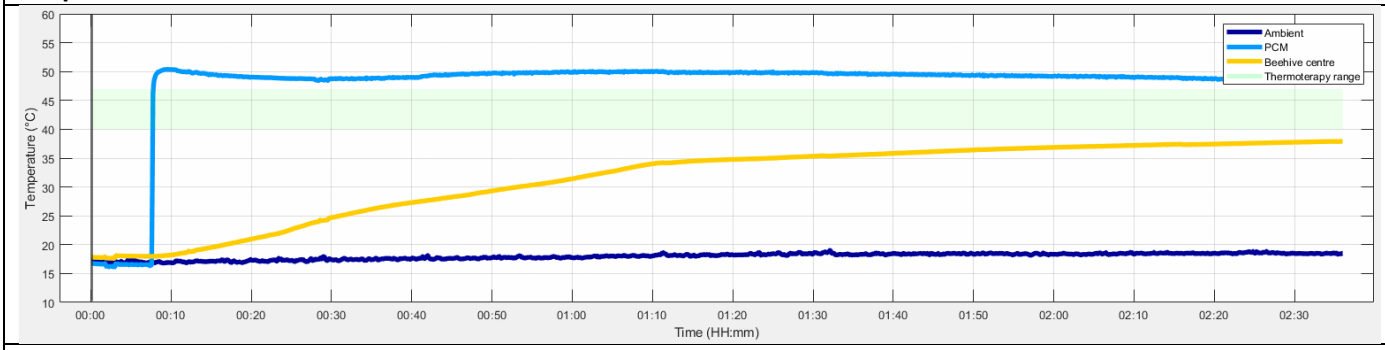
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	37.9	02:35:40
Maximum PCM temperature	50.4	00:09:35
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	18	--
Total test time	--	02:36:00

Graph



Comments

This test proves that a centralization of the packs helps to have a higher temperature at the centre.

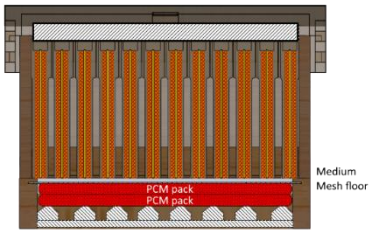
Laboratory experiments with EH Torne produced prototype floor, insulation crown board and plastic mesh floor

Test 39

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs)
- Plastic mesh floor
- Packs over ribbed insulation

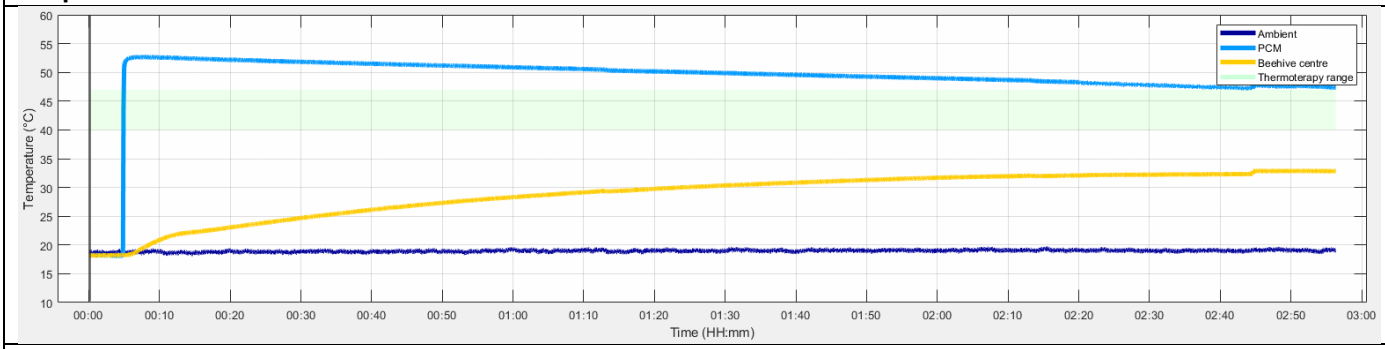
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	32.9	02:50:30
Maximum PCM temperature	52.7	00:08:05
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	19	--
Total test time	--	02:56:20

Graph



Comments

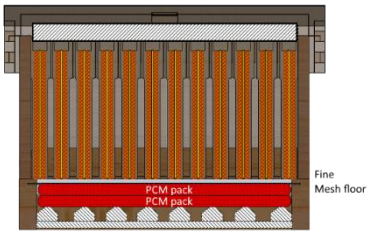
In this experiment, the packs were tested on a ribbed floor and a plastic mesh floor was placed between the PCM packs and the beehive. Meshes were shown to hinder heat flow.

Test 40

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs)
- Plastic mesh floor
- Packs over ribbed insulation

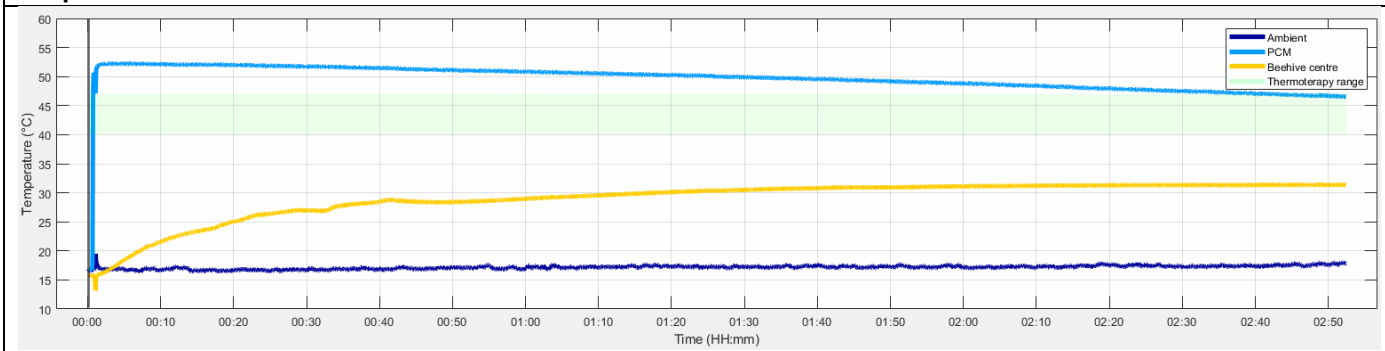
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	31.4	02:52:15
Maximum PCM temperature	52.3	00:07:45
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	17.2	--
Total test time	--	02:52:25

Graph



Comments

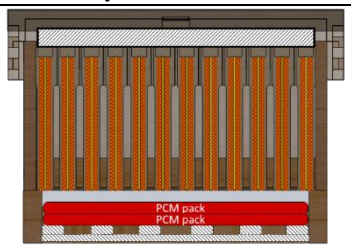
This test was almost the same as the previous one, this time with a finer mesh. The results agree with those of the previous test, showing that any barrier between the PCM and the beehive interrupts the flow of heat.

Test 41

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs)
- No mesh floor
- Packs over ribbed insulation

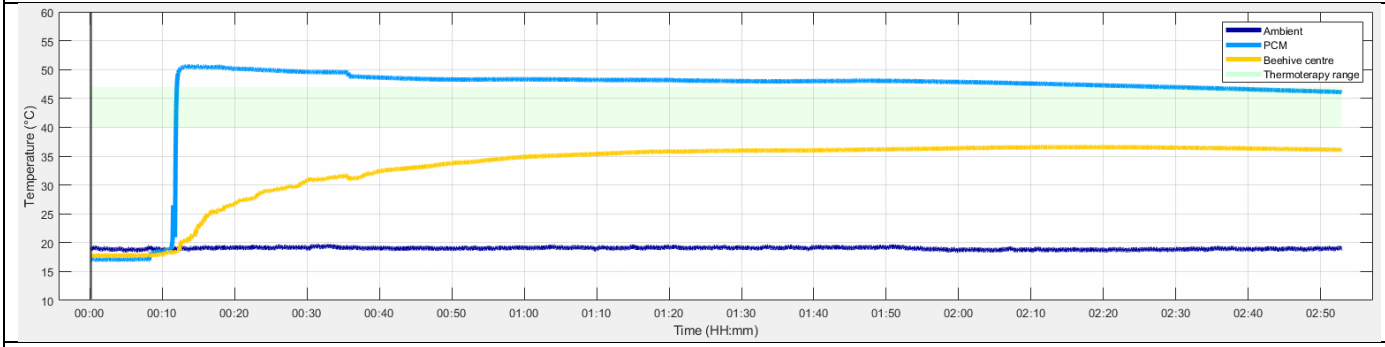
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	36.6	02:17:00
Maximum PCM temperature	50.6	00:13:20
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	19	--
Total test time	--	02:52:55

Graph



Comments

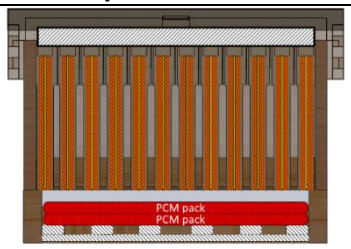
This test confirms that removing the plastic (or metal) meshes achieves a higher temperature inside the beehive.

Test 42

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs)
- No mesh floor
- Packs over ribbed insulation

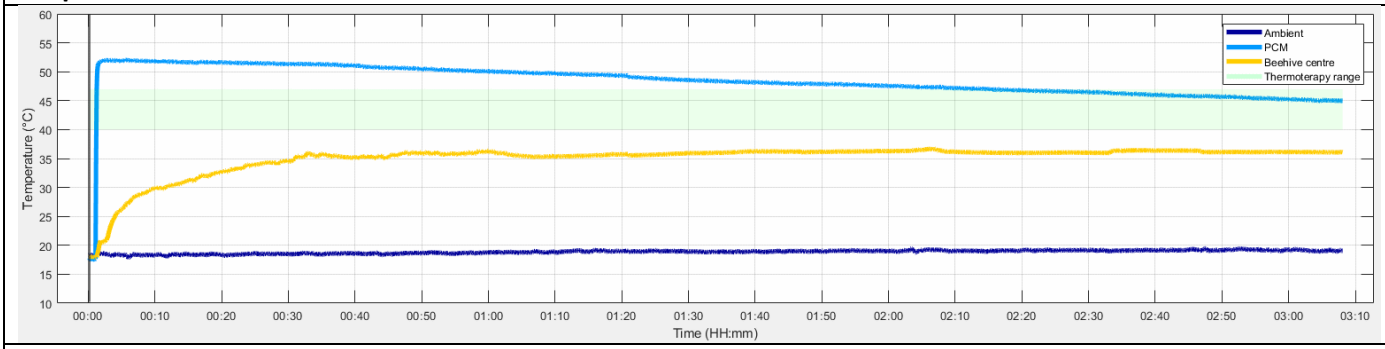
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	36.7	02:07:05
Maximum PCM temperature	52.1	00:05:35
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	18.9	--
Total test time	--	03:08:05

Graph



Comments

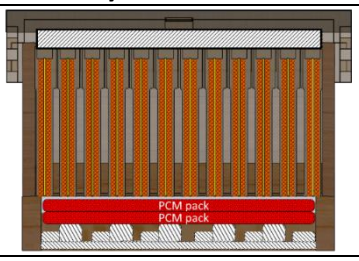
This test is similar to the previous one, both confirm that good performance is obtained with insulation on top and with a ribbed floor.

Test 43

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs)
- No mesh floor
- Packs over ribbed insulation

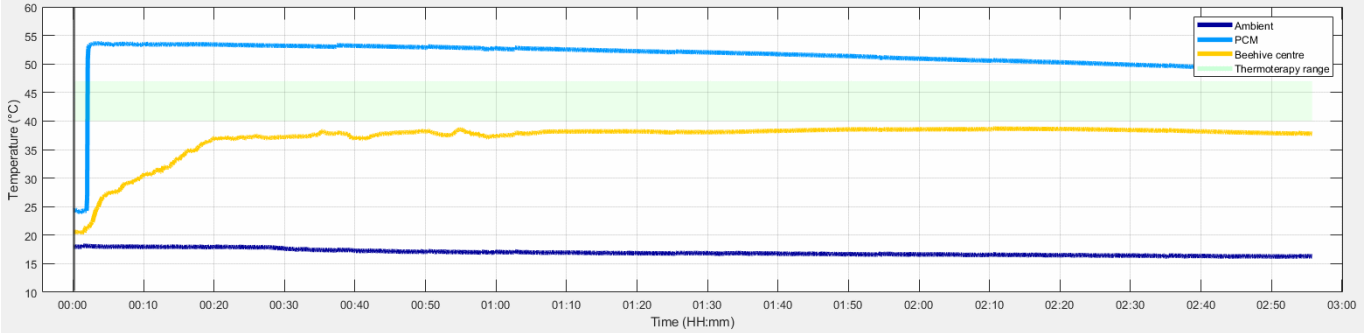
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	38.7	02:10:40
Maximum PCM temperature	53.7	00:04:10
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	17	--
Total test time	--	02:55:45

Graph



Comments

In this experiment it was tested with ribs a little higher on the floor. Thus, a higher temperature was obtained.

Test 44

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs)
- No mesh floor
- Packs over ribbed insulation

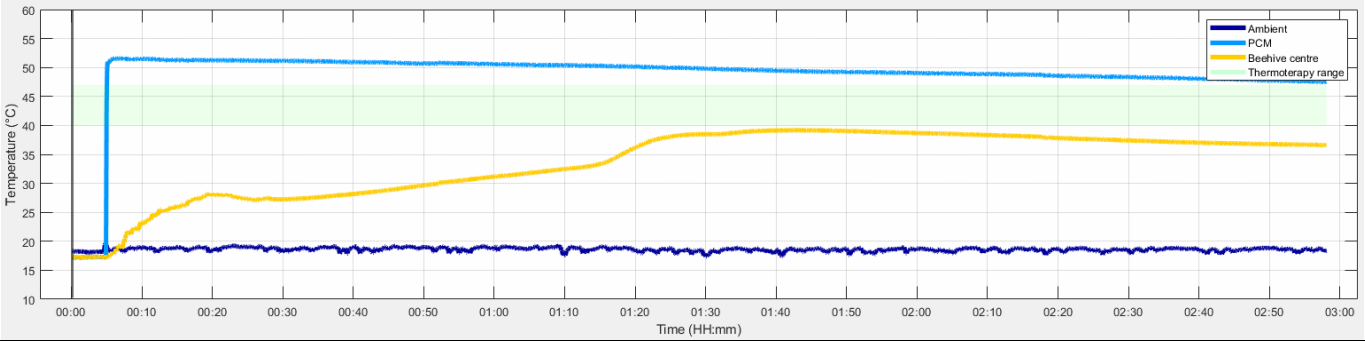
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	39.2	01:43:35
Maximum PCM temperature	51.6	00:07:30
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	18.6	--
Total test time	--	02:58:05

Graph

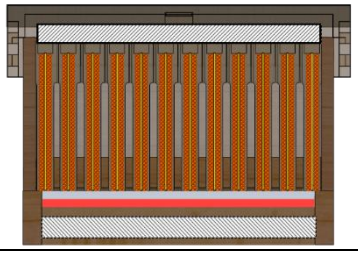


Comments

This test is the same as the previous one but with a slight configuration regarding the ribs of the floor. Again, it is shown that the desired temperature is almost reached.

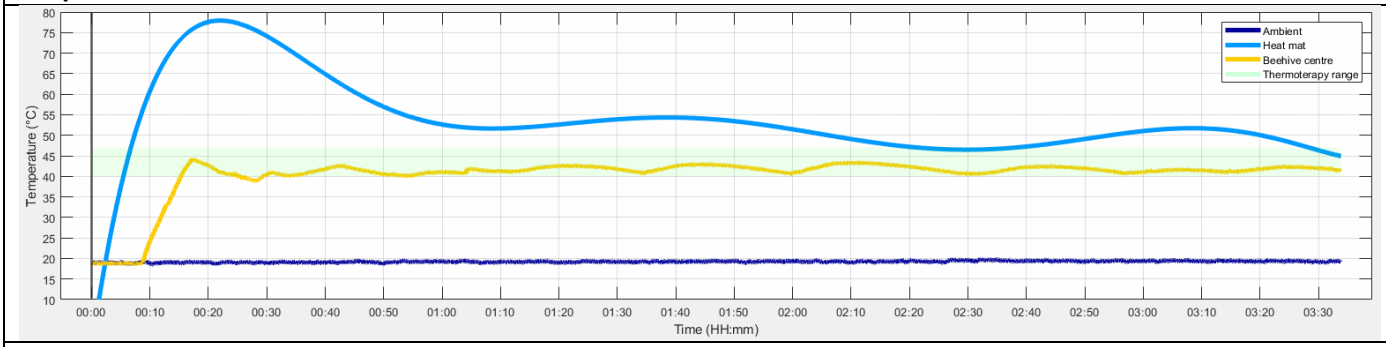
Laboratory experiments with electric heater mats

Test 45

Setup	Visual Key	Results
• Heater mat • Insulation top • 12 frames (wax combs) • No mesh floor		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	44.2	00:17:10
Thermotherapy	Achieved	03:14:20
Average ambient temperature	19.2	--
Total test time	--	03:33:50

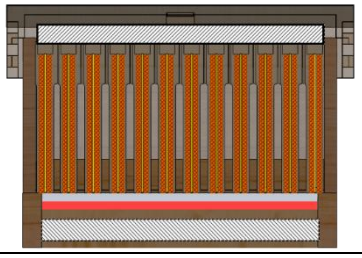
Graph



Comments

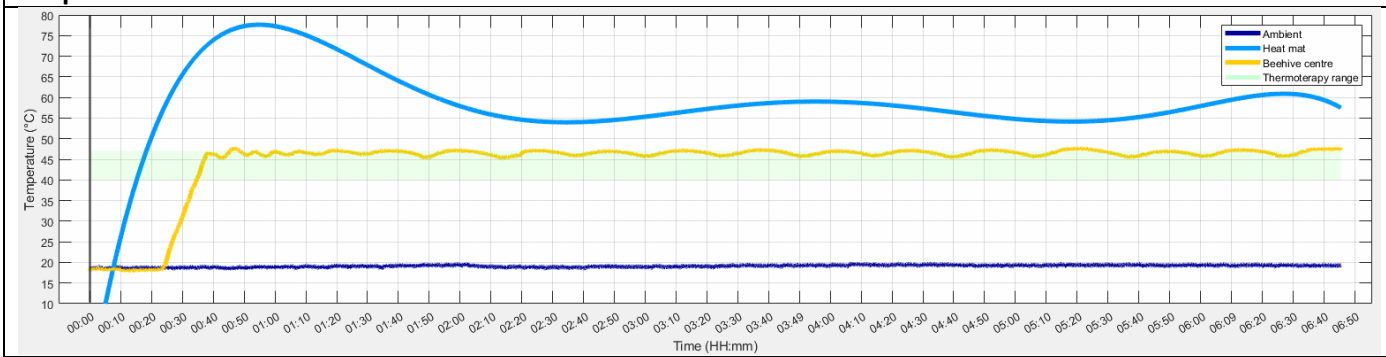
In this series of tests, the use of PCM was replaced by a heat mat as a heat source. The mat was regulated by a thermostat, whose sensor was in the centre of the beehive. The intention was to find the temperature ranges in which the heat source must operate to achieve thermotherapy. This test shows that to stay within this range, the source temperature must be between 60 and 45°C.

Test 46

Setup	Visual Key	Results
• Heater mat • Insulation top • 12 frames (wax combs) • No mesh floor		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	47.8	00:46:35
Thermotherapy	Achieved	06:11:00
Average ambient temperature	19.1	--
Total test time	--	06:45:30

Graph



Comments

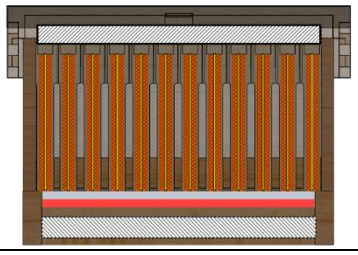
This test is similar to the previous one, only that on this occasion it was sought to reach the maximum limit of thermotherapy in the centre of the beehive, which is 47°C. To achieve such a temperature, the source had to be between 60 and 55°C.

Test 47

Setup

- Heater mat
- Insulation top
- 12 frames (wax combs)
- No mesh floor

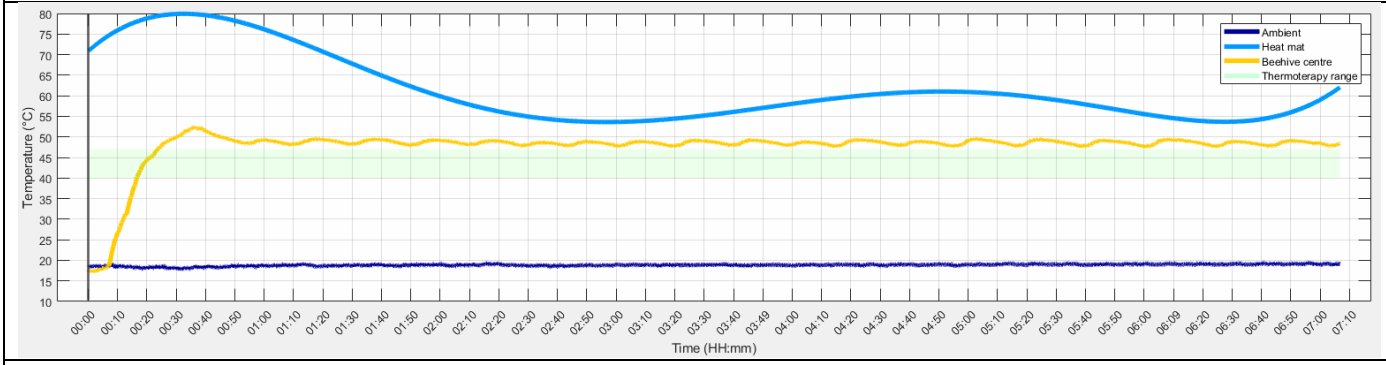
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	52.4	00:36:05
Thermotherapy	Achieved	06:50:10
Average ambient temperature	18.8	--
Total test time	--	07:06:45

Graph



Comments

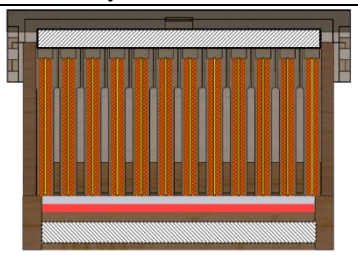
This test sought to find the range of temperatures required in the heat source to barely exceed the upper limit of thermotherapy. This range was 55 to 62°C. In a real scenario, this temperature would be equivalent to the death of the bees inside the beehive.

Test 48

Setup

- Heater mat
- Insulation top
- 12 frames (wax combs)
- No mesh floor

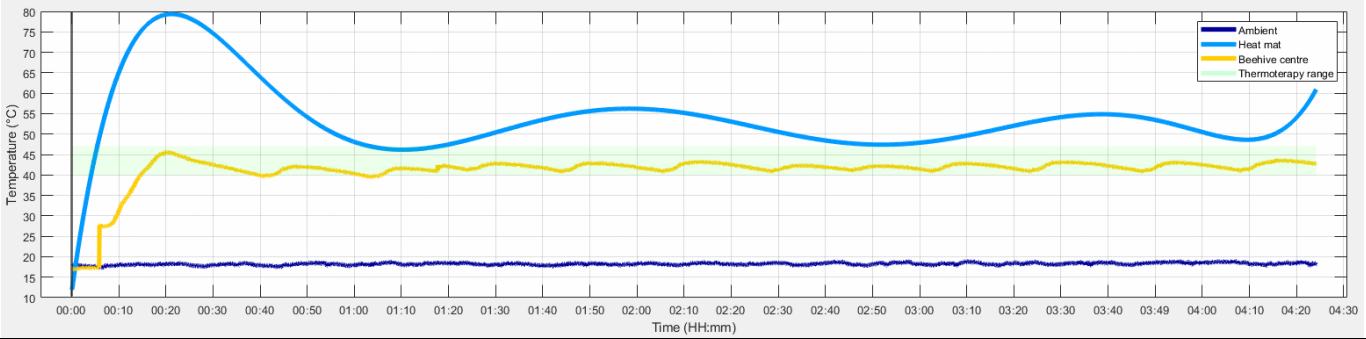
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	45.6	00:20:00
Thermotherapy	Achieved	04:02:10
Average ambient temperature	18.2	--
Total test time	--	04:24:10

Graph



Comments

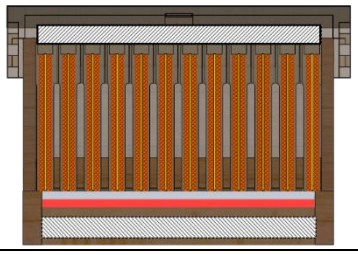
In this experiment, the temperature range for the source was sought to achieve the minimum lower limit for thermotherapy. The range found was 45 to 55°C.

