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Design and Experimental Assessment of a Minaret Integrated Passive Cooling System Performance for Mosque Buildings in Hot and Dry Climates

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Abstract

Energy efficiency and conservation in the building is becoming the focus in many countries. In countries with hot climatic conditions, space cooling in buildings consumes a large amount of fossil fuels derived energy with a negative environmental impact. Compared with other public buildings, Mosques are characterized by high consumption of energy per person. To reduce energy consumption for space cooling in buildings and provide human comfort, evaporative cooling technologies have been applied in many places of the world using different techniques and materials. For example, the applications of porous ceramics materials with evaporative cooling have been recently researched as a novel idea in this field. The aim of this research project is to determine the most effective form of the passive cooling of water evaporation in mosques in the hot, dry climate of the Kingdom of Saudi Arabia KSA.

Part of this research, will be using Design builder software to perform simulation on a case study for a typical mosque building in KSA to demonstrate that the energy saving strategies as passive cooling was applied to reduce cooling load. The result shows the full potential for exploiting design and construction features for improving environmental and energy performance of existing mosque buildings, The reduction of building cooling load in various locations in the KSA including Hail, Dhahran and Abha comes to about 37%, 30% and 40%, respectively compared to an uninsulated unshaded typical base case mosque building.

In this research, the design and integration of an evaporative cooling system into the envelope of a mosque, specifically the minaret, has been conducted, highlighting the construction forms, the purpose and location of various aspects of the mosque, and the evolving function of the minaret in modern mosques. Hence, the proposed design considers the cooler configuration, and the cooling specification of the building, together with the construction materials of both porous ceramic and synthetic materials in the form of grass mats. The ceramic

materials are compatible with integration into the structure of the minaret, while the synthetic material offers a modular design and flexibility for integration in the structure. The investigated cool minaret tower concept is intended to operate on the principle of sub-wet bulb temperature in which the air is cooled and supplied into the occupied space without increasing its moisture. The thermal performance of the proof-of-concept minaret prototype was evaluated in the laboratory under controlled climatic conditions. The cooling minaret tower was operated in three modes of evaporative cooling: in terms of Direct Evaporative Cooling (DEC), Indirect Evaporative Cooling (IEC), and Dew Point Evaporative Cooling (DPEC).The three modes allowed for the adaptation of the cooling performance, according to the prevailing weather conditions.

The findings of the experimental study of the thermal performance of the synthetic fiber grass mats for all three modes revealed an overall positive trend in terms of the physical principles of evaporating cooling as a favorable cooling mechanism at a high inlet air temperature and low humidity levels. It was found that the drop in temperature for the current three modes under similar various operating conditions, varied from 5.7-12.9, 5.2-10.2, and 5.1-10.3 ^{o}C for direct, indirect and dew point modes respectively. Moreover, with higher humidity air supply the cooling power and wet bulb effectiveness decrease. Increase in inlet dry air temperature leads to an increase in either effectiveness or air supply temperature. The DEC mode system achieved 20% better temperature drops than other indirect evaporative cooling modes. However, this might not be considered a significant difference if it fails to satisfy the cooling requirements of the space as effectively as the IEC does. Finally, evaporative cooling achieves cooling through displacement ventilation which is considered to provide a healthier indoor environment for worshippers in mosque. Further research could extend the concept of 'cool minaret' even by test the performance of different size and types of synthetic grass, different air gap channels and improving the flat rear materials of the matting to enhance its mass transfer surface as well as using computational fluids dynamics for model analyses of the synthetic grass materials within different building elements.