Test 49

Setup

- Heater mat
- Insulation top
- 12 frames (wax combs)
- No mesh floor

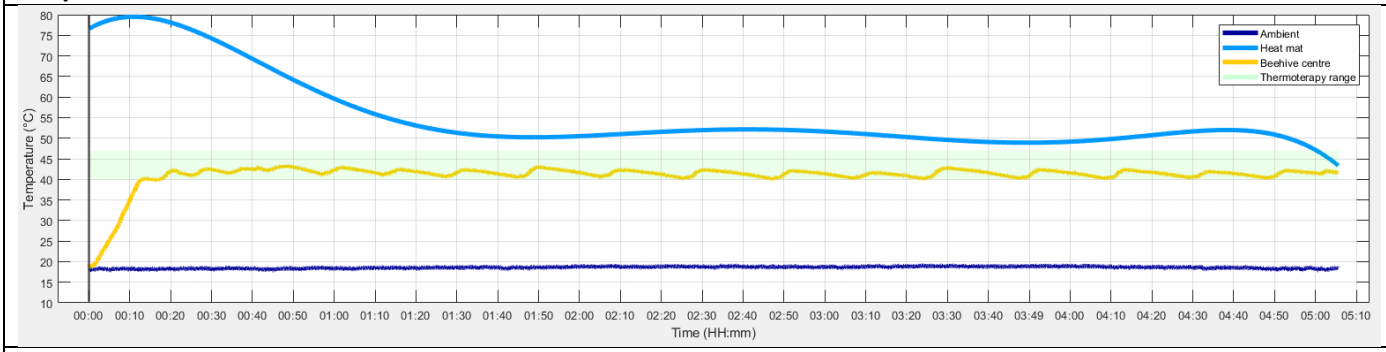
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	43.3	00:47:25
Thermotherapy	Achieved	04:50:20
Average ambient temperature	18.6	--
Total test time	--	05:05:35

Graph



Comments

This latest test shows that with a stable temperature between 50 and 55°C, a thermotherapy temperature can be maintained for many hours.

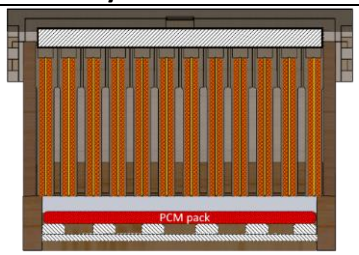
Laboratory experiments with EH Torne produced observation beehive

Test 50

Setup

- 2 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

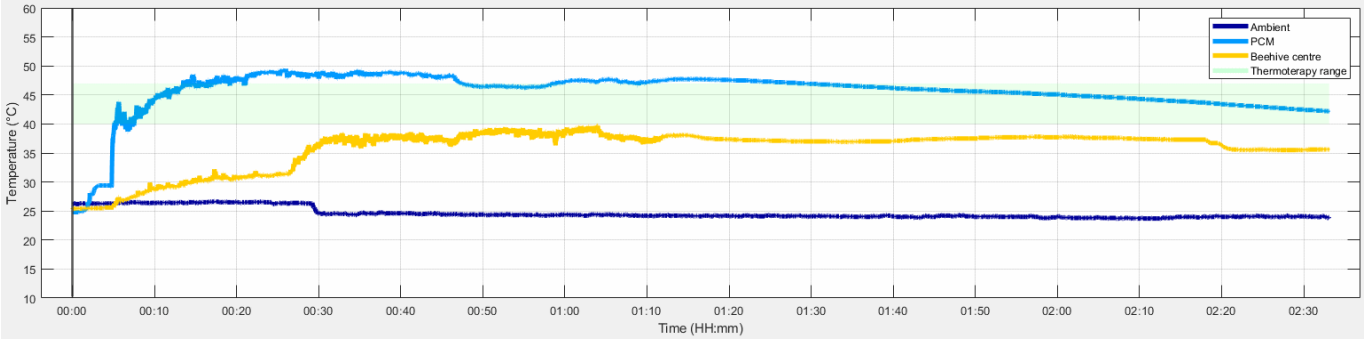
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	39.7	01:04:00
Maximum PCM temperature	49.5	00:26:00
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	24.6	--
Total test time	--	02:33:05

Graph



Comments

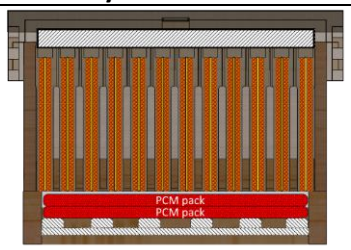
In this series of tests, the observation beehive was used, which has a ribbed floor. PCM packages with the refined formulation were also tested. This experiment showed that 2kg of PCM are not enough to reach the desired temperature.

Test 51

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

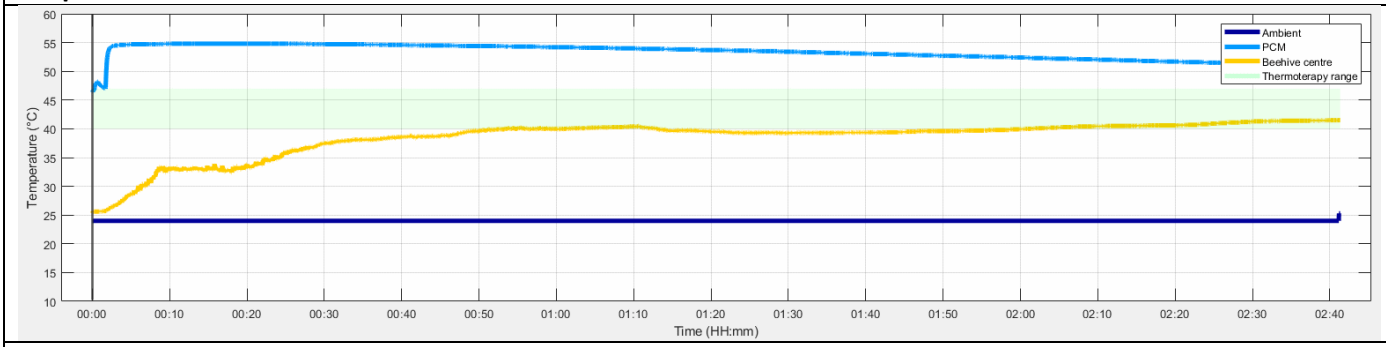
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.5	02:41:20
Maximum PCM temperature	54.9	00:13:11
Thermotherapy	Achieved	00:59:52
Average ambient temperature	24	--
Total test time	--	02:41:20

Graph



Comments

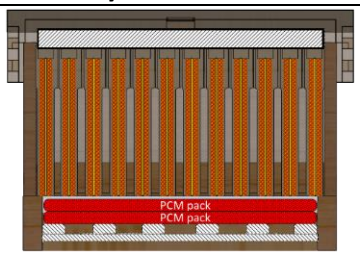
This test reached the thermotherapy temperature in the centre of the beehive using 2 packets of 2kg of PCM.

Test 52

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

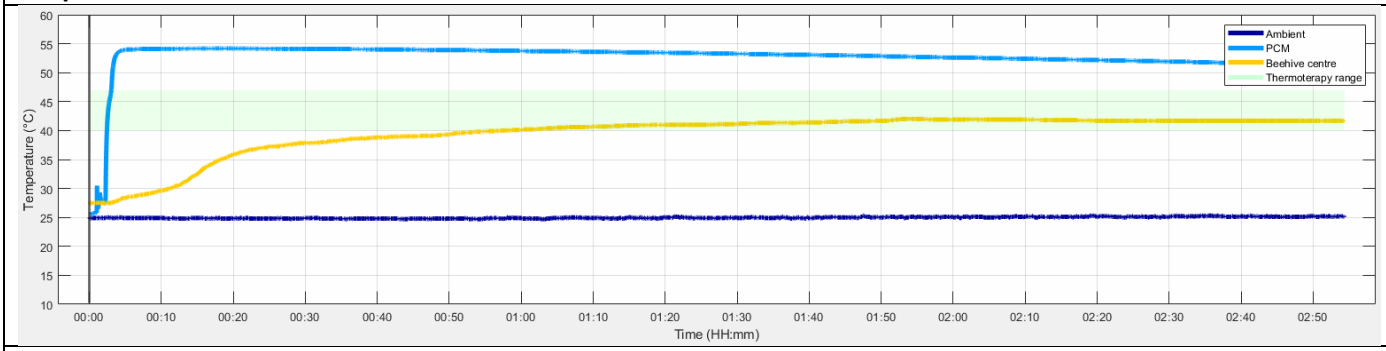
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	42.1	01:54:47
Maximum PCM temperature	54.2	00:31:32
Thermotherapy	Achieved	01:57:22
Average ambient temperature	25	--
Total test time	--	02:54:19

Graph



Comments

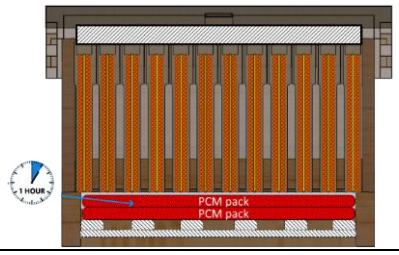
This experiment was very similar to the previous one. In this case, it was possible to reach the desired temperature for a longer period of time.

Test 53

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

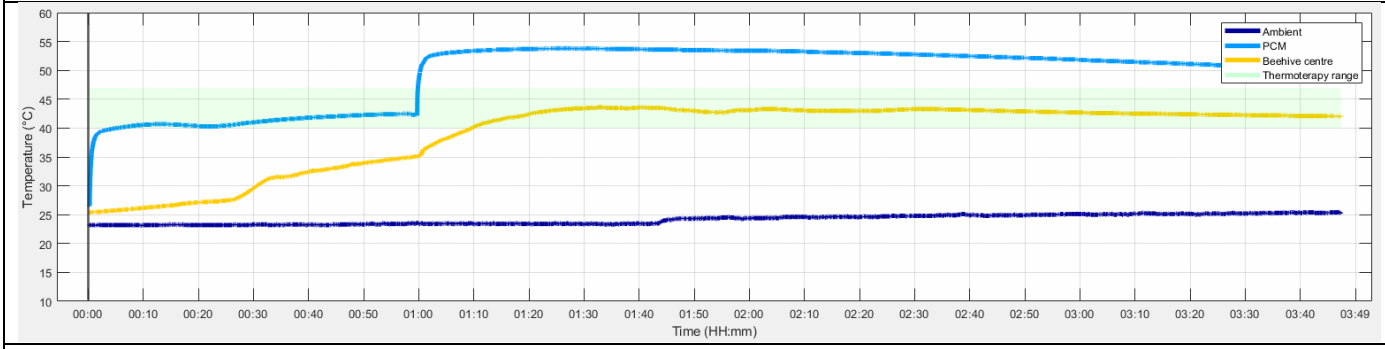
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	43.6	01:43:50
Maximum PCM temperature	53.8	01:35:33
Thermotherapy	Achieved	02:37:33
Average ambient temperature	24.2	--
Total test time	--	03:47:21

Graph



Comments

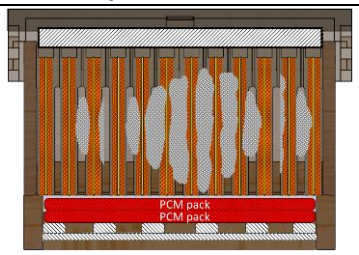
In this test, the activation by parts of the PCM was experimented with. In the first stage, the centre of the beehive and the secondary PCM are preheated, so that in the second activation, the second PCM has a better performance and the thermotherapy temperature is reached.

Test 54

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

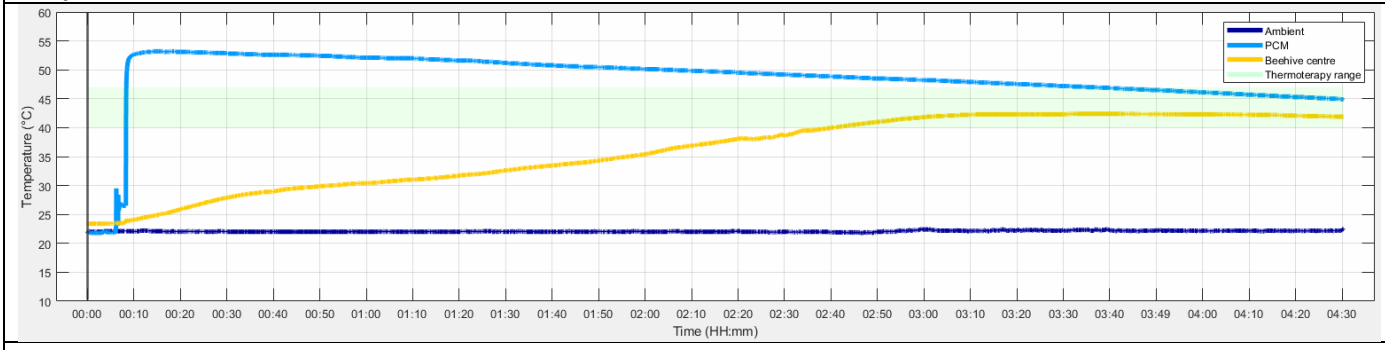
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	42.5	03:35:52
Maximum PCM temperature	53.2	00:19:04
Thermotherapy	Achieved	01:50:08
Average ambient temperature	22.1	--
Total test time	--	04:30:16

Graph



Comments

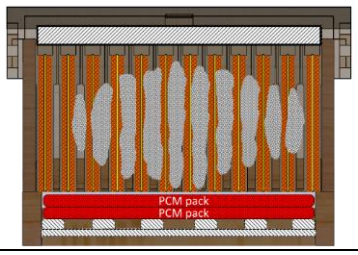
Although this test is similar to the previous ones in terms of its setup, it differs in that padding was placed inside the beehive to simulate the presence of bees.

Test 55

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

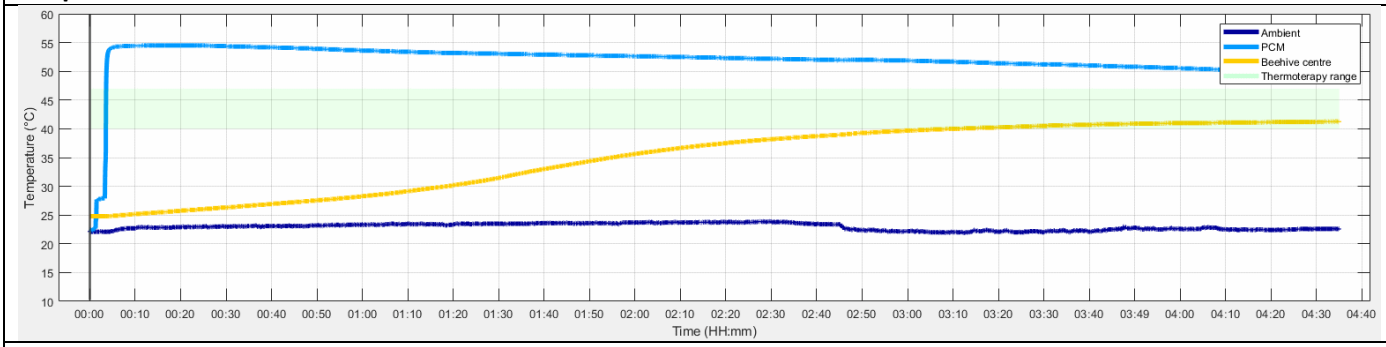
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.3	04:34:59
Maximum PCM temperature	54.6	00:16:29
Thermotherapy	Achieved	01:26:31
Average ambient temperature	23	--
Total test time	--	04:35:00

Graph



Comments

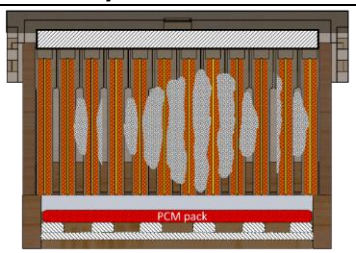
This test is like the previous one but with a higher amount of padding.

Test 56

Setup

- 2 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

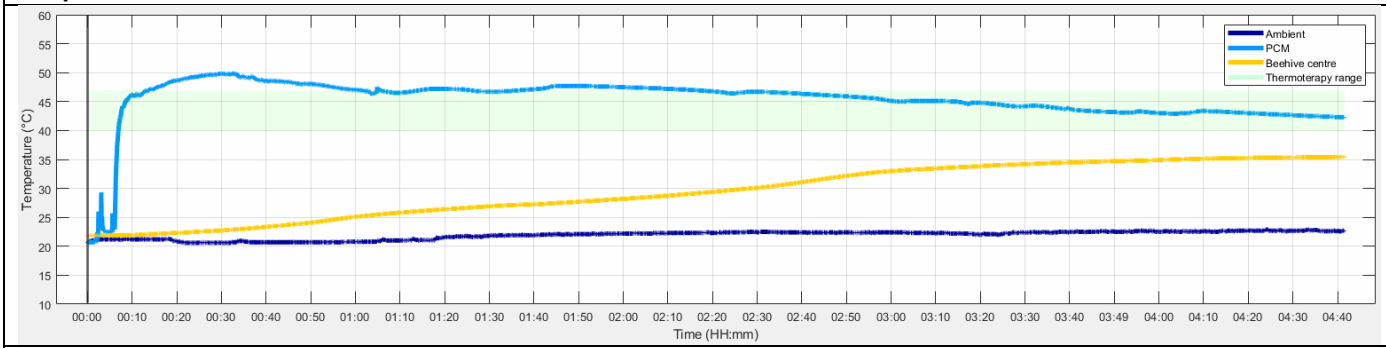
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35.5	04:41:30
Maximum PCM temperature	49.9	00:33:25
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	21.9	--
Total test time	--	04:41:30

Graph



Comments

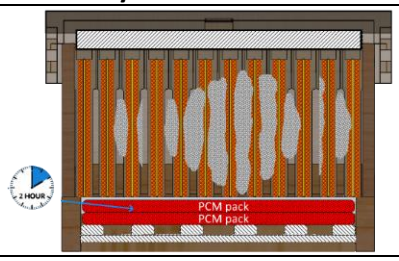
This experiment shows that 2kg is not effective, especially when bees are present.

Test 57

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

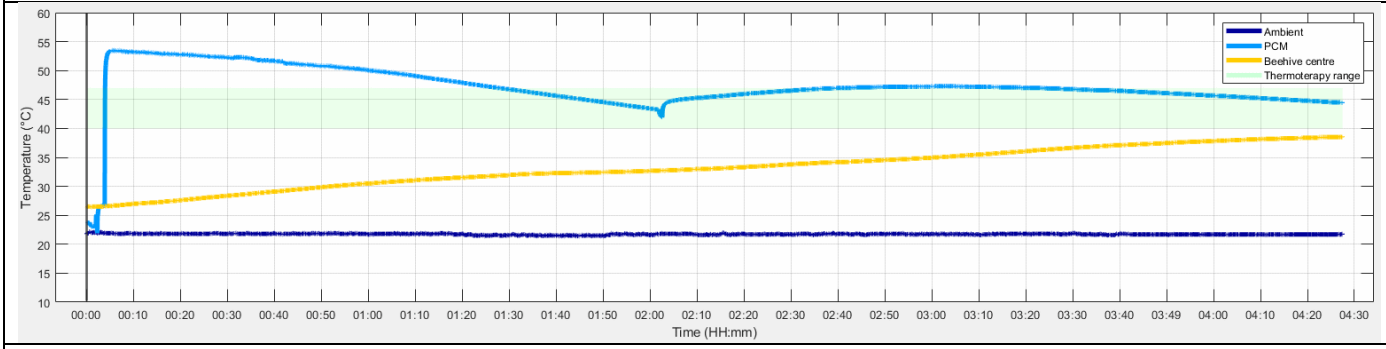
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	38.6	04:27:26
Maximum PCM temperature	53.5	00:07:18
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	21.7	--
Total test time	--	04:27:28

Graph



Comments

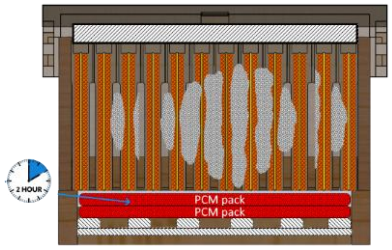
In this test, two-stage activation is again experimented with, applied to a filled beehive.

Test 58

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

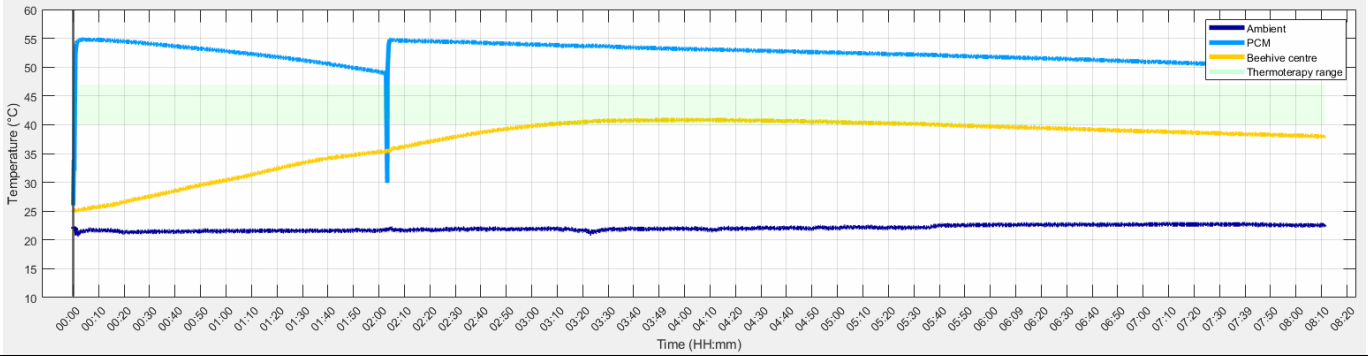
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	40.9	04:11:31
Maximum PCM temperature	54.8	02:05:14
Thermotherapy	Achieved	02:37:25
Average ambient temperature	22.1	--
Total test time	--	08:11:21

Graph



Comments

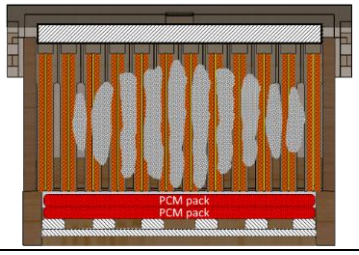
This test is similar to the previous one, but it was allowed to run for a longer time, since it was observed that when the activation is done in stages, the increase in temperature is slower.

Test 59

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

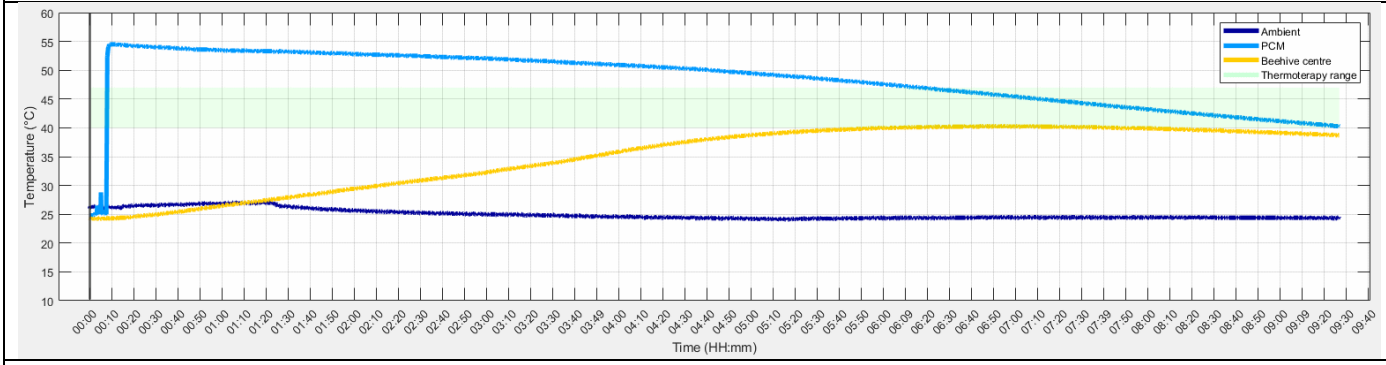
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	40.3	07:11:04
Maximum PCM temperature	54.5	00:13:24
Thermotherapy	Achieved	01:54:33
Average ambient temperature	25	--
Total test time	--	09:26:44

Graph



Comments

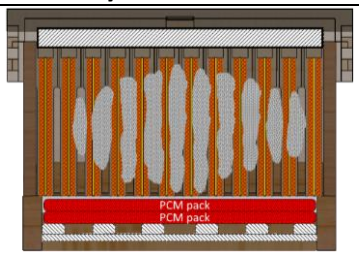
With the evidence given by the previous experiment, the test was repeated with 4kg and stuffing in the beehive, but it was allowed to run for a longer time. Indeed, it was observed that the desired temperature is reached but that the heat transfer time is long.

Test 60

Setup

- 4 kg PCM
- Insulation top
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

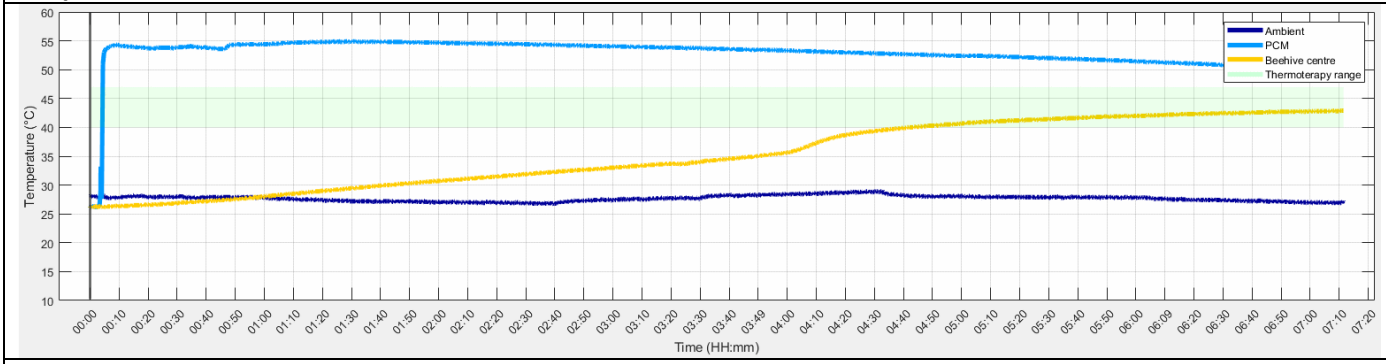
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	42.9	07:11:25
Maximum PCM temperature	54.9	01:42:02
Thermotherapy	Achieved	02:29:35
Average ambient temperature	27.7	--
Total test time	--	07:11:27

Graph



Comments

This experiment demonstrates the influence of ambient temperature on the performance of the PCM and on the internal temperature of the beehive.

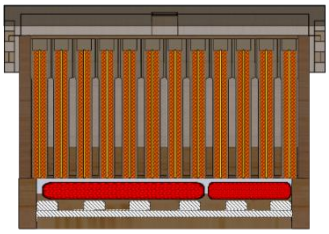
Laboratory experiments with Vacuum insulation panels (VIPs)

Test 61

Setup

- 3.4 kg PCM
- No insulation
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

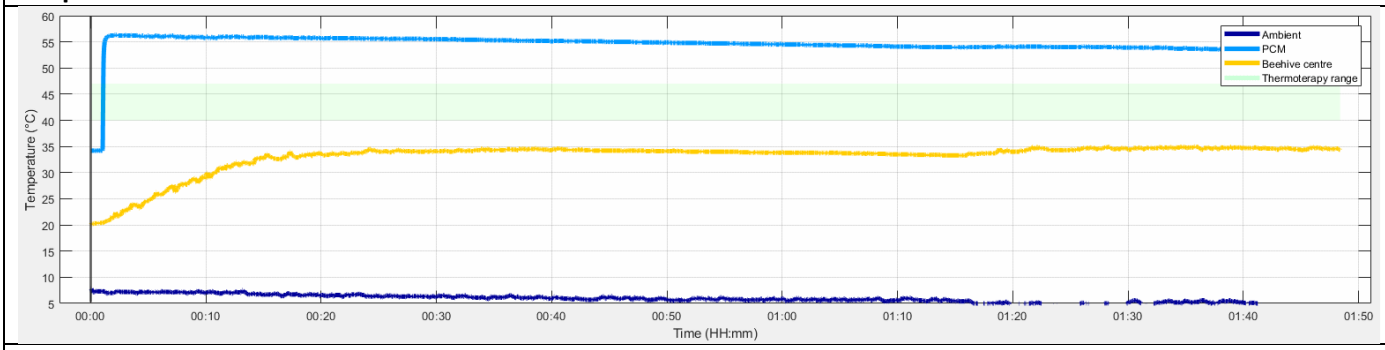
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35	01:35:48
Maximum PCM temperature	56.3	00:05:43
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	5.8	--
Total test time	--	01:48:23

Graph



Comments

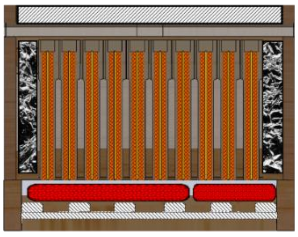
This test was done as a control experiment that served as a reference for a series of experiments where Vacuum insulation panels were used to test if adding them to the beehive, they can serve in low temperature environments to apply thermotherapy.

Test 62

Setup

- 3.4 kg PCM
- Insulation top and VIP on walls
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

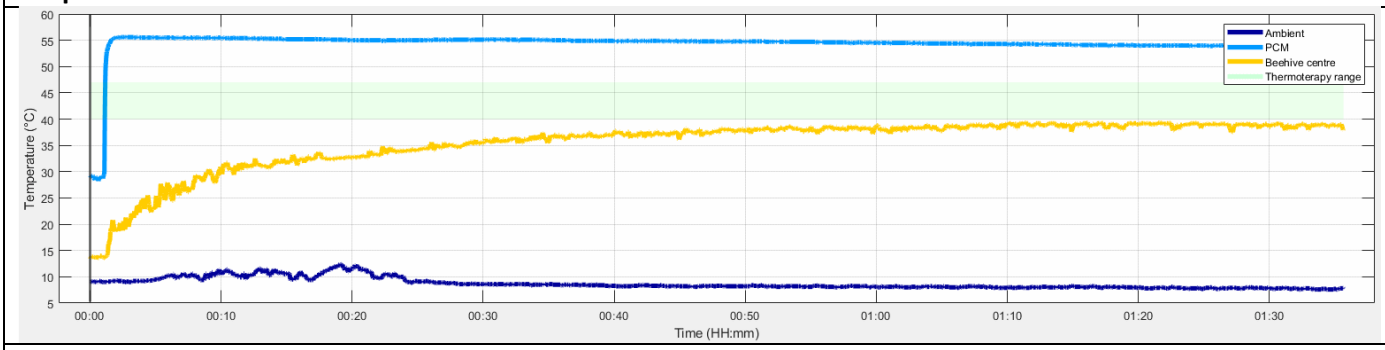
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	39.3	01:24:22
Maximum PCM temperature	55.7	00:03:20
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	8.7	--
Total test time	--	01:35:39

Graph



Comments

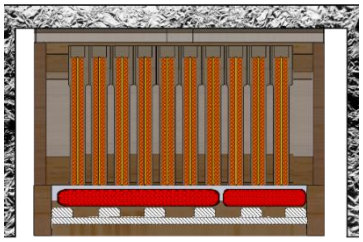
In this first test, the use of VIPs was combined with conventional insulation. In this case, the thermotherapy temperature was almost reached in a 9°C environment.

Test 63

Setup

- 2.2 kg PCM
- VIP insulation box
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

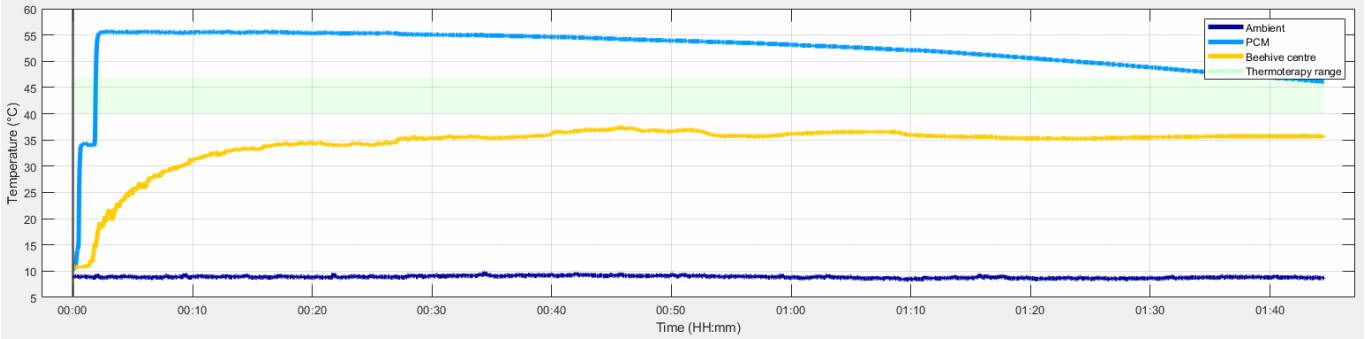
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	37.4	00:46:05
Maximum PCM temperature	55.9	00:03:18
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	8.9	--
Total test time	--	01:44:30

Graph



Comments

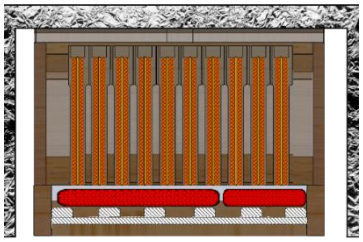
For this test, a VIP box was made and placed outside the beehive. Not being completely closed or sealed, the thermal insulation of the box was not very good. In this test 2.2 kg of PCM were used.

Test 64

Setup

- 3.4 kg PCM
- VIP Insulation box
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

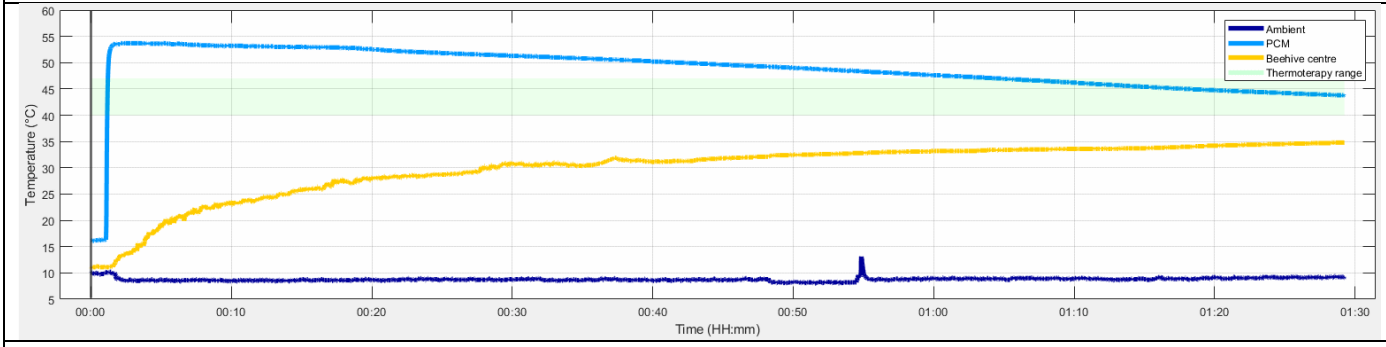
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	34.8	01:29:14
Maximum PCM temperature	53.8	00:03:20
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	8.8	--
Total test time	--	01:29:14

Graph



Comments

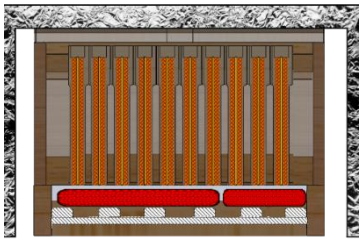
After the above test, it was decided to increase the mass of PCM to 3.4 kg. Unfortunately, even this mass was insufficient.

Test 65

Setup

- 4.4 kg PCM
- VIP insulation box
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

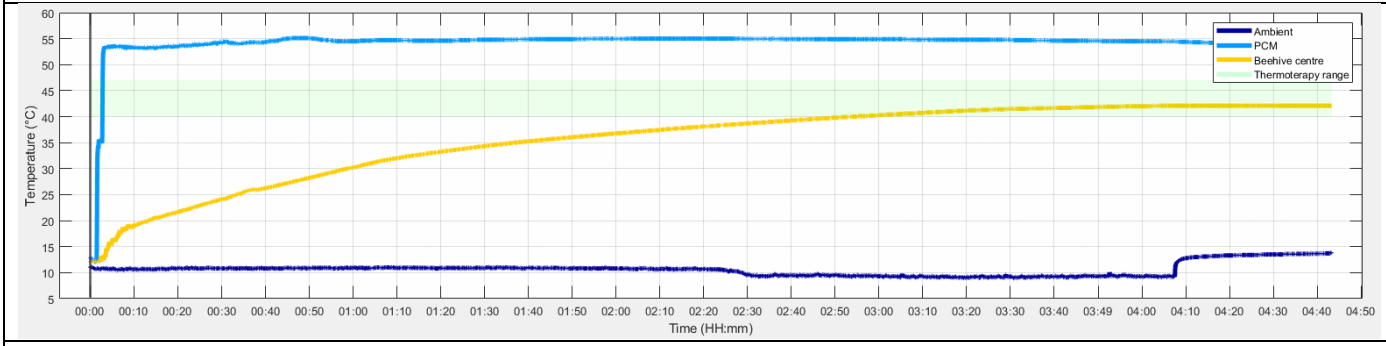
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	42.2	04:34:05
Maximum PCM temperature	55.2	00:48:18
Thermotherapy	Achieved	01:49:55
Average ambient temperature	10.6	--
Total test time	--	04:43:17

Graph



Comments

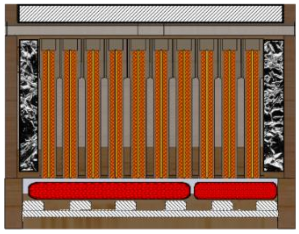
In this test, the same as in the two previous tests was repeated adding even more mass. With 4.4 kg and the VIP insulation box, the thermotherapy temperature was reached in an environment with 10 °C.

Test 66

Setup

- 4.4 kg PCM
- Insulation top and VIP insulation on walls
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

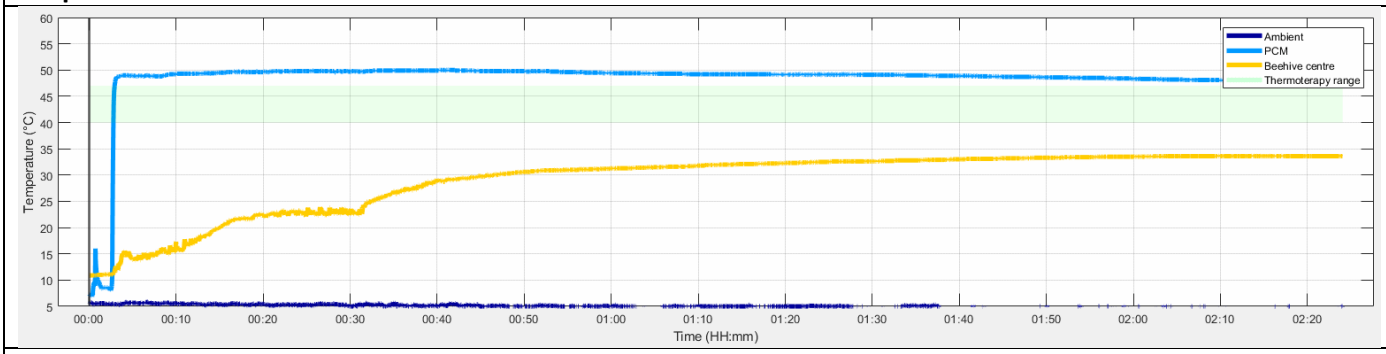
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	33.7	02:23:48
Maximum PCM temperature	50	00:42:44
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	5	--
Total test time	--	02:24:02

Graph



Comments

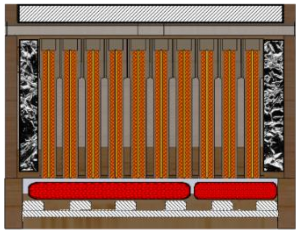
After seeing that 4.4 kg managed to reach the desired temperature in the previous test, this test returned to the initial setup with that mass. The ambient temperature strongly impacted and the thermotherapy temperature was not reached.

Test 67

Setup

- 4.4 kg PCM
- Insulation top and VIP insulation on walls
- 12 frames (wax combs with honey)
- No mesh floor
- Observation beehive

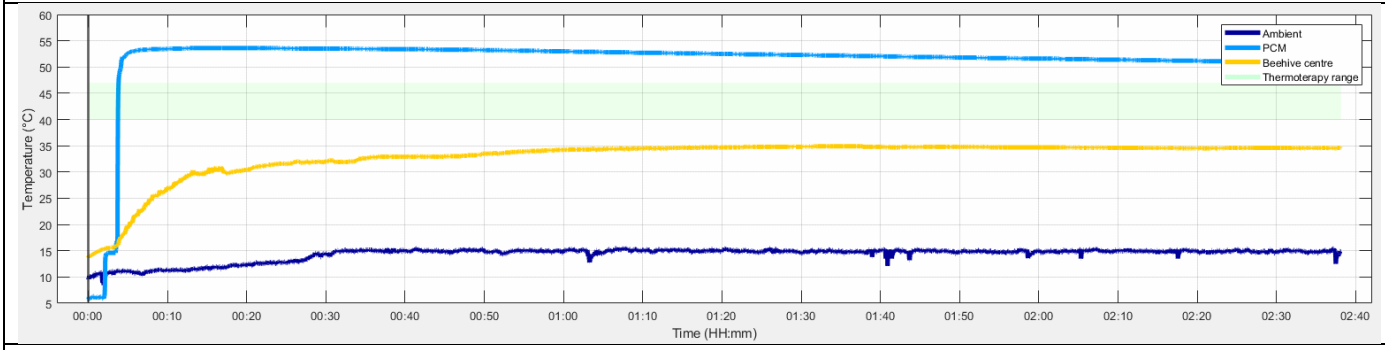
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35	01:37:31
Maximum PCM temperature	53.7	00:16:51
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	14.3	--
Total test time	--	02:38:07

Graph



Comments

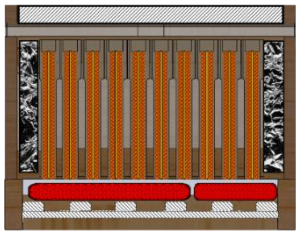
This test is a repeat of the previous test with a higher ambient temperature. However, this combination turned out to be ineffective.

Test 68

Setup

- 4.4 kg PCM
- Cork insulation top and cork VIP insulation on walls
- 12 frames (wax combs with honey)
- No mesh floor
- 1 mini fan
- Observation beehive

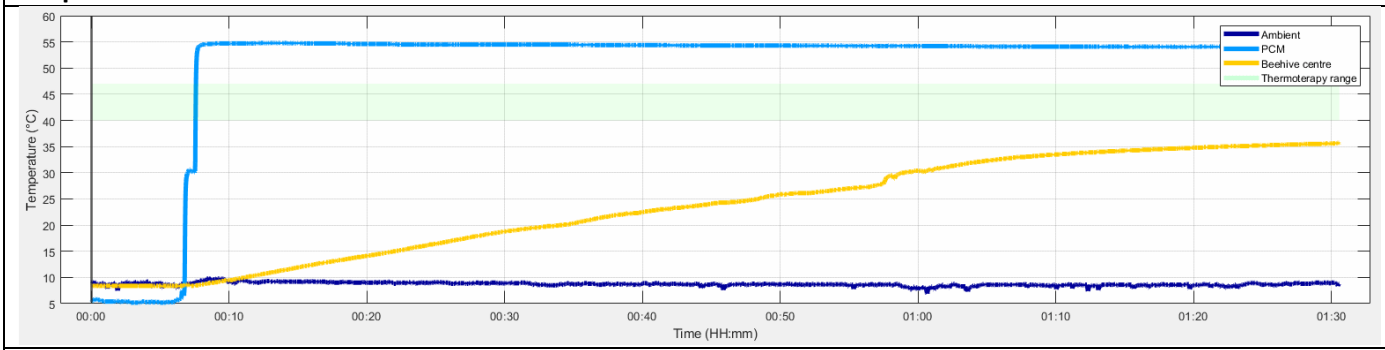
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35.7	01:30:34
Maximum PCM temperature	54.8	00:16:07
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	8.7	--
Total test time	--	01:30:34

Graph



Comments

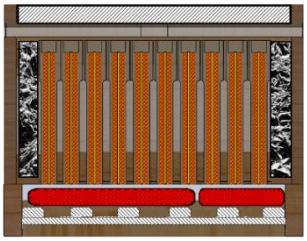
In this experiment laboratory-made cork core VIPs were tested. Additionally, it was tried to insert a mini fan with the intention of forcing convection inside the beehive. The VIP does not provide enough insulation.

Test 69

Setup

- 4.4 kg PCM
- Cork insulation top and cork VIP insulation on walls
- 12 frames (wax combs with honey)
- No mesh floor
- 1 mini fan
- Observation beehive

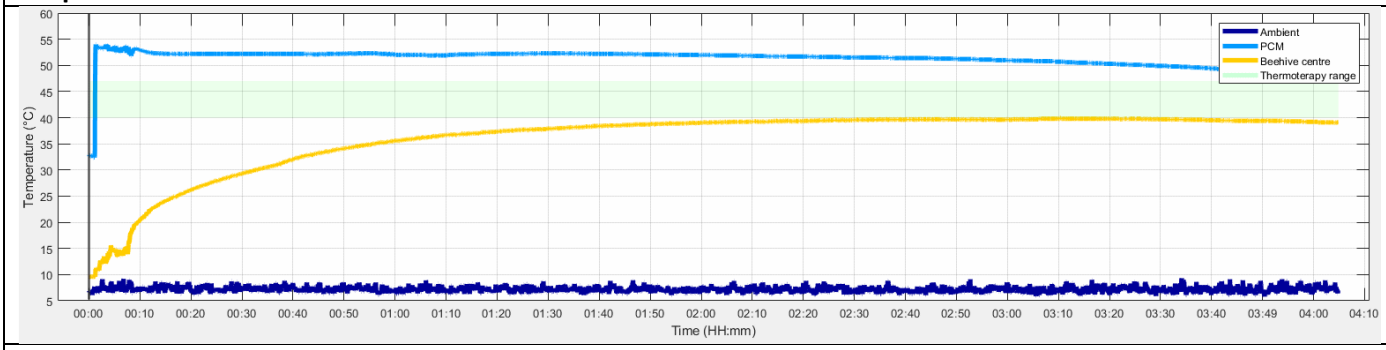
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	39.9	03:21:01
Maximum PCM temperature	54	00:03:23
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	7.2	--
Total test time	--	04:04:50

Graph



Comments

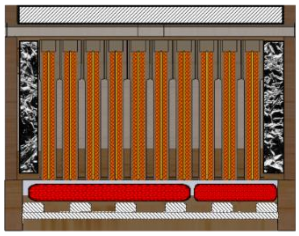
This is a repeat of the previous test, as the temperature was observed to continue to rise. In this case, the test was allowed to run for a longer time and it was observed that the thermotherapy temperature was almost reached.

Test 70

Setup

- 4.4 kg PCM
- Cork insulation top and cork VIP insulation on walls
- 12 frames (wax combs with honey)
- No mesh floor
- 1 mini fan
- Observation beehive

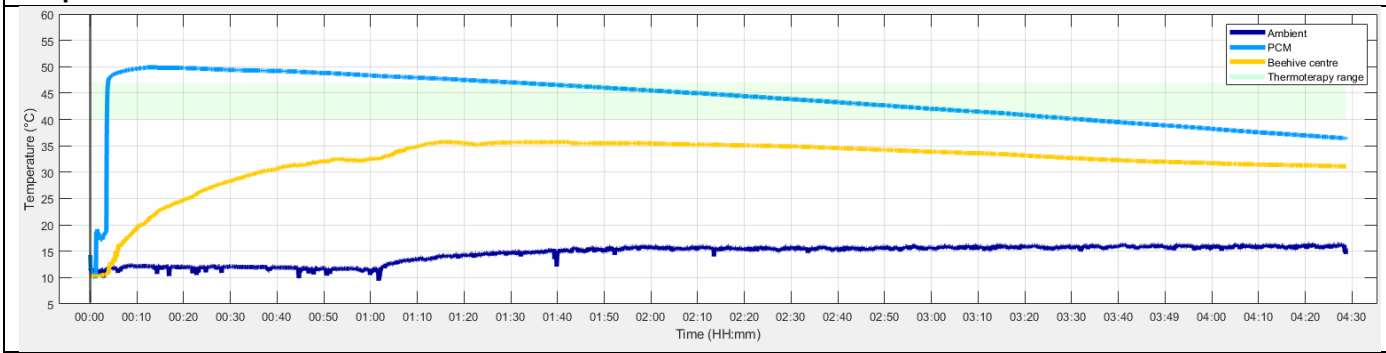
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	35.8	01:41:58
Maximum PCM temperature	49.9	00:14:18
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	14.6	--
Total test time	--	04:28:44

Graph



Comments

This test is a repeat of the previous test with a higher ambient temperature. PCM performance was not good.

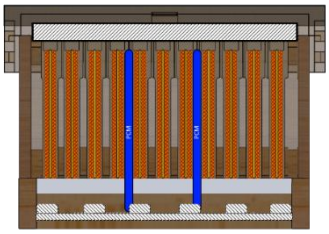
Laboratory experiments with vertical-placed rigid PCM containers

Test 71

Setup

- 2.2 kg PCM
- Insulation top
- 11 frames (wax combs with honey)
- No mesh floor
- Observation beehive

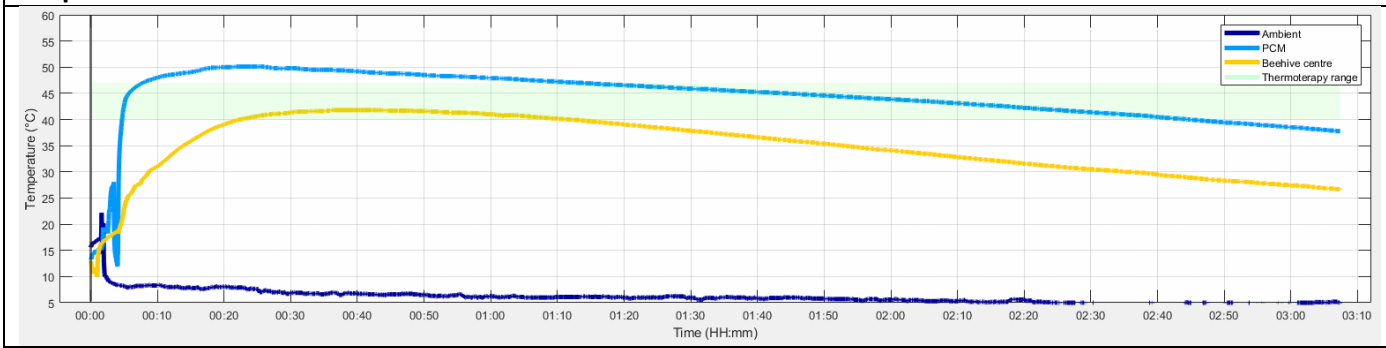
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.9	00:41:03
Maximum PCM temperature	50.2	00:24:01
Thermotherapy	Achieved	00:49:57
Average ambient temperature	6.1	--
Total test time	--	03:07:22

Graph



Comments

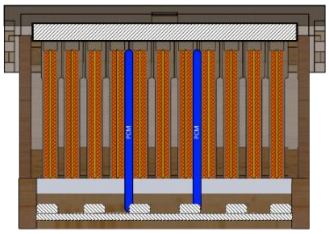
This series of tests served to test the prototypes of PCM packs made in rigid containers.