Publications

- Sultan Alfraidi, Rabah Boukhanouf and Aasem Alabdullatief. **COOL MINARET: A FUNCTIONAL ELEMENT OF PASSIVE COOLING FOR MOSQUES IN HOT-ARID CLIMATES.** Proceedings of the First International Conference on Mosque Architecture I December 2016

- Aasem Alabdullatief, Siddig Omer, Rami Zein Elabdein and Sultan Alfraidi. **GREEN ROOF AND LOUVERS SHADING FOR SUSTAINABLE MOSQUE BUILDINGS IN RIYADH, SAUDI ARABIA.** Proceedings of the First International Conference on Mosque Architecture I December 2016

- Omar E Amer,*, Rabah Boukhanouf, Sultan Alfraidi. **Building's evaporative air-cooling by means of heat pipes and porous ceramic tubes.** 16th International Conference on Sustainable Energy Technologies – SET 2017

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Nomenclature

Abbreviations

COP	Coefficient of performance
DEC	Direct evaporative cooler
DP	Dew point
DPT	Dew point temperature
IEC	Indirect evaporative cooler
IDEC	Combined indirect and direct evaporative cooler
DPEC	Dew Point Evaporative Cooler
WBT-IEC	Wet-bulb temperature indirect evaporative cooler
WBT	Wet-bulb temperature
DBT	Dry-bulb temperature
PDEC	passive downdraft evaporative cooling
PDC	Passive downdraft cooling
KSA	Kingdom of Saudi Arabia
UK	United Kingdom
DB	Design Builder
RH	relative humidity
IAQ	internal air quality
SBS	Sick Building Syndrome
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
KACST	King Abdul-Aziz City for Science and Technology
SCECO	Saudi Consolidated Electric Company
NPL	Natural pressure level

Nomenclature

A	Surface area, m^2
A_1	Total area of a finned heat pipe, $m2$
mi	Mass flow rate, kgs
T	Temperature, ℃
t	Time, sec
V	Air volumetric flow rate, m3s
$\Delta\rho$	density difference of the inner channel and the surrounding air
g	gravity acceleration
h_e	effective elevation of the column

Greek symbols:

ρ	Air density, kgm3⁄
ν	Kinematic viscosity of air, $m^2s⁄$
λ	Thermal conductivity, $Wm\ K⁄$
ε	Effectiveness
T_{in}	Inlet temperature
Ts	supply temperature
T_{wb}	Inlet wet-bulb temperature
Q_C	cooling capacity

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Chapter 1. Introduction

1.1. Background

Energy consumption trends are generally influenced by local climatic conditions and culture, and the local government's energy policies. The climatic conditions often have a direct impact on the energy consumption within buildings. In many countries, building regulations and construction standards establish a minimum requirement for energy consumption, using the specific U-values or R-values of the building envelope, and the energy efficiency of the energy products and services. The current drive of the energy sector is to achieve energy sustainability, and to reduce ever-increasing carbon emissions, through the construction of low energy buildings. The building sector worldwide contributes nearly 40% of the total energy consumption (Cao et al., 2016), and the equivalent of 33% of the carbon emitted into the environment (Chau et al., 2015).

The Kingdom of Saudi Arabia (KSA) has an overall capacity to produce 44,485 MW of electricity, using oil and natural gas. Oil contributes to 57% of the power production, whereas gas produces 43% (SEC, 2014). The main source of income for the KSA is the export of oil from its oil reserves. The country is a high energy consumer, and therefore contributes a high rate of pollution, caused by the release of carbon dioxide into the atmosphere. This high rate of consumption can be attributed to the country's hot climate, and

the resulting use of air conditioning cooling systems (Taleb and Sharples, 2011).

In economically developing countries, such as the KSA, there has been a sharp rise in energy consumption over the last 20 years (Al-Ajlan et al., 2006), an increase that is attributed to rapid economic growth, and the lack of suitable policies implementing energy conservation measures. Although the KSA is blessed with vast reserves of fossil fuels that account for the bulk of its exports, its domestic energy consumption is increasing at an annual average rate of approximately 6%, stimulated by the county's economic expansion, rising population, and low, subsidised energy tariffs. The country's electrical power generation is expected to increase to 120 GW, from the current level of approximately 60 GW by 2030 (Al-Ajlan et al., 2006), in part driven by the high demand for space air-conditioning in buildings in the hot summer months (Hagihara, 2013).