Test 72

Setup

- 2.2 kg PCM
- Insulation top
- 11 frames (wax combs with honey)
- No mesh floor
- Observation beehive

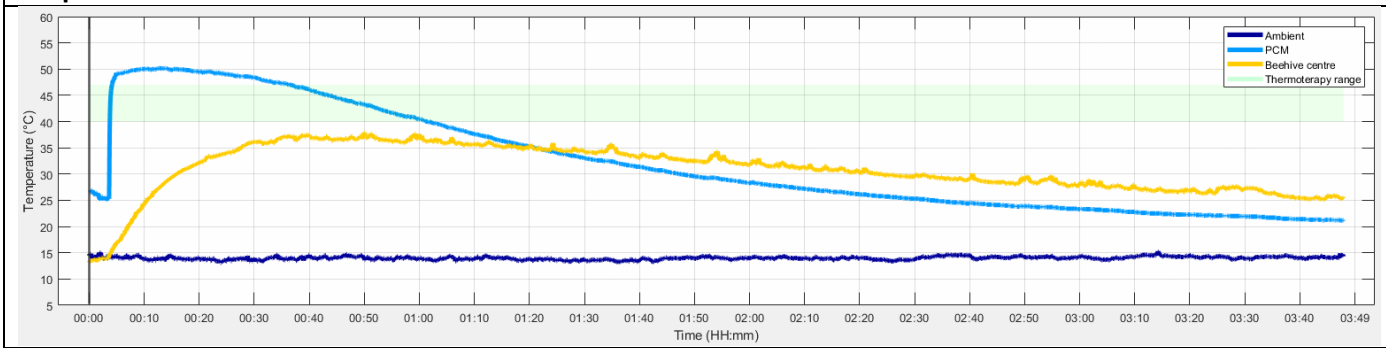
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	37.9	00:50:05
Maximum PCM temperature	50.2	00:14:05
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	14	--
Total test time	--	03:47:55

Graph



Comments

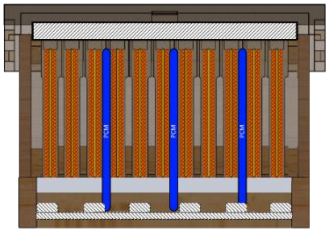
This test shows that being inside the beehive, the PCM packs are less influenced by ambient temperature. However, due to their low mass, they have poor performance.

Test 73

Setup

- 3.3 kg PCM
- Insulation top
- 11 frames (wax combs with honey)
- No mesh floor
- Observation beehive

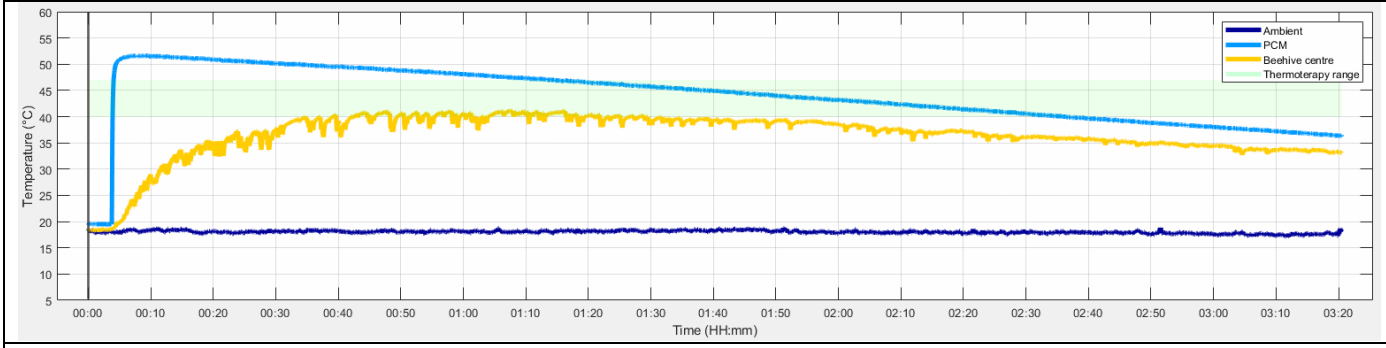
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.1	01:16:02
Maximum PCM temperature	51.6	00:11:14
Thermotherapy	Achieved	00:32:07
Average ambient temperature	18	--
Total test time	--	03:20:30

Graph



Comments

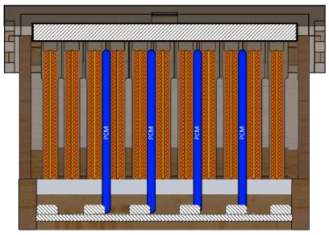
In this test, the mass of PCM distributed in three containers was increased. The thermotherapy temperature was marginally reached.

Test 74

Setup

- 4.4 kg PCM
- Insulation top
- 11 frames (wax combs with honey)
- No mesh floor
- Observation beehive

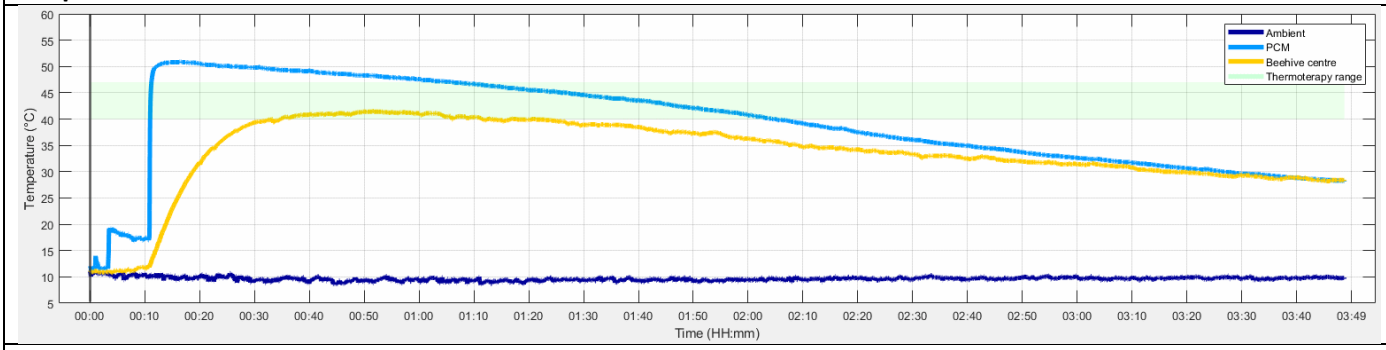
Visual Key



Results

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.5	00:51:50
Maximum PCM temperature	50.9	00:16:51
Thermotherapy	Achieved	00:39:54
Average ambient temperature	9.6	--
Total test time	--	03:48:43

Graph



Comments

Four is the maximum amount of these containers that can be placed inside the beehive without removing more than one frame. In this test the thermotherapy temperature was also reached.

In conclusion, the maximum PCM capacity inside the beehive is 6 kgs but 4 kgs are enough to rise the internal temperature above 40 °C. In general, insulation is desirable, mainly on top. On the other hand, the absence of a metal or plastic mesh floor improved the overall performance. To place the packs where the air can circulate resulted in a better convection and consequently higher temperatures. The effect of the ambient temperature over the heating performance was demonstrated.

Experimental work summary (Part 2)

This report shows a summary of each of the experiments carried out on site. The corresponding guidelines were always followed, and sanitary standards were obeyed at all times. In the collaboration, the personal distance and the use of face masks were always maintained. Groups of more than 5 people and car sharing were avoided, and tests were not conducted on dates where sanitary restrictions did not allow it. A total of 29 experiments were carried out in three different apiaries. In all sites the heat treatment was applied although not in all it was successful.

a)



b)

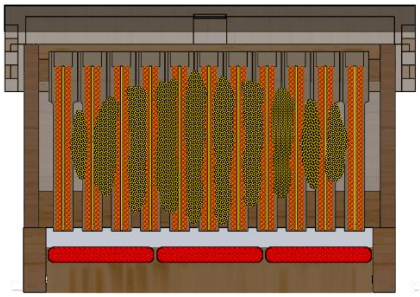
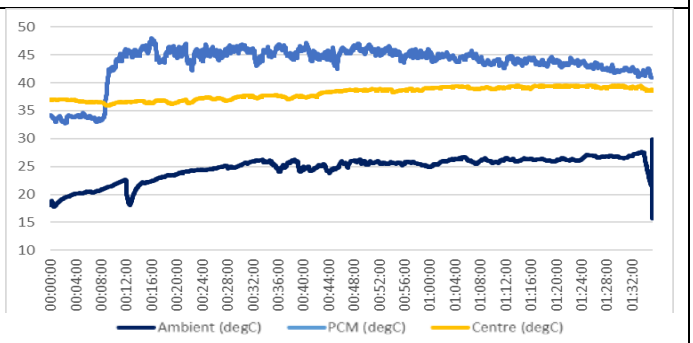


c)

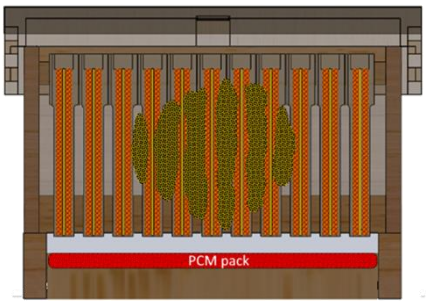
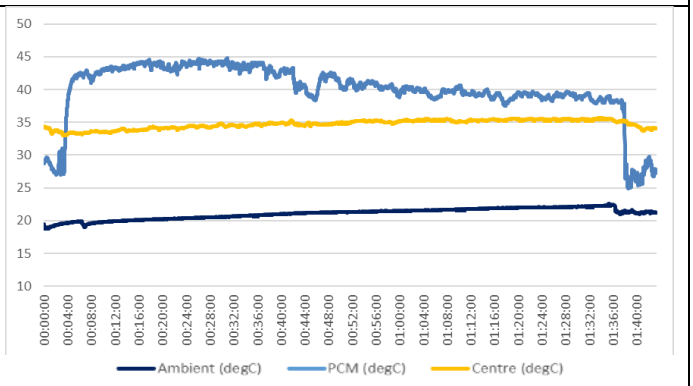


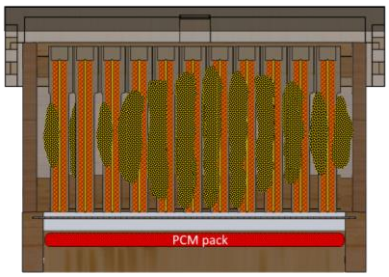
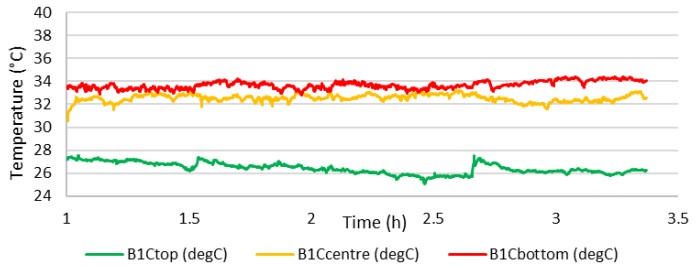
Figure A2 Photos of the different crew assemblies at the three different apiaries:
a) Risley, Derby
b)Halam, Newark
c) Market Rasen, Lincolnshire.

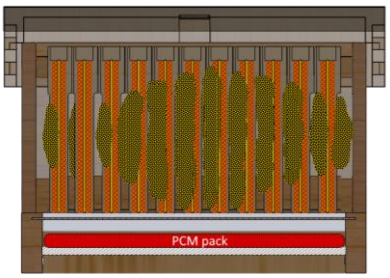
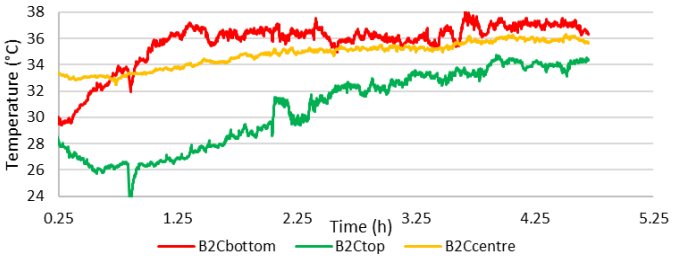
Field experiments

19/July/2019 - Risley		
Setup	Visual Key	Results (1.5 hrs)
• 1 kg PCM • 12 frames (bees, brood and honey) • No metal mesh floor • No insulation		
Comments		
This experiment was one of the most promising. Even though the PCM mass was not much, the heat transfer was good due to the metal packaging. Nearly 40 °C is reached in the centre even though the experiment only lasted an hour and a half. It is noteworthy that no thermal insulation was used in this test, however the environmental conditions were favourable.		



22/August/2019 – Risley		
Setup	Visual Key	Results (1.5 hrs)
• 2 kg PCM • 12 frames (bees, brood and honey) • No metal mesh floor • No insulation		
Comments		

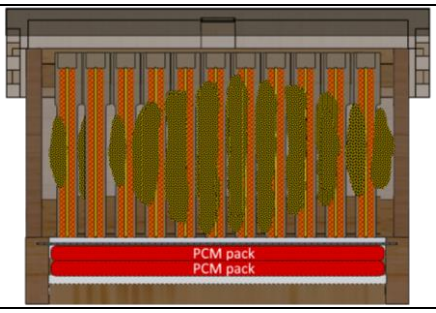
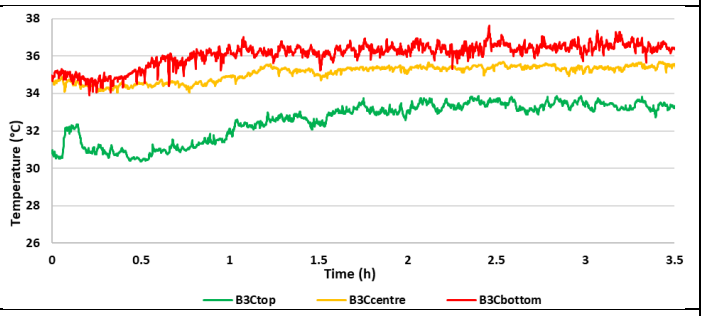
17/September/2019 – Bunny Park		
Setup	Visual Key	Results (3.5 hrs)
• 2 kg PCM • 12 frames (bees, brood and honey) • Metal mesh floor • No insulation		
Comments		
The average ambient temperature during the time of testing was 16.58 ˚C. The graphs show that the initial temperature of the beehive (before the heat treatment) at the centre brood area is within the optimum temperature of a beehive (i.e. between 32 ˚C to 36 ˚C). After two hours the pack was activated, the average maximum temperature at the bottom was between 35 to 36 ˚C meanwhile at the centre was between 33 to 35 ˚C.		

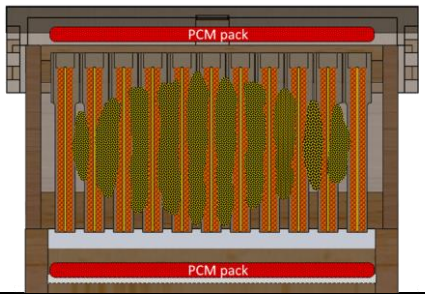
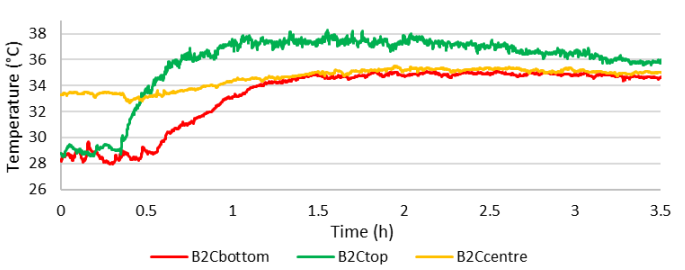
19/September/2019 – Bunny Park		
Setup	Visual Key	Results (4 hrs)
• 2 kg PCM • 12 frames (bees, brood and honey) • Metal mesh floor • No insulation • Insulation tray		
Comments		
The centre bottom temperature increased by seven ˚C in approximately 1.4 hours. With the initial average temperature of 30 ˚C, this means the maximum average temperature achieved was around 37.6 ˚C. A similar trend of the curve was observed for the top part of the beehive.		





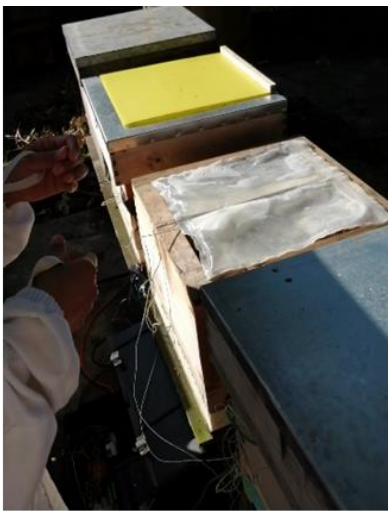


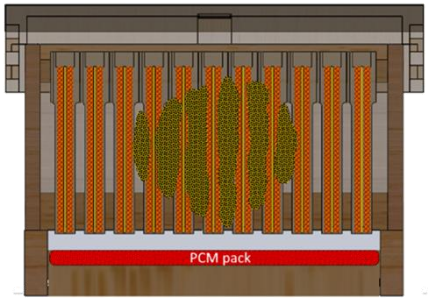
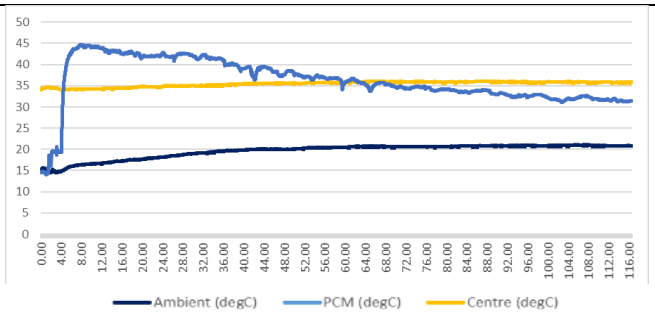
20/September/2019 – Bunny Park		
Setup	Visual Key	Results (3.5 hrs)
• 4 kg PCM • 12 frames (bees, brood and honey) • No metal mesh floor • No insulation		
Comments		
Focusing on the temperature at the centre of the beehive, like the first initial trial, the increase in the temperature was very low. The increase in temperature was insufficient for the heat treatment method to become effective- i.e. to kill the mites.		

20/September/2019 – Bunny Park		
Setup	Visual Key	Results (3.5 hrs)
• 4 kg PCM • 12 frames (bees, brood and honey) • No metal mesh floor • No insulation		
Comments		
The highest temperature increase was recorded at the top of the beehive (from approximately 30 ˚C to 37 ˚C in about 1 hour). This is due to the PCM pack placed at the top of the beehive (under the roof). Additionally, when compared with the last two tests, the centre temperature was found higher in comparison to the bottom temperature. However, the centre temperature only showed an increment by about two ˚C (from 33 to 35 ˚C) in almost 2 hours! After 2 hours the packs were triggered, the temperature was decreasing with time as the PCM pack solidified and was cooling down.		

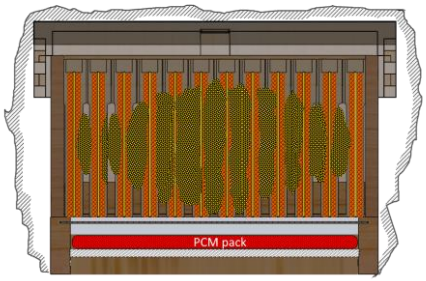
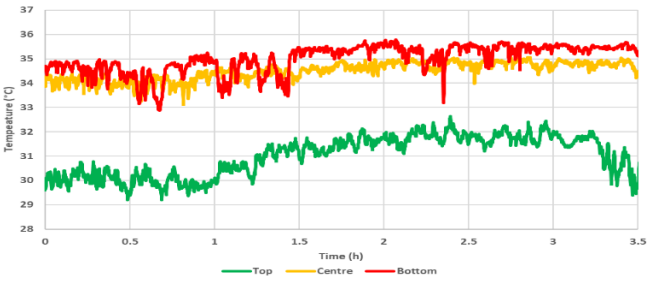


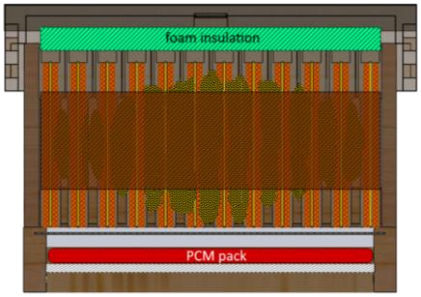
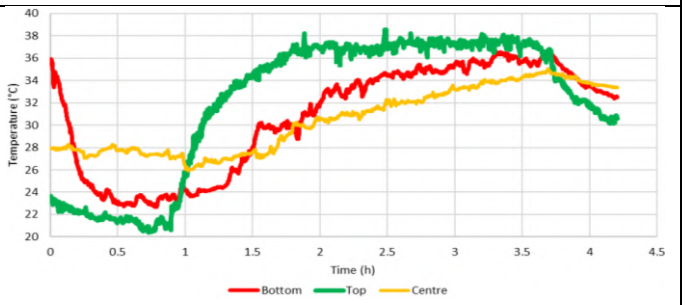




1/October/2019 – Risley		
Setup	Visual Key	Results (2 hrs)
• 2 kg PCM • 11 frames (bees, brood and honey) • No metal mesh floor • No insulation		
Comments		
On this test, the performance of the PCM was poor. The losses were too many and the beehive counted with no insulation. The bees maintained the same internal temperature in the centre.		

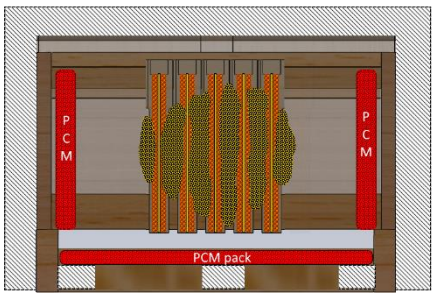
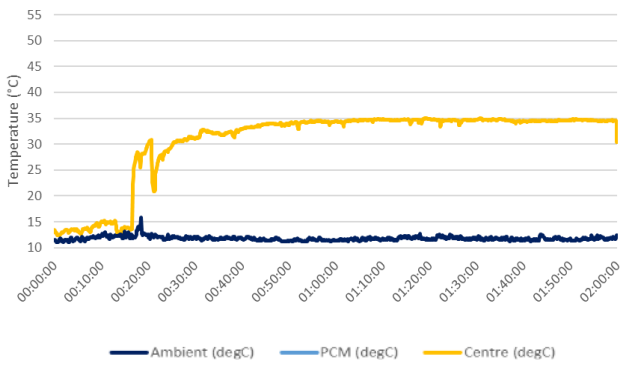


3/October/2019 – Bunny Park		
Setup	Visual Key	Results (3.5 hrs)
• 2 kg PCM • 12 frames (bees, brood and honey) • Metal mesh floor • Insulation jacket		
Comments		

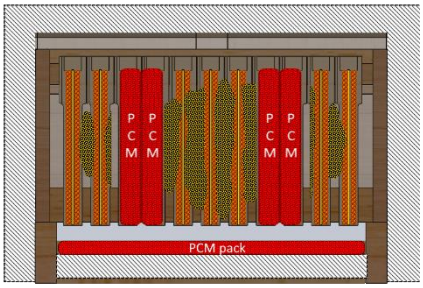
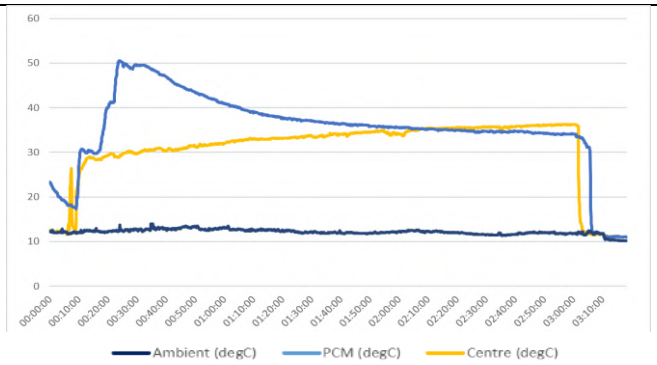
3/October/2019 – Bunny Park		
Setup	Visual Key	Results (4 hrs)
• 2 kg PCM • 11 frames (bees, brood and honey) • Metal mesh floor • SHINS Insulation • Insulation foam crown board		
Comments		



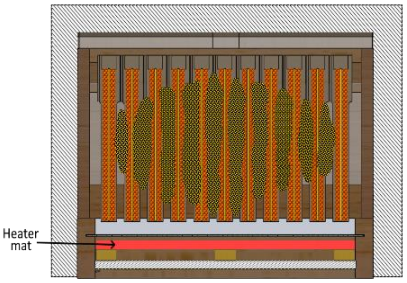
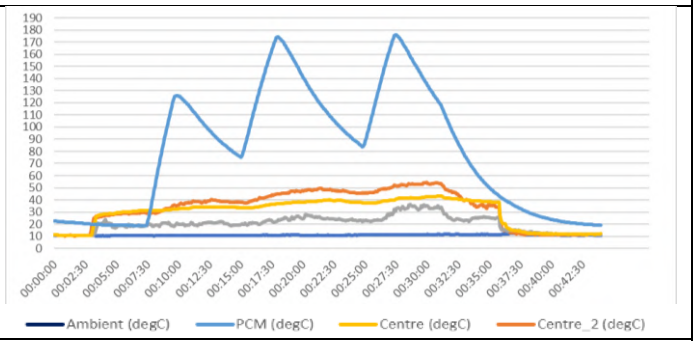


15/October/2019 – Risley		
Setup	Visual Key	Results (1.5 hrs)
• 6 kg PCM • Insulation box (50mm) • 5 frames (bees, brood and honey) • No metal mesh floor • 2 packs hanging on sides • 1 pack over insulation pieces		
Comments		
The heat transfer rate of the packs helped by thermal insulation was not higher than the cooling rate due to thermoregulation of bees and heat absorption. To reach 40 °C in the centre of the beehive was not possible. It must be considered that the ambient temperature was very low.		



18/October/2019 – Bunny Park		
Setup	Visual Key	Results (3 hrs)
• 6 kg PCM • Insulation box (50mm) • 7 frames (bees, brood and honey) • Metal mesh floor • 2 packs hanging • 1 pack over insulation board		
Comments		
It is possible that an amount of at least 1kg of honey in each of the three central frames, together with the amount of wax and bees, has slowed the distribution of heat. However, the PCM temperature decrease is rapid compared to the heat transfer rate inside the beehive. It is also demonstrated that at the distance in which the PCMs were placed from the centre, given the barrier that delays the heat transfer, it is not possible to perform the thermotherapy in 2.5 hours, however, the time could be reduced if the source of heat is closer to the centre.		

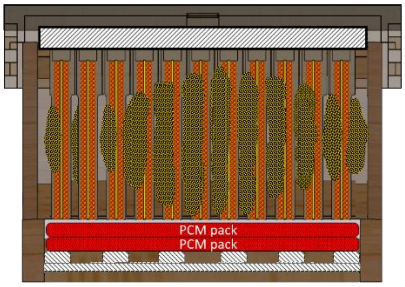


30/October/2019 – Bunny Park		
Setup	Visual Key	Results (0.5 hrs)
• 1 Heat mat • Insulation box (50mm) • 11 frames (bees, brood and honey) • Metal mesh floor		
Comments		
It was possible to achieve the temperature of 40°C and higher with a heater mat with a temperature between 70° and 170°C. Discarding the peaks, it can be seen in the graph that when the temperature drops below 110°C, the centre goes below 40°C. To achieve it in a short time is needed a very high temperature or a heat transfer ratio greater than the absorption.		



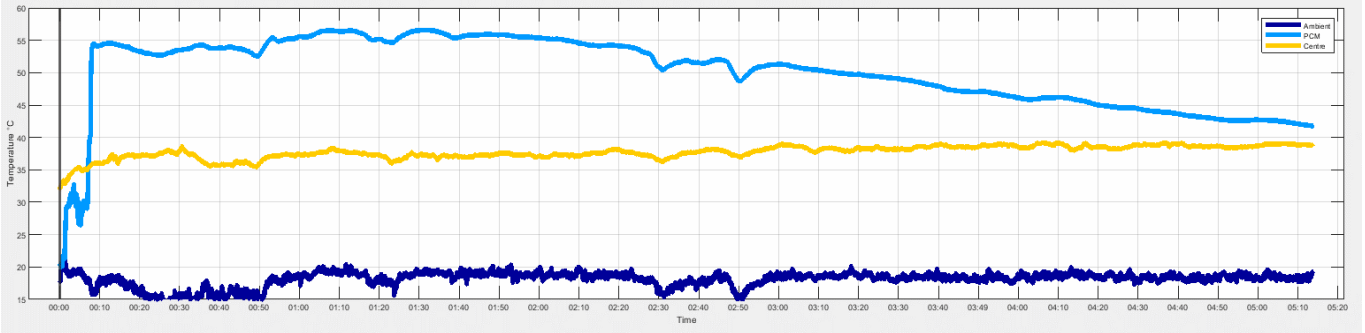




26/May/2020 – Matlock		
Setup	Visual Key	Results (5 hrs)
• 4kg PCM • Insulation crown board • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature	Time
Maximum temperature at centre	39.2	04:09:52
Maximum PCM temperature	56.6	01:32:56
Thermotherapy	Not achieved	00:00:00

Graph



Comments

This experiment shows that PCM is highly responsive to changes in ambient temperature. The maximum temperature of the PCM was 56.6 °C. It is also noteworthy that during the 5 hours of the experiment, the PCM remained above 40 °C.







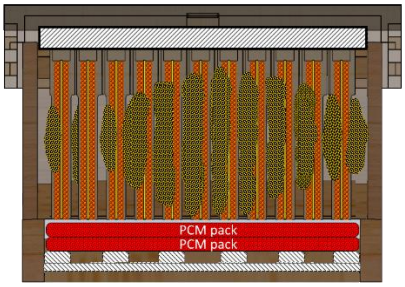






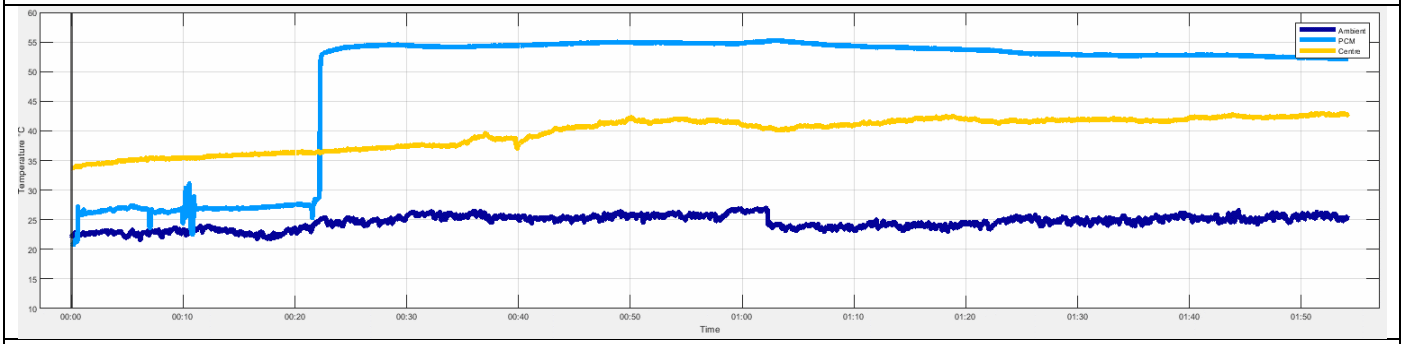


10/August/2020 – Risley

Setup	Visual Key	Results (2 hrs)
• 3.4kg PCM (preheated) • Insulation floor and crown board • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature	Time
Maximum temperature at centre	43	01:51:58
Maximum PCM temperature	55.2	01:03:44
Thermotherapy	Achieved	01:11:06

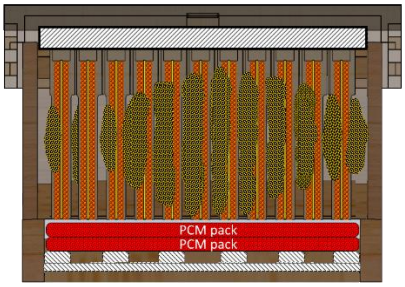
Graph



Comments

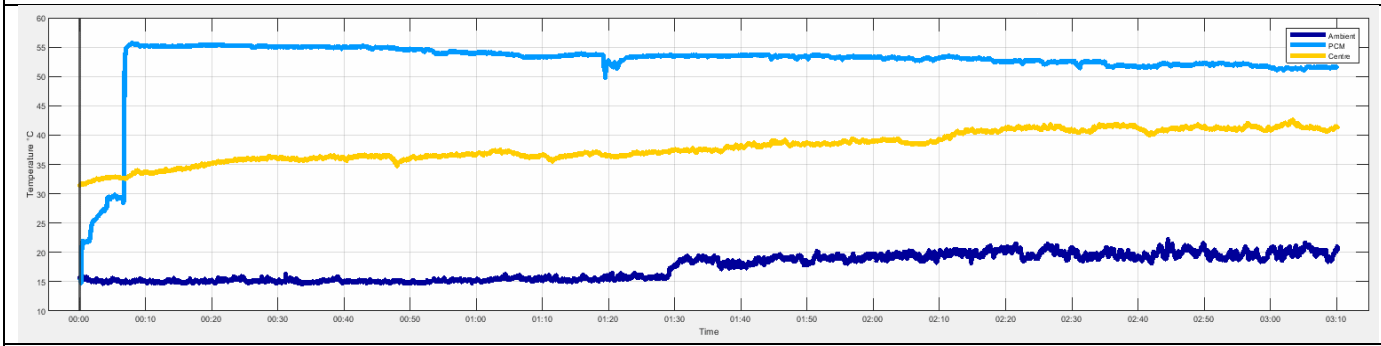
The results showed that the thermotherapy was achieved. This experiment represents a milestone in the development of the prototype for the heat treatment of bees against the varroa mite using a phase change material. All observations made in the previous 60 laboratory experiments and the 12 apiary experiments were considered for this test.



11/September/2020 – Risley		
Setup	Visual Key	Results (2 hrs)
• 4.5kg PCM (2.25+2.25 preheated) • Insulation floor and crown board • 11 frames (bees, brood and honey) • No metal mesh floor		

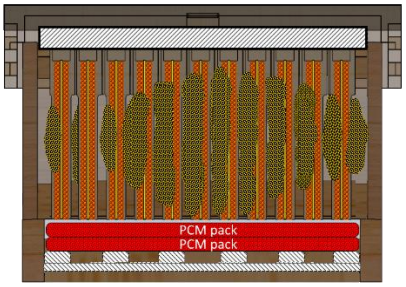
	Temperature	Time
Maximum temperature at centre	42.6	03:03:25
Maximum PCM temperature	55.7	00:07:54
Thermotherapy	Achieved	00:58:11

Graph



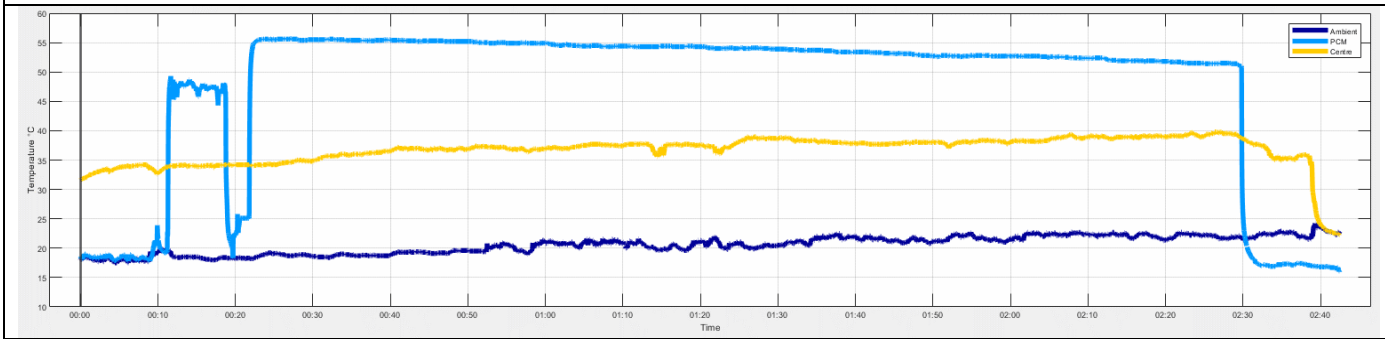
Comments

This was the second successful experiment. This time, the technique used was different as one PCM pack was inserted at the beginning and the second one after an hour. The weather conditions helped to reach the temperature, although the time to achieve it was longer compared to the previous test.

14/September/2020 – Risley		
Setup	Visual Key	Results (2 hrs)
• 2.25kg PCM (preheated) • Insulation floor and crown board • 11 frames (bees, brood and honey) • No metal mesh floor		

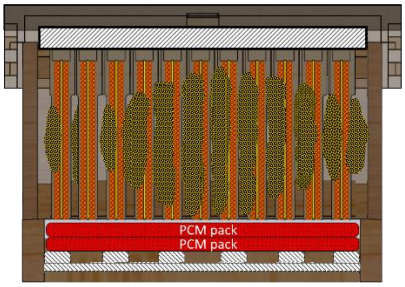
	Temperature	Time
Maximum temperature at centre	39.8	02:27:12
Maximum PCM temperature	55.7	00:27:20
Thermotherapy	Not achieved	00:00:00

Graph



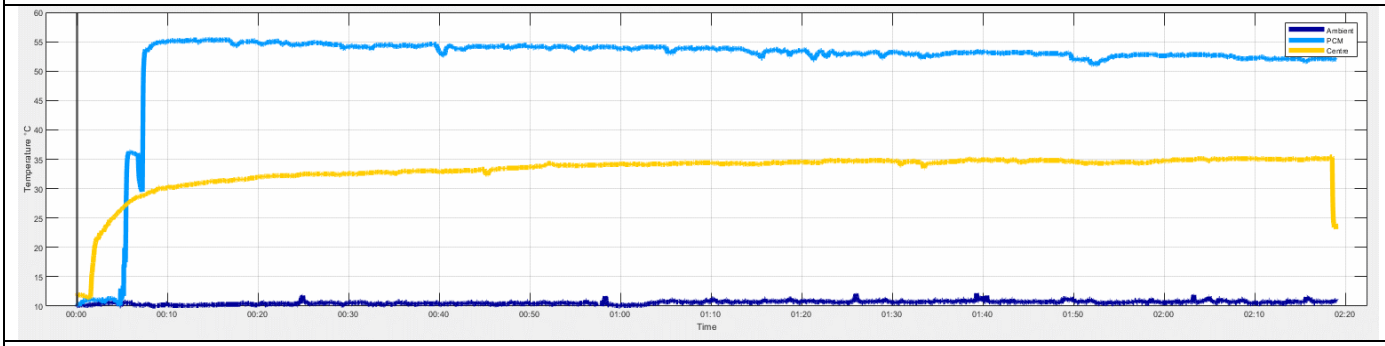
Comments

In this test it was sought to reach the thermotherapy temperature (40 °C) using a lower mass. In this case, only one PCM package was used. However, the time of the test did not allow to see if the desired temperature could be reached.

12/October/2020 – Risley		
Setup	Visual Key	Results (2 hrs)
• 3.4kg PCM (preheated) • Insulation floor and crown board • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature	Time
Maximum temperature at centre	35.4	02:18:32
Maximum PCM temperature	55.4	00:16:38
Thermotherapy	Not achieved	00:00:00

Graph



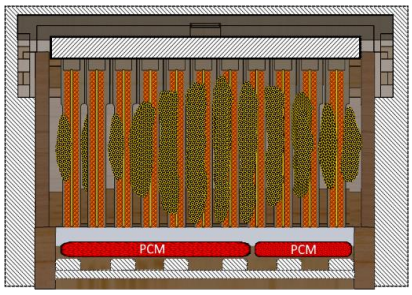
Comments

The results showed an increase in temperature from about 30°C to 35°C in 2 hours. The temperature never reached 40°C and therefore the treatment was not completed even though the temperature of the PCMs seems to be quite good. This is probably due to the strong influence of ambient temperature.
This was the first test that included honey sampling and taking pictures of the frames.



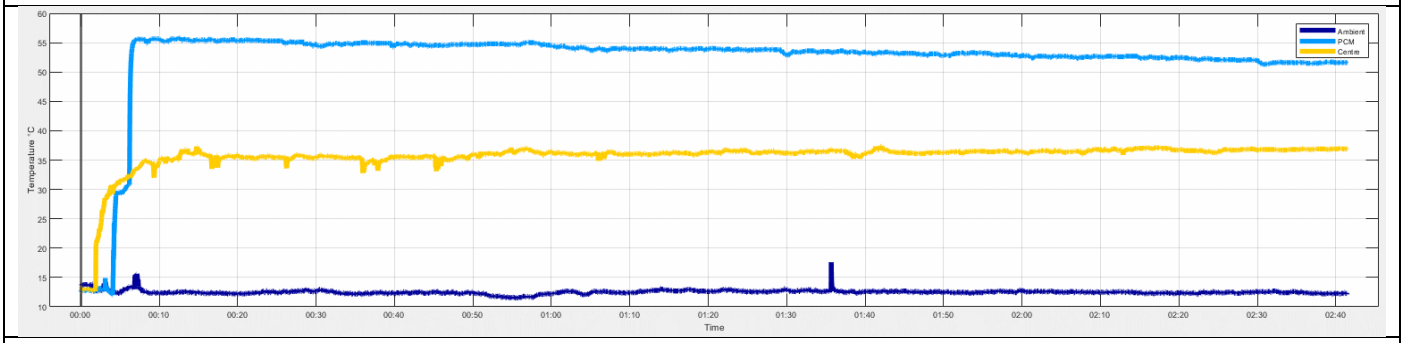





2/November/2020 – Risley		
Setup	Visual Key	Results (2.5 hrs)
• 3.4kg PCM • Insulation floor and crown board • Insulation box • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature	Time
Maximum temperature at centre	37.4	01:42:04
Maximum PCM temperature	55.9	00:12:40
Thermotherapy	Not achieved	00:00:00

Graph



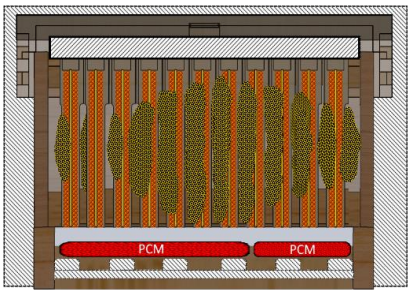
Comments

As it was carried out in low temperature environmental conditions (an average of 13 °C), it was decided to use an insulation box outside the beehive. However, despite this, the thermotherapy temperature was not reached.



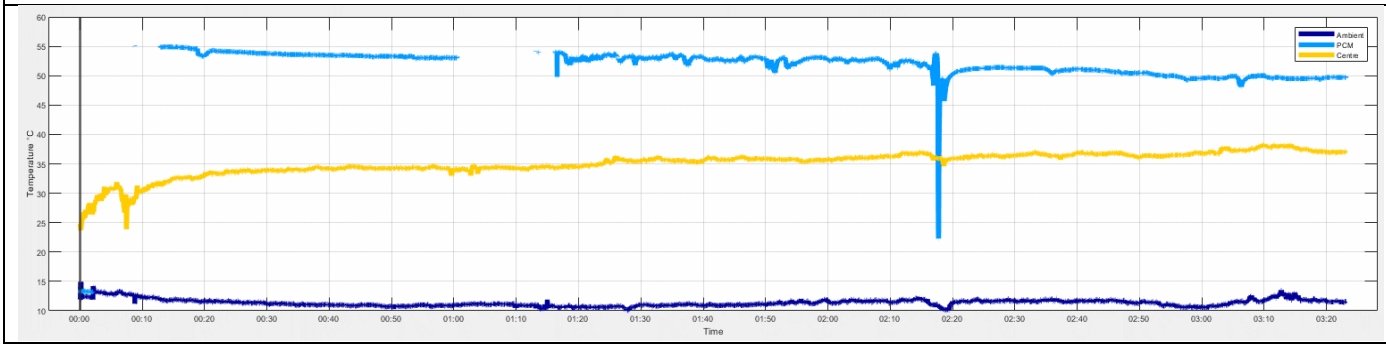





12/November/2020 – Newark		
Setup	Visual Key	Results (3 hrs)
• 3.4kg PCM • Insulation floor and crown board • Insulation box • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature	Time
Maximum temperature at centre	38.3	03:14:21
Maximum PCM temperature	55.1	00:08:48
Thermotherapy	Not achieved	00:00:00

Graph



Comments

This test was carried out on a beehive belonging to a volunteer. The result of this experiment is unsatisfactory since even though the insulation box was used, the outside temperature lowered the temperature of the PCMs, so it was decided to replace them with another set of the same mass after two hours. However, not even with the replacement could an increase in the core temperature be achieved

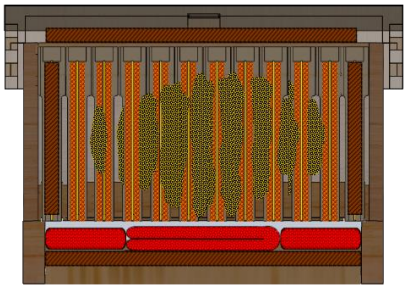






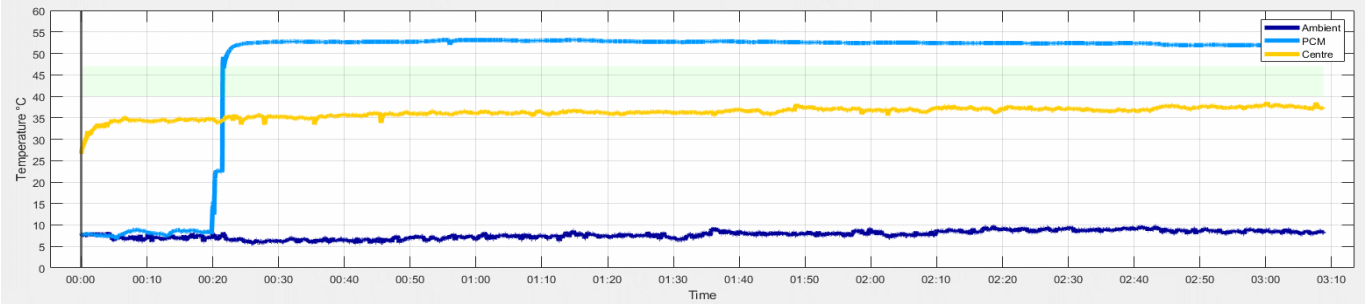




9/December/2020 – Lincoln		
Setup	Visual Key	Results (3 hrs)
• 4.4kg PCM • Cork insulation floor, crown board and walls. • 9 frames (bees, brood and honey) • No metal mesh floor		

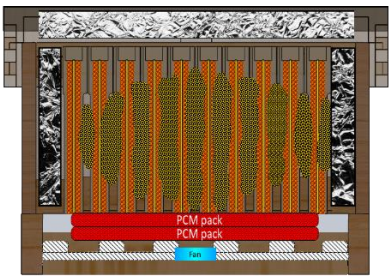
	Temperature	Time
Maximum temperature at centre	38.6	03:00:15
Maximum PCM temperature	53.2	01:15:25
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	7.7389	--
Total test time	--	03:08:45

Graph



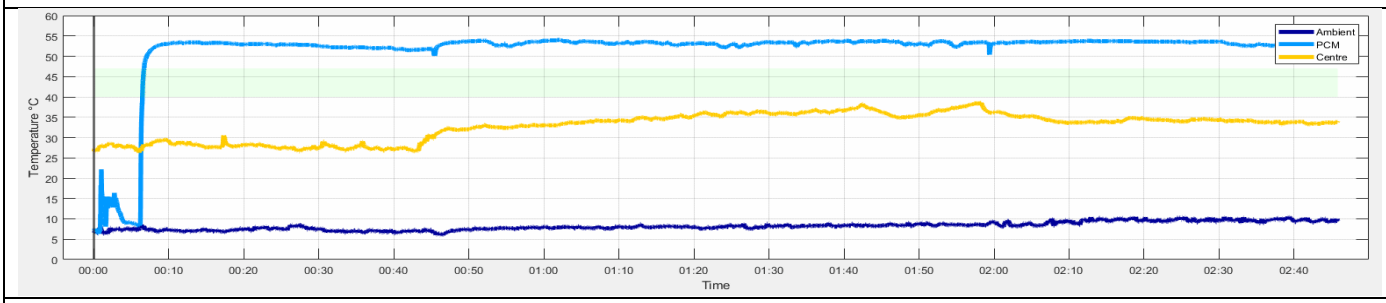
Comments

In this test the type of insulation was changed by one made of cork, the mass of PCMs was also increased by placing more packs in the interior of the beehive. Although the thermotherapy temperature was not reached, it was shown that this insulation is very effective, since the ambient temperature was 8 °C on average.

9/December/2020 – Lincoln		
Setup	Visual Key	Results (2.7 hrs)
• 4.4kg PCM • Cork insulation floor, crown board and walls • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature	Time
Maximum temperature at centre	38.6	01:58:17
Maximum PCM temperature	54	01:02:12
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	8.2219	--
Total test time	--	02:45:49

Graph



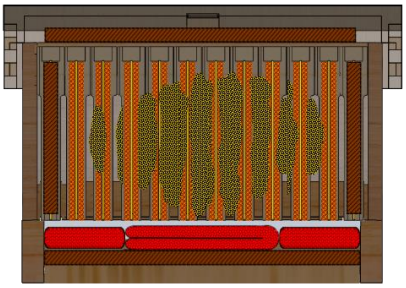
Comments

This test was the most ambitious, as not only was it tested with 4.4 kg of PCM but also a small fan was placed on the floor of the beehive to force convection. Vacuum insulated panels (VIP) were also used with the core of the same cork as the isolation of the above-mentioned experiment.