Public and institutional buildings in particular account for around 13.4% of the building sector's total energy consumption. This project focuses on mosques, which are characterized by a high consumption of energy per person, compared with other public buildings (Al-Homoud et al., 2005). Modern mosques are often equipped with mechanical air conditioning systems, to ensure the provision of a comfortable environment for worshippers. Moreover, mosques are unique in respect of their distinct times of operation, as they are open to worshippers at five separate times each day, throughout the year, and have a high occupancy rate for approximately an hour during each of these prayer sessions. The sustainable architectural design of mosques, in terms of addressing the high energy demands of these

buildings, coupled with ways in which to integrate passive cooling techniques to lower the energy use of their air-conditioning systems by as much as 82% (Abideen (1996), is therefore a matter of current contemplation in many parts of the world (Azmi and Kandar, 2019).

In hot, dry climates, such as that prevailing in a large area of the Middle East, energy intensive air conditioning systems can be substituted with energy-efficient, passive cooling systems. Indeed, for many centuries, space cooling in buildings in this regions, including in the KSA, employed traditional evaporative cooling methods to keep buildings cool in the soaring summer temperatures. Compared with vapour-compression air-conditioning, evaporative cooling systems saving around 75% of energy (Alharbi et al., 2014), and reduce carbon emission to the atmosphere by as much as 44%. However, the cooling performance of evaporative cooling systems is reliant on variations in the ambient temperature and humidity, and its application is therefore restricted to regions with hot, dry climates.

Evaporative cooling systems operate on the principle that when a liquid (water) evaporates, it removes sensible heat from the surrounding air, thereby reducing its temperature, but simultaneously increases the air humidity. A number of evaporative cooling configurations have been developed, including direct, indirect, and dew point evaporative cooling systems. The Direct Evaporative Cooling (DEC) system is a simple arrangement of a wet pad and a fan circulating air through it, which is also known as a swamp cooler. Meanwhile, Indirect Evaporative Cooling (IEC) systems allow the air to be cooled indirectly through a heat exchange surface, without adding moisture into the supply air. Currently, the

most promising evaporative cooling technology is the Dew Point Evaporative Cooler (DPEC), which is capable of cooling the ambient air below its sub-wet bulb temperature, without adding moisture to the supply air.

The aim of this research project is to determine the most effective form of the passive cooling of water evaporation in mosques for the hot, dry climate of the KSA. The project also aims to integrate the cooling technology of evaporation with the mosque's minaret, thereby extending its function from an aesthetic building feature to an environmentally active element by using the top opening of a minaret which can be employed to capture and channel fresh air from outside the building into the occupied space below, in the form of passive cooling. This traditional architectural design technique, known as a windcatchers, which has been practiced in the Middle East for centuries.

Current research regarding evaporative cooling concentrates on developing technological processes and cooling performance improvement. However, there are few examples concerning the integration of evaporative cooling into the building envelope, and those that do exist are restricted to DEC. Therefore, this research project seeks to extend the field of evaporative cooling application in buildings by investigating the adaptation of DPEC for the minarets of mosques. The material used as the wet media for holding the water, and forming the wet air channels, which occupied the middle section of the minaret. Such an integration necessitates combining the concept of windcatchers and evaporative cooling as an integral passive cooling concept. The structure of a minaret is highly suited

to playing an important role in energy efficient and passive cooling, and the overall aim of this project is therefore to adapt the minaret as a multi-functional element of the building, including serving as a passive air cooler, using an integrated windcatcher/evaporative cooling system.

1.2. Aim and objectives

The main aim of this research project is to develop a new concept of a 'cool minaret' for mosque buildings, by combining the concept of the windcatcher and passive evaporative cooling to cool the indoor space of the mosque, with a low energy consumption. Some of the challenges of the project include optimizing and adapting to the structure, materials, and geometrical size of minarets in order to create an effective windcatcher and air cooler. The specific objectives of this research project are:

- To evaluate and develop a typical mosque In terms of the comfort level of worshippers, the cooling load, and energy consumption and how they relate to the building's envelope;

- To design and analyse minaret configuration to incorporate an evaporative cooling system;

- To select evaporative cooling system materials that are suitable for integration in this context;