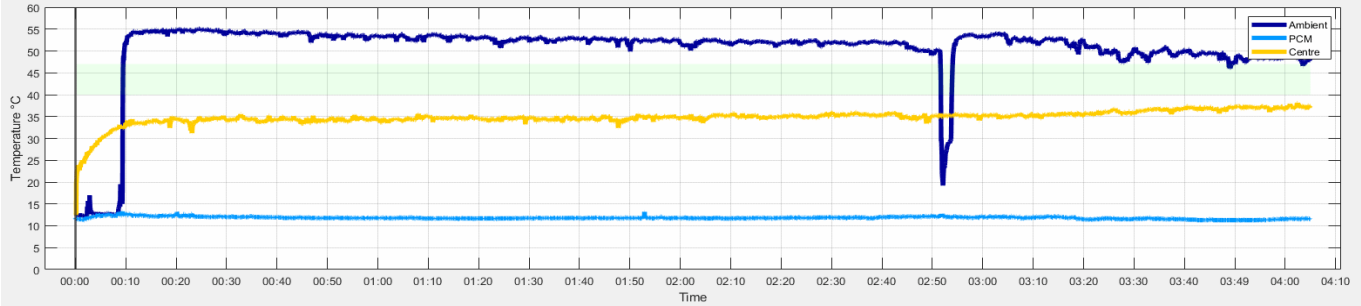





18/December/2020 – Lincoln		
Setup	Visual Key	Results (4 hrs)
• 4.4kg PCM • Cork insulation floor, crown board and walls. • 9 frames (bees, brood and honey) • No metal mesh floor		

	Temperature	Time
Maximum temperature at centre	38.1	04:02:30
Maximum PCM temperature	50.3	00:09:21
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	13.3	--
Total test time	--	04:04:57

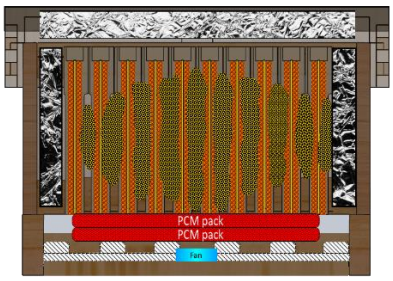
Graph



Comments

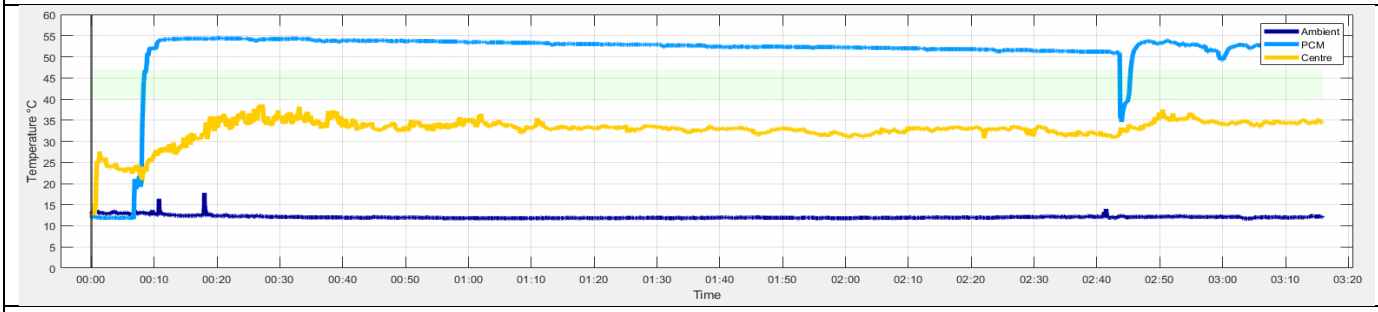
This experiment was a repetition of its equivalent in the previous date but with some improvements in its configuration and implementation, like a tighter insulation.

18/December/2020 – Lincoln

Setup	Visual Key	Results (3 hrs)
• 4.4kg PCM • Cork insulation floor, crown board and walls • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature	Time
Maximum temperature at centre	38.7	00:27:08
Maximum PCM temperature	54.4	00:21:13
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	12.0571	--
Total test time	--	03:15:53

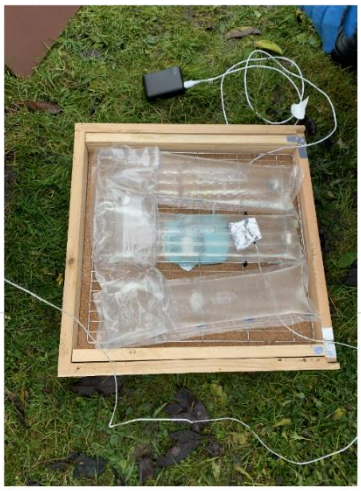
Graph



Comments

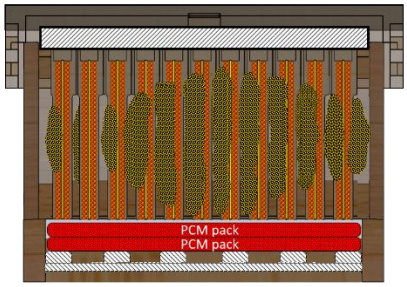
This experiment was a repetition of its equivalent in the previous date but with some improvements in its configuration and implementation such as a metallic grid for the bottom.



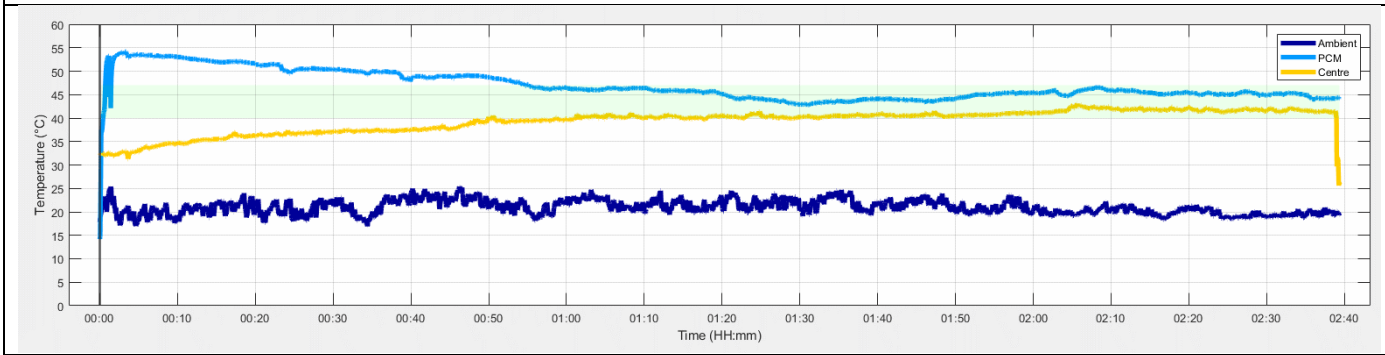


30/March/2021 – Risley

Setup	Visual Key	Results (2.5 hrs)
• 4.2kg PCM • Insulation floor and crown board • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	43.1	02:05:39
Maximum PCM temperature	54.2	00:03:21
Thermotherapy	Achieved	01:35:46
Average ambient temperature	21	--
Total test time	--	02:39:22

Graph



Comments

The first of picture taking and CO2 testing





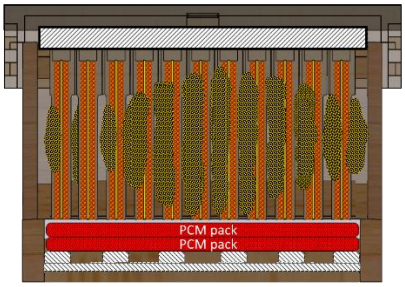


30/March/2021 – Risley

Setup

- 4.2kg PCM
- Insulation floor and crown board
- 11 frames (bees, brood and honey)
- No metal mesh floor

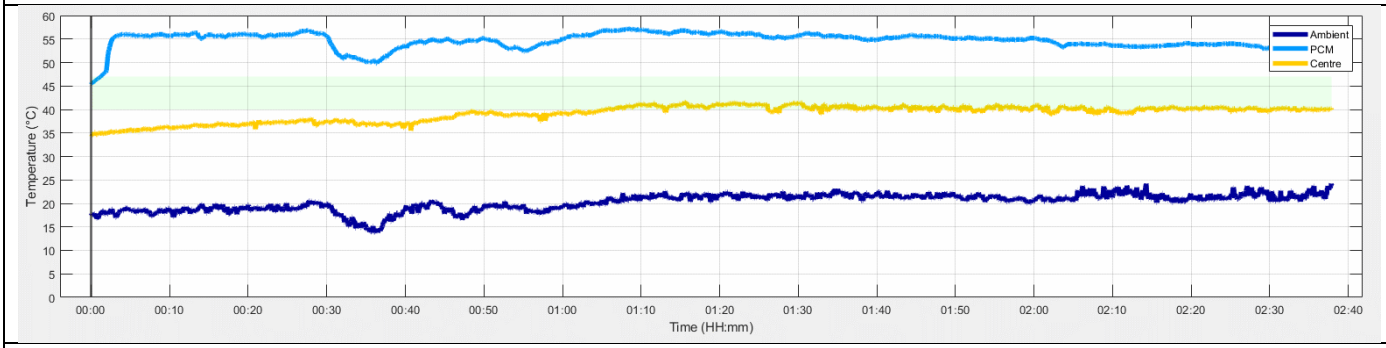
Visual Key



Results (2.5 hrs)

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.7	01:15:33
Maximum PCM temperature	57.2	01:08:34
Thermotherapy	Achieved	01:13:24
Average ambient temperature	20.2	--
Total test time	--	02:37:52

Graph

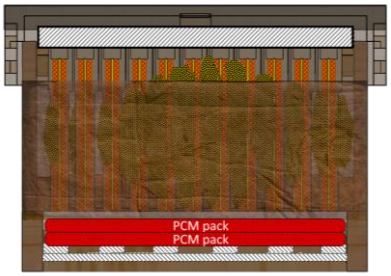


Comments



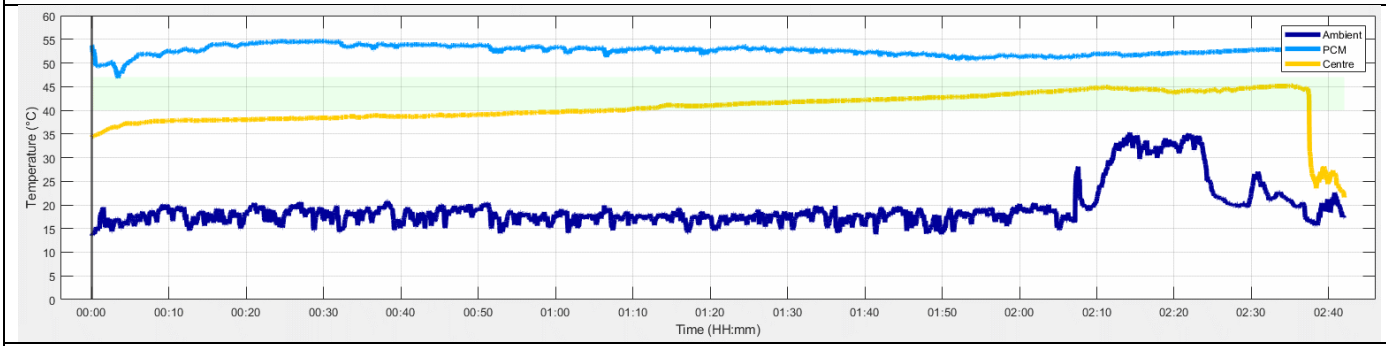




20/April/2021 – Lincoln		
Setup	Visual Key	Results (2.5 hrs)
• 4.2kg PCM • Insulation floor, crown board and woollen jacket over walls • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	45.2	02:35:20
Maximum PCM temperature	54.7	00:30:04
Thermotherapy	Achieved	01:30:38
Average ambient temperature	19.3	--
Total test time	--	02:42:01

Graph



Comments



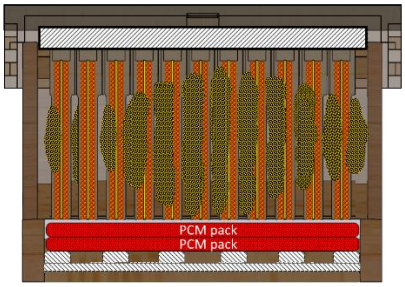






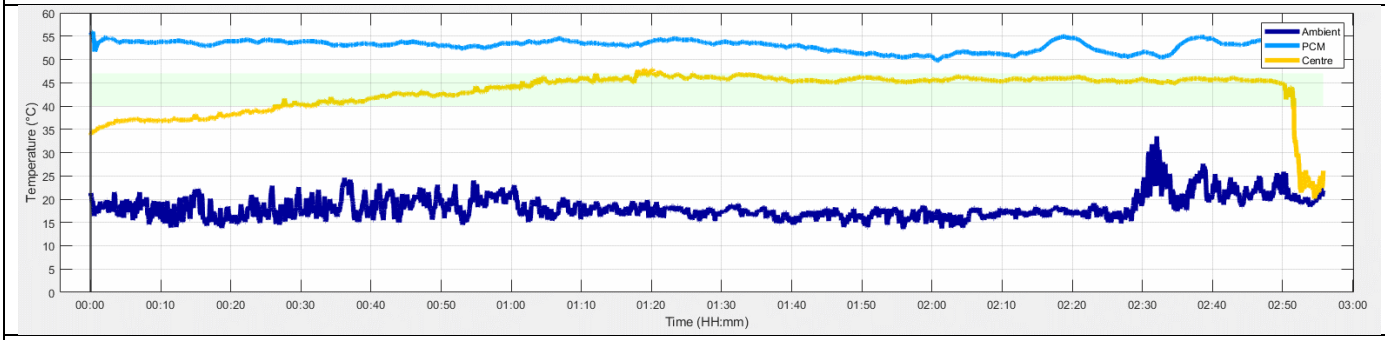


20/April/2021 – Lincoln

Setup	Visual Key	Results (3 hrs)
• 4.2kg PCM • Insulation floor and crown board • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	47.9	01:20:07
Maximum PCM temperature	56	00:00:12
Thermotherapy	Achieved	02:23:55
Average ambient temperature	18.2	--
Total test time	--	02:55:47

Graph



Comments



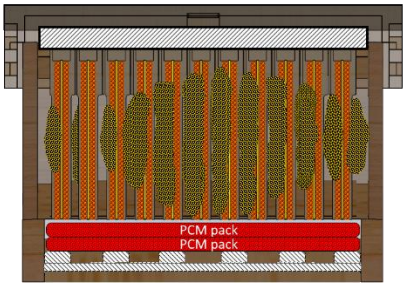






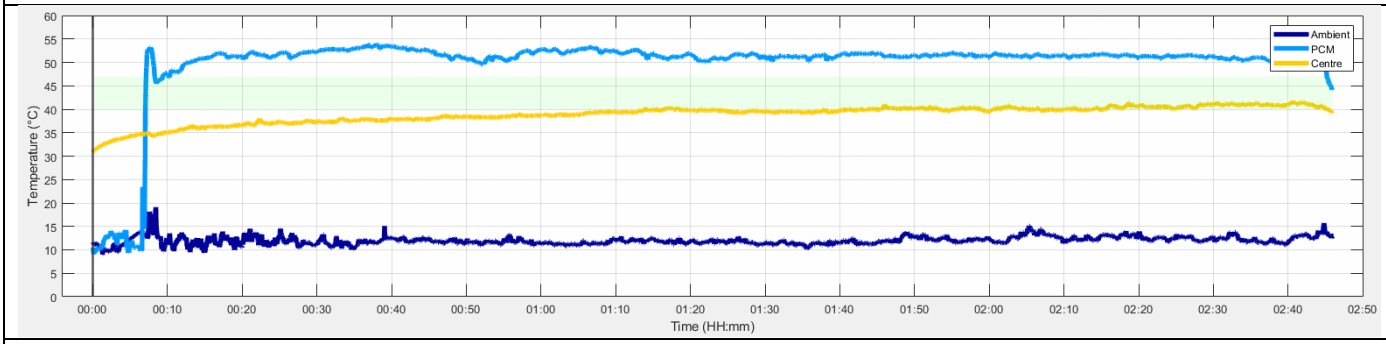


22/April/2021 – Risley

Setup	Visual Key	Results (2.5 hrs)
• 4.2kg PCM • Insulation floor and crown board • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	41.7	02:40:40
Maximum PCM temperature	53.8	00:38:16
Thermotherapy	Achieved	00:53:52
Average ambient temperature	12	--
Total test time	--	02:45:56

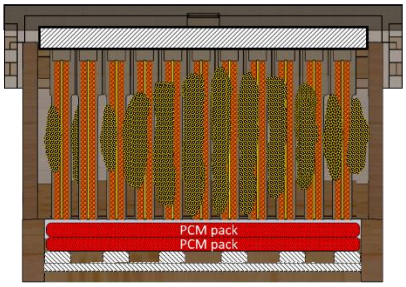
Graph



Comments

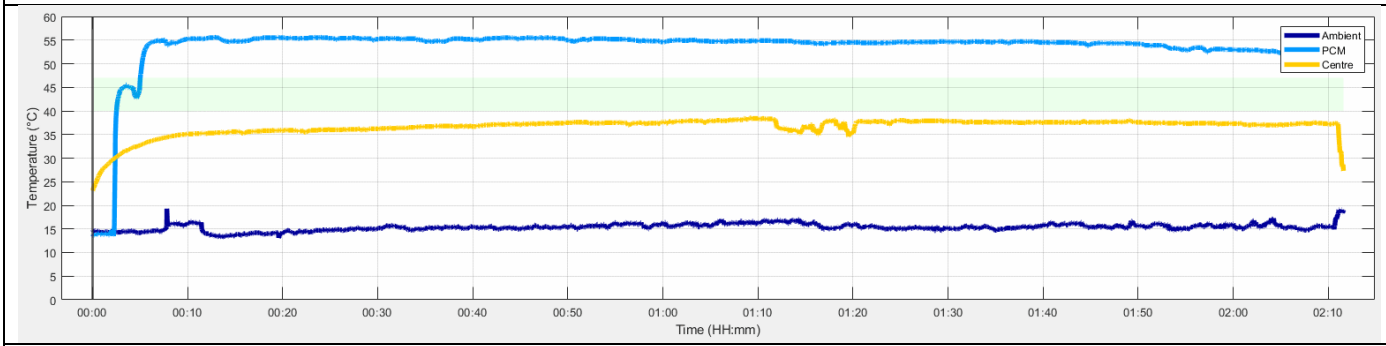




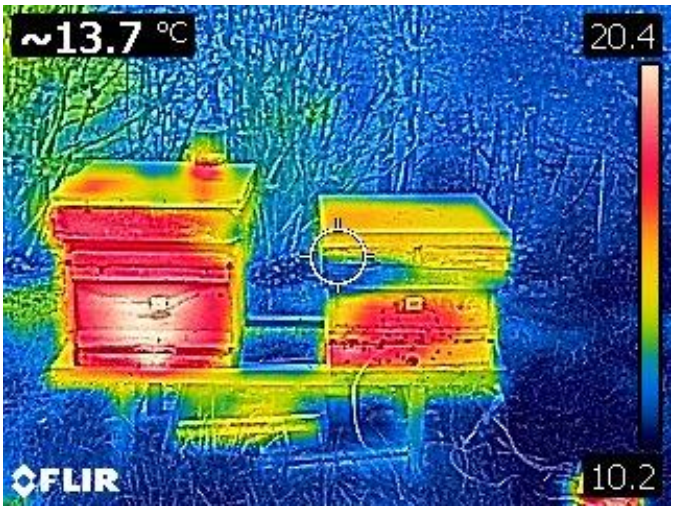
13/May/2021 – Risley		
Setup	Visual Key	Results (2 hrs)
• 4.2kg PCM • Insulation floor and crown board • 11 frames (bees, brood and honey) • No metal mesh floor		

	Temperature (°C)	Time (HH:mm:ss)
Maximum temperature at centre	38.6	01:09:12
Maximum PCM temperature	55.6	00:24:07
Thermotherapy	Not achieved	00:00:00
Average ambient temperature	15.4	--
Total test time	--	02:11:36

Graph



Comments





Appendix 4

Varroa counting

Standard procedures for BeeSave mass testing

In order to perform the mass test in a standard way and minimise the duration of the test, the following standard procedures are created for the testers to follow. The setup for the tested beehives is completed first and then data of the control beehive is captured.

Treated beehive

1. CO2 mite counter to establish the infestation level. This requires a sample of approximately 200 bees from the beehive;
2. Insert thermocouples into the beehive from the crown board and start the data logger. The probes can be inserted without removing the crownboard;
3. Place the PCM pack in the drawer and attach a thermocouple onto the surface of the PCM;
4. Activate the PCM and replace the existing beehive floor with the treatment floor that contains the PCM pack. This is a two-men job, with one lifting up the beehive and the other swapping the floor;
5. Leave the treatment for 2.5 hours, check the internal temperature ever 30 mins, or more frequently when possible. Normally, the broodbox remains completely closed during the treatment unless the temperature is above 41°C. In which case, the upper part of the drawer will be opened to allow fresh air to enter and some bees to exit.
6. When the treatment is done, swap the original floor back taking special care not to move it abruptly or in such a way that the Varroa mites on the PCM packs fall out;
7. Remove the thermocouples;
8. Take honey sample by filling the sample tube to 1/3. The sample should be taken using a sterile scalpel and gloves, preferably from the central frames;
9. Take photos of both sides of all the frames in the beehive. The order of the photos has to be the same as described in the Standard capture template document;

Control beehive

1. CO2 mite counter to establish the infestation level;
2. Take the honey sample by filling the sample tube to 1/3;
3. Take photos of both sides of all the frames in the beehive;

Data capture template for mass testing in Spring-Summer 2021

Template for treated beehive

Test location	Healthy Bees	Test date	30-march-2021
Outdoor temperature	21 °C	Weather conditions	Sunny
Beehive No.	21	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	2
No. of frames	11		
Treatment duration (hour)	1:35	Average achieved treatment temperature (℃)	41°C
No. of mite dropping after treatment	6	Other notes	The CO2 tank was faulty.

Template for control beehive

Test location	Healthy Bees	Test date	30-march-2021
Outdoor temperature	21 °C	Weather conditions	Sunny
Beehive No.	6	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	--
No. of frames	11		

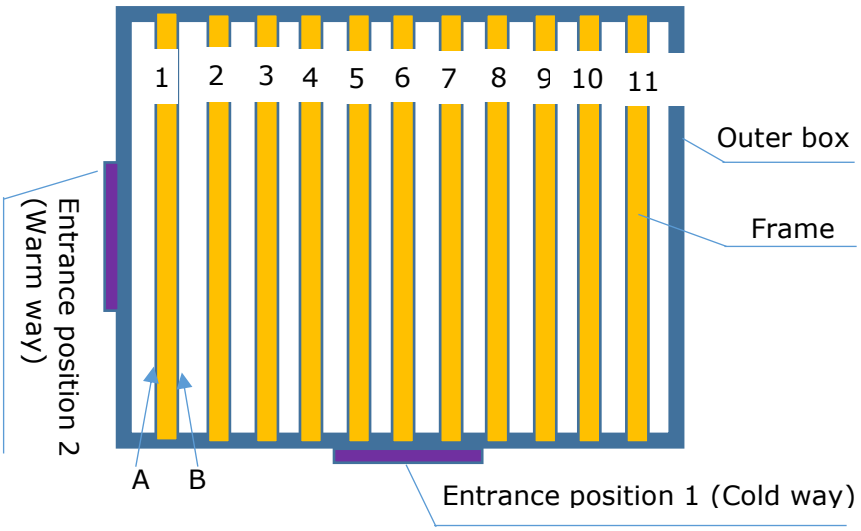


Figure 1 A standard numbering system in the top view of a beehive

Data capture template for mass testing in Spring-Summer 2021

Template for treated beehive

Test location	Healthy Bees	Test date	30-march-2021
Outdoor temperature	20.2 °C	Weather conditions	Sunny
Beehive No.	22	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	2
No. of frames	11		
Treatment duration (hour)	1:13	Average achieved treatment temperature (℃)	40°C
No. of mite dropping after treatment	1	Other notes	The floor fell off, so some mites could fall out.

Template for control beehive

Test location	Healthy Bees	Test date	30-march-2021
Outdoor temperature	20.2 °C	Weather conditions	Sunny
Beehive No.	12	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	--
No. of frames	11		

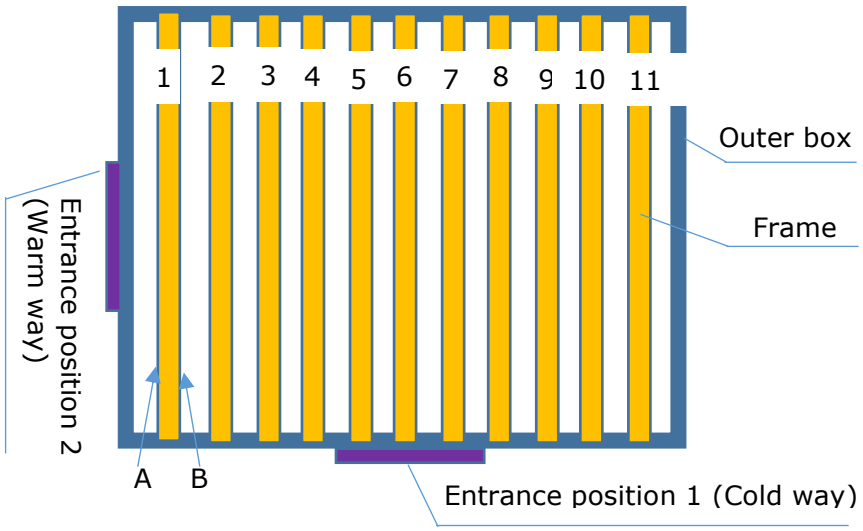


Figure 2 A standard numbering system in the top view of a beehive

Data capture template for mass testing in Spring-Summer 2021

Template for treated beehive

Test location	Thorne	Test date	20-april-2021
Outdoor temperature	18.2 °C	Weather conditions	Sunny
Beehive No.	A3	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	2
No. of frames	12		
Treatment duration (hour)	2:23	Average achieved treatment temperature (℃)	45°C
No. of mite dropping after treatment	17	Other notes	

Template for control beehive

Test location	Thorne	Test date	20-april-2021
Outdoor temperature	18.2 °C	Weather conditions	Sunny
Beehive No.	C4	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	3
No. of frames	12		

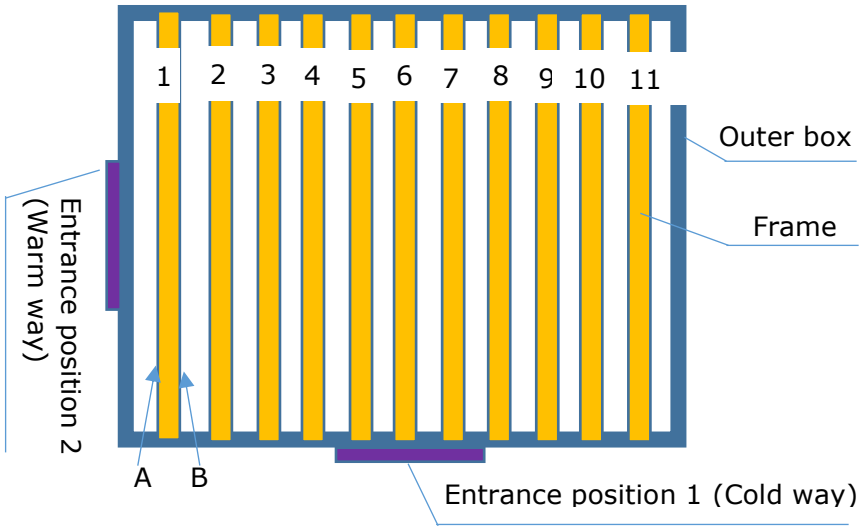


Figure 3 A standard numbering system in the top view of a beehive

Data capture template for mass testing in Spring-Summer 2021

Template for treated beehive

Test location	Thorne	Test date	20-april-2021
Outdoor temperature	19.3 °C	Weather conditions	Sunny
Beehive No.	1	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	2
No. of frames	12		
Treatment duration (hour)	1:30	Average achieved treatment temperature (℃)	42°C
No. of mite dropping after treatment	6	Other notes	

Template for control beehive

Test location	Thorne	Test date	20-april-2021
Outdoor temperature	19.3 °C	Weather conditions	Sunny
Beehive No.	2	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	3
No. of frames	12		

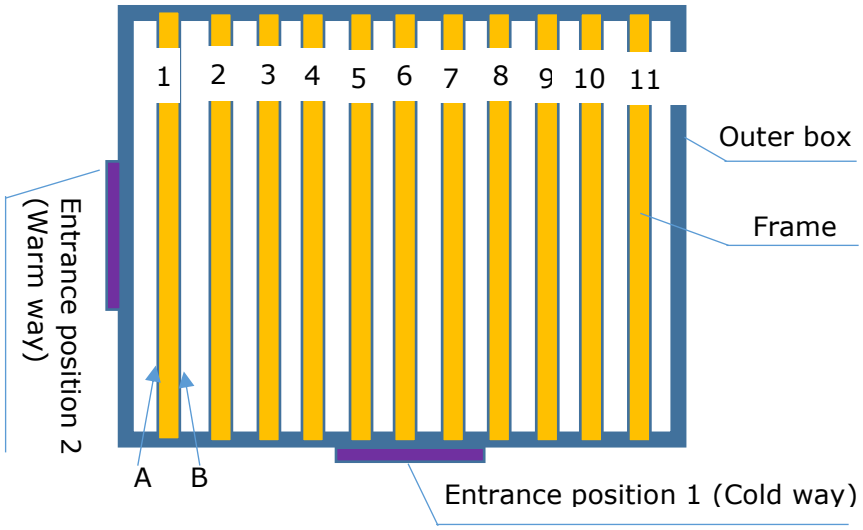


Figure 4 A standard numbering system in the top view of a beehive

Data capture template for mass testing in Spring-Summer 2021

Template for treated beehive

Test location	Healthy Bees	Test date	22-april-2021
Outdoor temperature	12 °C	Weather conditions	Sunny
Beehive No.	25	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	1
No. of frames	11		
Treatment duration (hour)	00:53	Average achieved treatment temperature (℃)	40°C
No. of mite dropping after treatment	17	Other notes	

Template for control beehive

Test location	Healthy Bees	Test date	22-april-2021
Outdoor temperature	12 °C	Weather conditions	Sunny
Beehive No.	45	Beehive type (warm way or cold way)	Cold way
Approx. colony size		Infestation level (CO2 mite counter)	1
No. of frames	11		

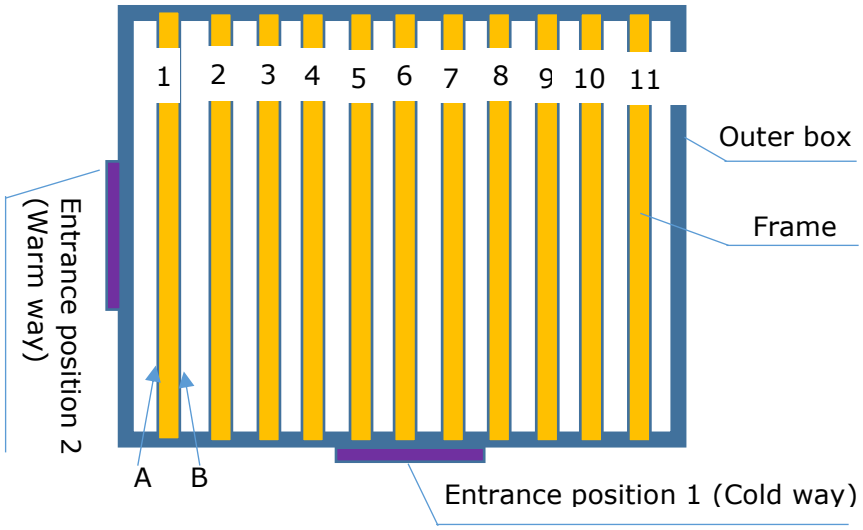


Figure 5 A standard numbering system in the top view of a beehive

Appendix 5

List of papers published

List of publications

Papers

Jarimi, H., Tapia-Brito, E., & Riffat, S. (2020). A Review on Thermoregulation Techniques in Honey Bees'(Apis Mellifera) Beehive Microclimate and Its Similarities to the Heating and Cooling Management in Buildings. *Future Cities and Environment*, *6*(1).

Conference proceedings

E.Tapia, S.Riffat, CFD simulation of a sustainable heat storage device suitable for thermotherapy in honeybees, 19th International Conference on Sustainable Energy Technologies, 16-18 August 2022, Istanbul, Turkey.

E.Tapia, H.Jarimi, S.Riffat, A review on green and sustainable technology in protecting honey bees against Varroa destructor, 18th International Conference on Sustainable Energy Technologies, 20-22 August 2019, Kuala Lumpur, Malaysia.

H.Jarimi, E.Tapia, S.Riffat, Thermoregulation Techniques in Honey Bees' (Apis Mellifera) Beehive Microclimate and its Similarities to our Buildings, 18th International Conference on Sustainable Energy Technologies, 20-22 August 2019, Kuala Lumpur, Malaysia.

Appendix 6

Poster

University of Nottingham
UK | CHINA | MALAYSIA

Preliminary laboratory tests for the application of PCM for honey bees treatment against *Varroa mite*

Emmanuel Tapia Brito
Supervisor: Saffa B. Riffat

1. Introduction

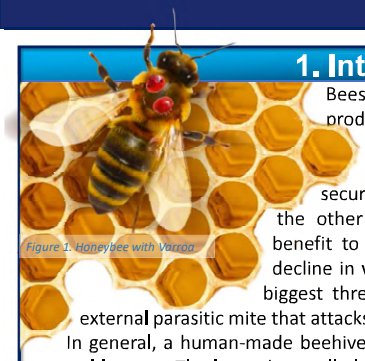


Figure 1. Honeybee with Varroa

Bees as pollinators are critically important for the production of vegetables and fruits, providing the first step in the flowering/fruiting process and thus having a significant role in food security. They are essential to flowering plants and the other wildlife, and provide considerable economic benefit to humans. However, there has been an overall decline in wild and honey bees[1]. In the UK, one of their biggest threats s the *Varroa destructor*. The Varroa is an external parasitic mite that attacks adult bees and their brood (Figure 1).

In general, a human-made beehive consists of rectangular wooden boxes without top and bottom. The lower box, called brood chamber, contains the brood area of the beehive on its frames (Figure 2). The focus of this application is the brood chamber of a National Beehive, particularly the central temperature, as there is the higher brood concentration.

The common methods to control Varroa mites mostly involve a chemical treatment which is potentially dangerous for bees and their products. Recently, it has been observed that applying temperatures between 40-47°C, Varroa can be killed[2]. However, that temperature is close to the lethal for bees.

In order to provide a sustainable, renewable and portable heat source, it was decided to innovate using a supercooled phase change material (PCM) that met the desired characteristics. By using a PCM, it is also possible to limit the maximum temperature to avoid harming the bees or their brood. The first stages of the development of this project are described below.

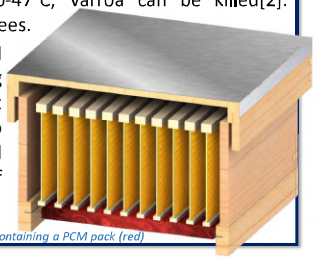


Figure 2. 3D model of National Beehive's brood box containing a PCM pack (red)

2. Objectives

- Select the PCM to obtain the desired temperature in the centre of the brood box.
- Calculate the required mass of the PCM considering the heat transfer.
- Find the optimal location and position of the PCM packs within the beehive, according to the availability of internal space in the brood box.
- Identify potential obstacles in the implementation of the PCM packs for thermotherapy.

3. Methodology

Energy balance

First, the box was modelled under steady-state condition to estimate the amount of PCM required to give the temperature increase in the middle of the beehive at the desired temperature (i.e. 40-47 °C) in 150 minutes. The simplified mathematical model developed is the following.

$$\frac{m_{pcm}L_{pcm}}{\Delta T} = h_{pcm_f}A_{pcm}(T_{pcm} - T_{beehive}) \quad \text{---①}$$

$$\frac{\rho_f C_f V_f}{\delta t} = h_{pcm_f}A_{pcm}(T_{pcm} - T_{beehive}) - U_l A_{beehive}(T_{beehive} - T_a) \quad \text{---②}$$

In this study, we have set T_{pcm} as 54 ˚C which is the average melting temperature of the selected material and $T_{beehive}$ as 45 ˚C which is the average maximum temperature that must be reached by the internal hive for the heat treatment method to become effective. The temperature distribution is shown in Figure 3. The latent heat L_{pcm} was set at 256 kJ/kg based on the literature. From the simple steady state analysis, the predicted amount of PCM required for heating duration of 150 minutes is 3.4 kg.

Laboratory testing

Later, several 2kg PCM packs (same concentrations) were manufactured for use in a beehive (without honeybees) instrumented with thermocouples under laboratory conditions. The packs were first placed in their position and then triggered so they released heat during nucleation.

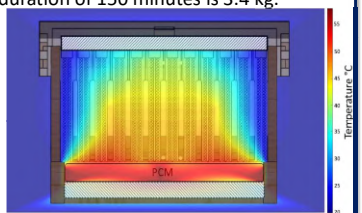
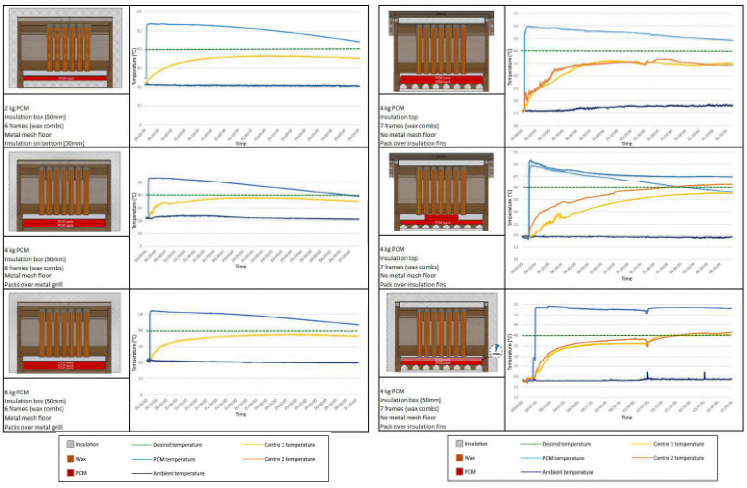


Figure 3. Theoretical distribution of temperature (steady-state) inside the brood chamber

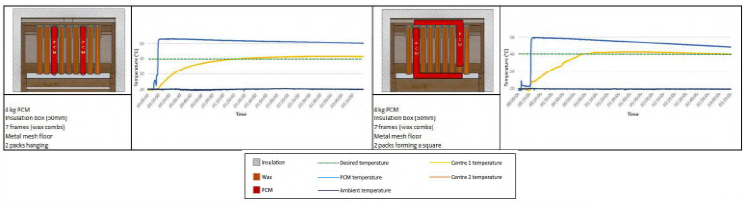
4. Results

In total, 60 experiments were carried out in laboratory. Different masses and positions of the PCM packs along with various configurations of the beehive were alternated in order to find the one that presented the best results. Furthermore, the tests helped to evaluate the possible obstacles at the time of their implementation in a real honeycomb. Below are some of the most representative cases in each category.

Mass **Configuration**



Position



5. Conclusions

- The use of PCM is promising to apply as heat source for the thermotherapy.
- In some tests the desired temperature was reached. However, some of those options were ruled out as being difficult to perform if bees were in the hive.
- It was observed that the horizontal position is the optimum.
- It is necessary to improve the heat transfer. For this, materials with better thermal conduction could be used. Another option is to increase the surface area of the packs.
- The distribution of the PCM can be improved. A way to concentrate the PCM in the centre can be find since there is where higher temperatures are most required.

6. Future work

In respect to the PCM packs, some improvements need to be done based on the conclusions of the presented tests. After the improvements, new tests in laboratory should be carried. The next stage of this project will involve the test in-site with bees and real conditions. The results of those experiments will determine the feasibility of the use of PCM for thermotherapy. It is important to do a transient mathematical modelling and CFD analysis that considers the internal components of the beehive including bees. This model can be validated with the experiments performed.

7. References

1. Potts, S.G., Roberts, S.P., Dean, R., Marris, G., Brown, M.A., Jones, R., Neumann, P. and Settele, J., (2010). Declines of managed honey bees and beekeepers in Europe. Journal of apicultural research, 49(1), pp.15-22.

2. Bičík, V., Vagera, J. and Sádovská, H., (2016). The effectiveness of thermotherapy in the elimination of Varroa destructor. Acta Musei Silesiae, Scientiae Naturales, 65(3), pp.263-269.

Acknowledgments: The author would like to thank Innovate UK's financial support through Newton Fund (Project reference no:105043) and CONACyT for their sponsorship for the realization of this project. I would also like to thank my academic supervisor Prof Saffa Riffat for providing me with this opportunity and support throughout this project.

Appendix 7

Press release

BeeSave turns up heat on parasitic varroa mite

By The Engineer 16th October 2020 12:02 am

Researchers at Nottingham University are developing BeeSave, an eco-friendly alternative to pesticides against the varroa mite, one of the biggest threats to honeybees in the UK.



Image by Suzanne D. Williams from Pixabay

BeeSave is a patented, self-heating pack, being promoted by Professor Saffa Riffat, Fellow of the European Academy of Sciences and President of the World Society of Sustainable Technologies and his research team at the University.

ChainStore takes thermal energy storage to the match

Subterranean roads could cut pollution and congestion levels in urban areas

Bees as pollinators are critically important to produce vegetables and fruits, providing the first step in the flowering/fruiting process. They are essential to flowering plants and the other wildlife and the loss of a small fraction of honeybees would damage the agricultural industries that depend on them and threaten to make food more expensive.

The drop in Britain's bee population has been exacerbated by the varroa mite, which is a parasite of Asian bees that transferred to European worker bees and has been reported in the UK honeybee population since 1992.

Varroa mites can feed and live on adult honeybees, but they mainly infest their larvae and pupae, causing malformations and killing off hives. The use of pesticides against varroa is potentially harmful to bees as well as their honey.

Thermal treatment is safer than any chemical alternative as the temperature required only affects the parasite at the cellular level and can be applied repeatedly without the parasite building resistance. However, the thermal method presents many challenges and complications in its application. Researchers at Nottingham University found a way to overcome these limitations by using phase change material packs (PCMs).

The BeeSave pack uses a supercooled PCM which releases heat at 42°C after being triggered by a small electric charge.

"The pack is similar to a hand warmer," Prof. Riffat told *The Engineer*. "If you heat a normal PCM – say wax – it goes into a liquid. The wax is then solidified after a short period of time as it loses heat to the surrounding room/environment. You cannot control the time you wish the wax to go back into a solid. The supercooled PCM remains liquid at room temperature, just like inside a very well insulated box. You can activate/solidify the supercooled PCM at any time when you need the heat."

He added that each BeeSave pack can be used over 100 times and that each pack can remain at 42°C for two hours or more.

"We can increase or decrease the time required by using more or less PCM," he said.

During the heat treatment, the PCM packs are inserted at the bottom boards of the beehives. Once there, they release heat and increase the temperature inside. According to the University, this technique has proven to be effective, resulting in the immediate drop of the varroa mite from the brood box to the floor of the beehive. Additional studies have demonstrated that the treatment is harmless to honey and larvae.

To develop the packs, Nottingham University worked with PCM Products Ltd as a project partner. Prof. Riffat and his team are now working beehive manufacturer EH Thorne Ltd to commercialise BeeSave packs.

Innovate UK provided £400,00 financial support for the BeeSave project.

Latest Articles

Comments (10)

Comments

- Valli Cawte 16th October 2020 at 9:23 pm

  Will the 42°C affect the wax or wax production?

  Reply Link Quote

- Philip 16th October 2020 at 9:26 pm

  I'm very interested in this ive just started bee keeping so anything new and to help sounds amazing. How much are these please.

  Reply Link Quote

- Professor Saffa Riffat 22nd October 2020 at 9:29 am

  No. The melting point of wax is about 68C.

  Reply Link Quote

- Professor Saffa Riffat 22nd October 2020 at 9:30 am

  The cost is about £10 per pack

  Reply Link Quote

- Saffa Riffat 22nd October 2020 at 9:34 am

  You can find more information about this work in http://www.wsset.org

  Reply Link Quote

- Professor Saffa Riffat 23rd October 2020 at 6:03 pm

  It has no impact.

  Reply Link Quote

- Professor Saffa Riffat 23rd October 2020 at 6:04 pm

  Safe to use

  Reply Link Quote

- Andy Coles 29th November 2020 at 11:27 am

  Where can these units be purchased?

  Reply Link Quote

- Peter 29th November 2020 at 2:20 pm

  Very interested in this. Any idea when it will become available commercially?

  Reply Link Quote

- Norman 7th March 2021 at 10:15 am

  Really interested in this. Could you let me know when it becomes available please

  Reply Link Quote

- Post a comment

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Appendix 8

Website layout



INNOVATIVE TECHNOLOGY

The thermal tolerance of Varroa mites and honeybees differs, with mites showing a much greater sensitivity to higher temperatures than honey bees. Research shows that mites can
be killed during all development stages if they are exposed to a specific temperatures range for ~ 150 minutes. These temperatures are safely tolerated by honey bee brood and adults and do not damage the honeycomb. Thus, heat treatment is seen as an effective method to control Varroa mites.

The innovative system is compact, robust and low cost and does not require electricity. The technology is highly portable and simple to use.



KEY INNOVATIONS

SUSTAINABLE

The BeeSave does not use any harmful chemicals, nor does it require any electricity to operate. The BeeSave is completely non-toxic and can be disposed of by simply throwing in the bin. However, that day will come after many rounds of successful Varroa mite treatments as the BeeSave is completely reusable. Just pop in a pan of boiling water and you're ready to go.

NON-CHEMICAL TREATMENT

The BeeSave uses heat in order to treat the bee hives for verroa mite infestations as opposed to current products on the market which use chemicals such as Oxalic Acid. This is very effective for terminating mites, but is also very good at killing the bees too. BeeSave is completely harmless to bees and deadly to the mites, showing no adverse effects to the hive.

ON-SITE / NON-INVASIVE APPLICATION

Most of beehives are located in remote areas. It is not easy to move a large number of bee frames/hives to another site to use thermal treatment and result in greater disturbance of bee activities. BeeSave does not require frames to be moved. All BeeSave-fitted hives in an apiary can be treated simultaneously, which has benefits in terms of convenience and time saving.

EASY TO USE

The BeeSave is easy to operate, simply click the metal disc located inside the pack. This will begin the reaction and heat will start to be generated. Slip the BeeSave into the drawer and wait for the hive to gradually warm and reach the correct temperature. When the treatment is complete, simply pop the BeeSave into a pan of boiling water for 10 - 15 minutes until the solution is melted again. You've now successfully recharged the BeeSave and you're good to go again!

POWERED BY weebly



BEHIND THE BEEHIVE

The development of this product was carried out by a consortium made up of world leading companies in their field working in conjunction with researchers from the University of Nottingham to make prototypes and do a large number of tests and experiments that led to the creation of the BeeSave.

MEET THE DEVELOPERS

POWERED BY weebly

Appendix 9

Treatment evaluation proposal

Introduction

The aim of this report is to review the work conducted by other researchers in thermotherapy method in terms of the experimental design and the effectiveness evaluation method. At the end of this report, two experimental designs for Beesave are proposed.

Experiment 1

Title	Solar hive Thermotherapy method
Ref	https://www.beehivethermalindustries.com/resources/studies/mite-elimination-thermotherapy-2015/
Key Objectives	• To kill Varroa distructor in sealed brood • To investigate the efficiency of thermotherapy compared to chemical drugs
Number of beehives	• 8 Beeehives • 4 for thermotherapy • 4 treated with chemical
Varroa Infestation method	• Natural- heavily infested hives. Determined by observing natural fallout. • 48 hours before treatment, the infested colonies transferred into thermosolar hive.
Season/period of treatment	• In the spring- before stacking honey chambers • In the simmer-before extracting the last honey
Experimental design/steps	**<u>Spring treatment</u>** **First treatment (day 1):** For the heat treatment hives: 1. If ambient temperature is low, close the entrance 2. Heat the hives at treatment temperature (40-47 degC) for 2 hours. 3. Check the dead broods or death of adult bees. 4. Every day, record the dead mites on the floor (for 7 days). For the control hives: 1. Apply the chemical method to the other 4 control colonies at the same time when the solar hives is heated. 2. The chemical removed after four days. 3. Every day, record the dead mites on the floor (for 7 days). **Second treatment (after 7 days from day 1):** Repeat the same methods above for both heat treated and control colonies. But this time, counting of the dead mites continue until 12 days after treatment. **<u>Summer treatment</u>** **First treatment (day 1):** For the heat treatment hives:

1. Take place at the end of August-after the honey supers removed.
2. Use the same 4 colonies from the previous heat treatment method and chemical treated method,
3. Open the hives entrance to avoid overheating
4. Heat the hives at treatment temperature (40-47 degC) for 2 hours.
5. Check the dead broods or death of adult bees.
6. Every day, record the dead mites on the floor (for 7 days).

For the control hives:

1. Apply the chemical method at the same time when the solar hives is heated.
2. The chemical removed after four days.
3. Every day, record the dead mites on the floor (for 7 days).

Second treatment (after 14 days from day 1):

Repeat the same methods above for both heat treated and control colonies.
But this time, counting of the dead mites continue until 12 days after treatment.

Winter treatment- only using chemical

Thermotherapy Effectiveness Evaluation

The effectiveness of the heat treatment method was evaluated by comparing the number of fallout mites between the two set of beehives:

$$\eta_{eff\_thermo} = \frac{n_{mites\_thermo}}{n_{mites\_control}}$$

Experiment 2

Title	Second experiment on thermosolar hive
Ref	
Key Objectives	• To investigate the effectiveness of thermotherapy method
Number of beehives	• 5 thermo solar hives
Varroa Infestation method	• 5 heavily infested frames with mites- indicated by a natural fallout of two or more mites per day-monitored at the floorboard
Season/period of treatment	Spring and Summer
Experimental design/steps	1. 3 sealed brood combs from different hives that are heavily infested placed in the super of the thermosolar hive. **Bees were brushed off.** 2. Heated for 150 mins at 40-47 degC 3. After heating, the combs were removed and placed into a bag of dense solid mesh and moved into the brood chamber in the ordinary hives the originally taken. 4. After all broods have emerged (after about 14 days) dead bees and mites were calculated from the bottom of the bag. 5. Using the same colony o the same day, apply fumigation using Varidol- after 2 hours, count how many dead mites=n_{mites}. Additional observation: 1. Monitor bee mortality until day 14 after treatment. 2. Visible deformation of the combs (right after heat treatment) 3. Inspect brood combs and honey combs- the virgin and post brood combs **How to count number of dead bees?** Count how many brood cells altoghether for one frame n_{brood}. Count the number of frames. Calculate the mean numbers of bees hatched, n_{totql}.
Thermotherapy Effectiveness Evaluation	The effectiveness of thermotherapy method $= \frac{n_{mites\cdot}}{n_{mites\cdot}+n_{varidol\cdot}}$

Experiment 3

Title	Hyperthermia a non-chemical control strategy against Varroa (use heater)
Ref	Goras, G. (2015). "Hyperthermia -a non-chemical control strategy against varroa." Journal of the Hellenic Veterinary Medical Society **66**: 249-256.
Key Objectives	To treat honey bees using thermotherapy method against Varroa mites
Number of beehives	• 27 colonies of one storey hives with 10 frames in brood chamber (5-8 with broods)
Varroa Infestation method	N/A- assumed natural occurring
Season/period of treatment	Not mentioned but treated during night time
Experimental design/steps	1. The device temperature was adjusted to 42°C and the thermal treatment was applied on 27 complete bee colonies for a time range of 12 to 480 minutes. 2. The duration in particular was 12, 20, 30, 40, 60, 120, 240, 360 and 480 minutes.
	To count dead mites from beehives (n_heat_beehive): 1. After each treatment the varroa in the bottom drawer was counted as well. 2. The counting-every day until the 7th day 3. Using the same colonies, on the 7th day, apply chemical method. 4. Then count how many dead mites on the floor and inside the cells. 5. Count how many dead mites on the floor. 6. To find whether varroa mites that fell in the bottom drawer after the treatment were dead, irreversibly hurt or alive they were placed in a petri dish inside an incubator, set on 35°C along with bee larvae' and they were checked for the next two days. 7. The total number of Varroa(n_tot_beehive) = the number of dead mites after applying chemical(n_chemical) + the number of dead mites due to heat treatment (n_heat_beehive)
	To count dead mites from the brood cells (n_heat_bc): • Right after treatment, 300 brood cells from three different combs of each colony were uncapped and the state of the mites in the cells was recorded (dead or alive). • Total number of mites(n_tot_bc)= mites that were still alive after treatment (n_alive)+ dead mites (n_heat_bcc)
Additional observation	• Counting dead bees in front of the hive and also by marking 100 brood cells from each colony and following their development. • Bees' behavior (aggressiveness), queen replacement and the overall development of the bee colonies treated with hyperthermia were recorded
Thermotherapy Effectiveness Evaluation	The efficacy of the hyperthermia was estimated as =(*n_mites_therm*)/ (n_tot_beehive) And =(n_heat_bc)/ (n_tot_bc)

Experiment 4

Title	Final report for LNE96-066
Ref	https://projects.sare.org/project-reports/lne96-066/
Key Objectives	32 colonies were monitored over the course of a year-to observe the health and productivity of heat treated colonies relative to a control group. Parameters being monitored: Symptoms of disease, brood levels, Varroa mites and honey productions
Number of beehives	• 32 beehives • 16 infested • 16 control colonies
Varroa Infestation method	However, for the purpose of efficiency study on 4 hives were selected Infest the colonies from donor colonies that had been infested for two years and exhibited symptoms of deformed wing
Season/period of treatment	Spring and fall
Experimental design/steps	1. Only 4 colonies were selected. 2. Bees are shaken, brushed and/or blown from the hives frames into the heat-treatment cage via a large funnel and thus transferred into the 'cabinet' for heating up to 47 degrees Celsius (116.6˚ F). 3. The actual heating can take less than 15 minutes per hive while the handling of the bees can take twice as long. 4. Count how many mites fall during the heat treatment. 5. After heat treatment, the bees returned to an empty hives free from broods and mites-no bees allowed to enter and leave. 6. Immediately apply Apiston- and count how many mites fall in 8-14 days.
Additional observation	• The winter survival of the heat treated colonies was observed. • The health and honey productions following first summer of spring heat treatments.
Thermotherapy Effectiveness Evaluation	• The efficiency= no of mites fall during heat treatment/no of mites fall during heat treatment+ after apply chemical

Experiment 5

Title	Toxicity of Selected Acaricides to Honey Bees (Apis mellifera) and Varroa (Varroa destructor Anderson and Trueman) and Their Use in Controlling Varroa within Honey Bee Colonies. Gregorc A[1,2], Alburaki M[3], Sampson B[4], Knight PR[5], Adamczyk J[6].
Key Objectives	To investigate the efficacies of various chemical to control Varroa mites in the lab and in the field (the focus in the report)
Number of beehives	• 4 beehives for each chemical treatment and 4 control beehives. • The experimental colonies were queen-right, fully developed and housed in 10-frame Langstroth deep hive boxes. • The colonies occupied 6-8 brood combs
Varroa Infestation method	• Natural infestation method
Season/period of treatment	• End of summer and early autumn
Experimental design/steps	1. Place corrugated board to capture dead Varroa 2. Wire screens were installed above the boards to prevent bees from coming into contact with dead mites 3. The overall duration- 31 May to 21 September at 3 – 4 days interval 4. The pre treatment natural Varroa count- the first 7 of sampling dates before treatment 5. The first treatment-19 July - sugar shake1 -count number of mites on the floor 6. The second treatment – 18 August- sugar shake2 -count number of mites on the floor)+CheckMite® 7. Sugar shake3 – to check the effectiveness of chemical treatment
How to estimate the mites	Sugar shake diagnostic method prior to and after treatments. All sugar shake methods involve 100 bees. 1. half fill the bucket with clean water 2. place a heaped tablespoon of icing sugar into the jar after removing 3. light a smoker and open a hive to be tested 4. shake some bees from three combs containing honey bee brood onto a double thickness of newspaper or upturned hive lid placed on the ground. If brood is not present, shake bees from one comb taken from the centre of the cluster of bees. If you find the queen on these combs, place her back into the hive 5. scoop or pour about 300 bees (half a cup) into the jar. Place the lid on the jar to prevent bees from escaping 6. gently rotate the jar for 2 minutes ensuring all bees are dusted with sugar. Wait 2-3 minutes, and rotate the jar a second time for 2 minutes. Be careful not to lose any sugar. (The hive may be reassembled during this waiting period) 7. gently shake the icing sugar (and any mites) through the holes in the lid into the bucket half filled with water. The sugar will dissolve and any mites will float on the surface of the water. Do the shaking in a sheltered position protected from strong wind that could blow mites away 8. release the bees from the jar onto the ground close to the hive entrance in case the queen is present.

The effectiveness evaluation	• Use data and statistical analyses • The Varroa counts were log-10 transformed. ANOVA and Tukey HSD in R-environment. • The sugar shake before and after treatment to measure Varroa infestation, and the cumulative varroa mortalities.

BeeSave draft experimental design 1

Key Objectives

- To kill Varroa destructor in sealed brood and worker bees
- To investigate the efficiency of thermotherapy compared to chemical drugs

Number of beehives

- 4 heat treated beehives
- 4 control beehives

Varroa Infestation method

- Natural- heavily infested hives. Determined by observing natural fallout.?? Check with Beekepers

Season/period of treatment

- In the spring- before stacking honey chambers
- In the early autumn-before extracting the last honey
- Additional benefit of our project is we can apply the treatment during the summer when the honey supers are on.

Experimental design/steps

<u>Spring treatment (18 March??)</u>

First treatment (day 1):

1. If ambient temperature is low (Ta at average of 25 degC and below), close the entrance.
2. Trigger the PCM packs and leave for 2 hours and a half.
3. Check the dead broods or death of adult bees.
4. Every day, record the dead mites on the floor (for 7 days).

For the control hives (spring only):

1. Apply the chemical method to the other 4 control colonies at the same time when Beesave is operated.
2. Every day, record the dead mites on the floor (for 7 days).

Second treatment (after 7 days from day 1):

Repeat the same methods above for both heat treated and control colonies.
But this time, counting of the dead mites continue until 12 days after treatment.

<u>Summer treatment (optional) (18 June??)</u>

1. Use the same 4 colonies from the previous heat treatment method and chemical treated method,
2. Open the hives entrance to avoid overheating
3. Trigger the heat packs and leave for 3 hours.
4. Remove the PCM pack.
5. Check the dead broods or death of adult bees by examining the floor board.
6. Record the dead mites on the floor (for 7 days).

Second treatment (after 7 days from day 1):

Repeat the same methods above. But this time, counting of the dead mites continue until 12 days after treatment.

Please note that, chemical method for the control hives is not possible when honey supers are on.

Autumn treatment or End of Summer??

First treatment (day 1):

For the heat treatment hives:

1. Take place at the end of August-after the honey supers removed.
2. Use the same 4 colonies from the previous heat treatment method and chemical treated method,
3. Open the hives entrance to avoid overheating
4. Trigger the heat packs and leave for 3 hours.
5. Remove the PCM pack.
6. Check the dead broods or death of adult bees by examining the floor board.
7. Record the dead mites on the floor (for 7 days).

For the control hives:

1. Apply the chemical method at the same time when the solar hives is heated.
2. The chemical removed after four days.
3. Every day, record the dead mites on the floor (for 7 days).

Second treatment (after 7 days from day 1):

Repeat the same methods above for both heat treated and control colonies.
But this time, counting of the dead mites continue until 14 days after treatment.

Additional observation:

1. Monitor bee mortality until day 14 after treatment.
2. Visible deformation of the combs (right after heat treatment)
3. Inspect brood combs and honey combs- the virgin and post brood combs
4. Inspect the honey quality and health.—Using honeybee complete??

Thermotherapy Effectiveness Evaluation

The effectiveness of the heat treatment method was evaluated by comparing the number of fallout mites between the two set of beehives for the total of three treatments for heat treatment method and two treatments for the：

$$\eta_{eff\_thermo} = \frac{n_{mites\_thermo}}{n_{mites\_control}}$$

A detail data and statistical analysis using ANOVA etc.,

BeeSave draft experimental design 2

Key Objectives	• To kill Varroa distructor in sealed brood and worker bees • To investigate the efficiency of thermotherapy compared to chemical drugs
Number of beehives	• 5 infested beehives
Varroa Infestation method	• Natural- heavily infested hives. Determined by observing natural fallout. Check with Beekepers
Season/period of treatment	• In the spring- before stacking honey chambers • In the early autumn-before extracting the last honey • Additional benefit of our project is we can apply the treatment during the summer when the honey super are on.
Experimental design/step	**Spring and Autumn treatment** 1. Trigger the PCM packs and heat for 3 hours. 2. After heating, count the number of dead mites on the floor board every day for 14 days. 3. After all broods have emerged (after about 14 days) dead bees and mites were calculated again from the bottom of the bag. 4. Using the same colony on the same day (day 14), apply fumigation using chemicals after 2 hours, count how many dead mites=$n_{mites\cdot}$. 5. Inspect honey production Additional observation: 5. Monitor bee mortality until day 14 after treatment. 6. Visible deformation of the combs (right after heat treatment) 7. Inspect brood combs and honey combs- the virgin and post brood combs 8. Inspect the honey quality and health.—Using honeybee complete
Thermotherapy Effectiveness Evaluation	The effectiveness of thermotherapy method $= \frac{n_{mites\cdot}}{n_{mites\cdot}+n_{chem\cdot}}$

Appendix 10

Route to market

Route to market

Statistics shows that in 2020, there were about 94 million beehives worldwide, increasing from 93.5 million beehives in the previous year.[1] The EU numbers approximately 600,000 beekeepers and 16 million hives according to 2016 data reported by the Member States in the European parliament. With Varroa being a widespread issue and resulting in wiping out nearly the entire population of wild honeybees with almost all honey bees now belonging to domesticated bee hives.

The outcome of this research has the potential to develop into a successful product capable of entering the market for Varroa mite therapies on honeybees. Once the market has been established fully within the UK it would be the next step to enter the global market via either mass production here in the UK or more likely to manufacture the system through license to prevent the impact of shipping costs being passed on to the end consumer to maximise sales.

Short Term (Year 1)

In the first year, the most critical step in turning this prototype into a product is more testing at the appropriate seasons. Some of the studies conducted throughout the preparation of this thesis occurred during the winter, and as previously stated, further successful field trials are necessary to prove the product's efficiency. Moreover, it is critical to perform additional study on temperature management methods. Because regarding of hyperthermia, beekeepers frequently worry about overheating and consequent death of bees.

After optimising the two preceding points, the next step would be to apply for a patent in thermotherapy utilising PCM. As demonstrated throughout this thesis, this is a novel concept, so it would need to be protected in order to be marketed. Then a licence agreement, a joint venture, or even an independent business might be established. Later on, the concept might be expanded to encompass a variety of other types of beehives and materials. The prototype developed here was created for a National Standard beehive, but there are various types of beehives and also beehives constructed of other materials (e.g. polystyrene or plastic), which means that more testing would need to be conducted to scale the PCM packs to each type of beehive.

Additionally, a survey of prospective beekeepers evaluating the product's pricing should be conducted to assure its profitability. The product may be given away to trustworthy and reputable purchasers for feedback.

Manufacturing facilities must be set up at this level. Government assistance (Countryside Productivity Small Grants) may be solicited if necessary.

After completing the preceding steps, it will be necessary to create a brand, packaging, and instructions for the product. To connect with clients, a website and presence on social media, in beekeeping journals, and at related events would be useful. The objective for the first year would be to capture 1% of the UK market share.

[1] M. Shahbandeh, "Beehive numbers worldwide 2010-2020", Statista (2022).

Medium Term (Years 2 – 4)

This is the time to review the supply chain and focus on fixed pricing. Additionally, staff must be trained.

Once this is finished, the product should be launch, ideally at a beekeeping exhibition, particularly the National Honey Show, the largest event in the United Kingdom. Afterwards, exhibitions and open days should continue to be attended. Live demonstrations could even be done. The aim for this period is to capture market share of 5% within UK.

Long Term (Year 5 onwards)

After five years, the panorama becomes less clear. However, advertising at Apimondia, the bi-annual beekeeping convention, can be envisaged. Licence agreements with third-party companies such as Vetopharma or Vita are also a possibility.

This is the stage at which the product's variety might be expanded by adapting the PCM pack to different sizes of beehives thoroughly tested. The aim by this time would be to capture market share of 10% within UK and 5% of EU.

Financial Analysis

When all considerations are taken into account, such as labour expenses, treatment costs, and the necessity for recurrent treatments, an estimate of £15 per colony on a small scale is a reasonable estimate. For the 264,000 bee colonies in the UK, this results an estimated market of £3.6 million annually, with an assumption that 90% of the bee colonies use chemical treatment. The product derived from this research can reduce the use of chemicals within the beekeeping community and capitalize on this market share.

Product pricing

The PCM pack designed can be integrated into existing National beehives, it is estimated a design to cost of £60 per beehive and for it to operate for over 10 years. A single treatment unit can be used with any number of beehives due to its capacity to be rechargeable. The final product can be supplied as either a starter kit, which may include the PCM heat pack, test floor and crown board or alternatively the PCM pack can be purchased separately. This technology can be used to treat apiaries with more than one hive by simply resetting the PCM pack, the option to buy more than one pack will enable beekeepers to treat more than one beehive without having to reheat the pack. The target is at least 1% of the bee colonies market in the UK within the first 2 years after project end creating a revenue of £150k - £300k annually.

Figure A3 depicts a comparative examination of one chemical treatment, four state of the art heat treatments, and the product generated as a result of this investigation (in the graph it was named "BeeSave").

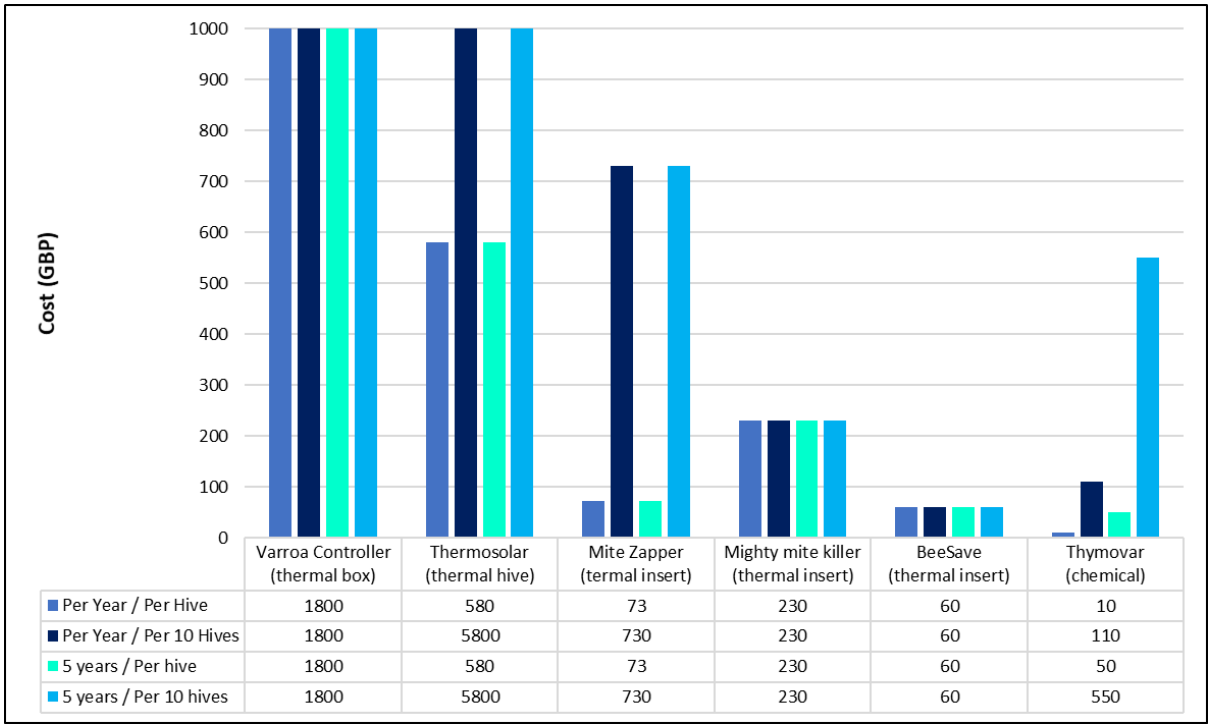
As can be seen, a thermal box treatment like the Varroa Controller can provide service to several beehives for several years but the devices are very expensive. A thermal hive, like the Thermosolar hive, is not only expensive per unit, but because it is a beehive, it can only treat one colony at a time, implying that many of these specialised beehives would be required to treat each colony in an apiary, increasing the cost to extremely high levels.

On the other hand, while the initial cost of thermal insert treatments such as the MiteZapper may be minimal, the cost quickly multiplies as additional beehives are treated. These treatments appear to be economical per unit in the short term, but their cost grows according to the number of beehives to be treated.

Some thermal treatments, like the Mighty Mite Killer, offer the benefit of treating between one and ten beehives with a single device that has a lifespan of five or more years. However, the initial investment is substantial.

Chemical treatment is now the most extensively used approach, which, as previously explained, is extremely toxic to bees, humans who consume their products, and even the plants they fertilise. It is, nonetheless, the most popular due to its inexpensive price. At least that appears to be the case, as while the yearly cost is fairly cheap, the medium and long term costs are significantly higher than those associated with heat therapy. For this kind of products, the costs are twice or tripled, as the therapy must be repeated throughout the year.

Concerning the product produced as a result of this study ("BeeSave" on the graph), it has a cheap starting cost and a relatively lengthy usable time. Various PCM packs and add-on kits can be purchased for less the price of any other heat treatment.



	Varroa Controller (thermal box)	Thermosolar (thermal hive)	Mite Zapper (termal insert)	Mighty mite killer (thermal insert)	BeeSave (thermal insert)	Thymovar (chemical)
Per Year / Per Hive	1800	580	73	230	60	10
Per Year / Per 10 Hives	1800	5800	730	230	60	110
5 years / Per hive	1800	580	73	230	60	50
5 years / Per 10 hives	1800	5800	730	230	60	550

Figure A3 Price comparison between anti-Varroa treatments.

Sales and revenue forecast

Sales forecasts for this product are shown in Table A1, which covers the next five years.

Table A1 Sales forecast for 5 years.

	Year 1	*Year 2*	*Year 3*	*Year 4*	*Year 5*
Number of items sold	2640	5000	10000	15000	25000
Item cost (GBP)	£60.00	£60.00	£60.00	£65.00	£65.00
Revenue (GBP)	**£158,400**	**£300,000**	**£600,000**	**£975,000**	**£1,625,000**
Cost of sale (GBP)	£36.00	£35.00	£34.00	£33.00	£32.00
Gross profit (GBP)	£63,360	£125,000	£260,000	£480,000	£825,000
Gross profit (%)	0.4	0.42	0.43	0.49	0.51
Marketing costs	£10,000	£5,000	£7,500	£7,500	£10,000
R&D costs	£20,000	£5,000	£5,000	£5,000	£5,000
Other costs	£20,000	£36,000	£100,000	£80,000	£100,000
EBIT (GBP)	£13,360	£79,000	£147,000	£387,000	£710,000
EBIT (%)	21%	63%	57%	81%	86%
Taxes (GBP)	£2,538.40	£15,010.00	£28,025	£73,625.00	£134,900.00
Net profit (GBP)	£10,821.60	£63,990.00	£119,475.00	£313,875.00	£575,100.00
Cumulative net profit	£10,821.60	£74,811.60	£194,286.60	£508,161.60	£1,083,261.60
New employees	1	2	3	4	5

The graph shown in Figure A4 shows the revenue projection made. It is expected that in the first year there will be an approximate revenue of £ 158,400 and following a standard growth curve it is estimated that for the fifth year the revenue could be close to £ 1,625,000.

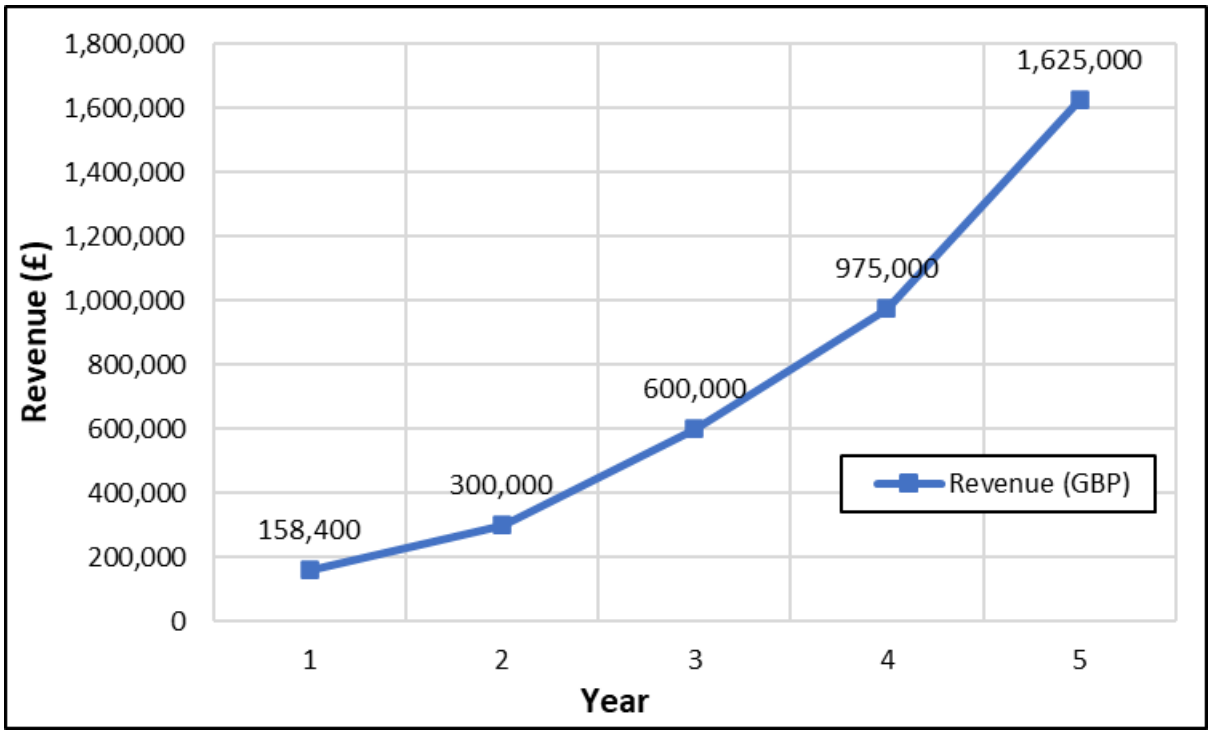


Figure A4 Forecasted Revenue (GBP).