- To assess and test the material effectiveness

1.3. Methodology

The objectives of this research project will be addressed as follows:

i) A thorough and extensive literature review of passive cooling methods, natural ventilation system cooling loads, and approaches to thermal comfort will be conducted;

ii) The energy consumption in mosques will be evaluated using a computer simulation of the thermal performance where to validate the simulation data by comparing with an actual electricity bill of 12 months of select case study buildings. The software, Design Builder plugin engine by Energy-Plus will be employed to predict the energy consumption, and environmental performance, and to evaluate the passive cooling techniques, and energy efficiency targets;

iii) The concept of a 'cool minaret' will be developed by studying variants such as geometrical configurations, airflow patterns, and materials;

iv) An experimental prototype of a laboratory rig will be constructed and tested. The test rig will be fully instrumented, and the test procedure will be defined to include aspects such as measuring the cooling loads, the ambient and supply air temperatures, the humidity, and flow rates.

1.4. Novelty and contribution to knowledge

The core concept of an integrated 'cool minaret' in a mosque building is novel in itself. The concept seeks to address the important issue of energy consumption in buildings, the thermal comfort within them, and their impact on the environment. The project advances knowledge in the field of the design of windcatchers or towers, passive cooling techniques, and material compatibility. The latter is considered to be crucial for improving the performance of evaporative cooling systems, including their operation life, and minimizing the health risks associated with the technology. The project considers two types of wet media materials: porous ceramics and a synthetic grass material in the form of a woven mat, which will be tested for their performance.

The ultimate contribution of this project will be to provide a healthy indoor environment for worshippers in mosque at a low environmental impact.

1.5. Thesis structure

This thesis is divided into seven chapters.
Chapter 1 briefly introduces the wider context of the research, in terms of the importance of energy conservation in buildings, and establishes the aims and objectives, and research methodology of the present study, and its contribution to current knowledge.

Chapter 2 reviews the concept of the elements of a building envelope, specifically thermal insulation, natural ventilation, building form,

orientation, and shade, and their contribution to reducing energy consumption. In addition, the cooling concept of evaporative cooling technologies is explained and reviewed in detail, including their structure, materials, working principles, and the merits and demerits of such systems.

Chapter 3 presents an investigation and discussion of a case study, evaluating the energy consumption of a typical mosque in various climates in the KSA (Hail, Abha, and Dhahran). The model of the mosque in question was built in Design-builder, taking into consideration the actual monthly electricity bills, and application of various energy saving techniques for improving and reducing the cooling load.

Chapter 4 discusses how the wet media of evaporative cooling can be designed and integrated into a minaret, in the mosque's envelope, and details the proposed usage of the minaret of a contemporary mosque for this purpose, together with discussing its use and location, and construction form. It also seeks to address how a minaret can be used in place of a passive air cooler by utilizing an internal evaporative cooling system in the form of a windcatcher.

Chapter 5 discusses the experimental work conducted using a laboratory-scale unit of the cooling system suggested by this project, including details of the experimental setup, the fabrication process, the cooler's parts, and the test procedure, together with relevant schematic photographs and diagrams.

Chapter 6 analyses and discusses the outcomes of the experiments and the projected data, including a consideration of, and comparison with, the extant research in the fields of DPEC, IEC, and DEC.

Chapter 7 discusses the research findings and the primary aspects of the new passive cooling system proposed by this study, and its weak aspects, together with recommendations for future work.

Chapter 2. Review of passive cooling strategies

2.1. Background

In appropriate architectural designs, the cooling load of buildings can be reduced by curtailing direct heat conduction and solar gain through the envelope. Summer heat, in particular, imposes the most thermal stress on the envelope of buildings in hot regions. The climatic design of a building should therefore address its summer performance issues, and a reduction in the indoor temperature should be the primary focus of the design, alongside enabling adequate natural ventilation, when it is prudent. In addition, some of the regions that experience hot summers also have cold winters, and it therefore important that the winter performance of buildings in such regions is also considered (Givoni, 1994).

Besides mechanical improvements employing small powered fans or pumps (hybrid cooling), the natural processes of heat transfer by convection, conduction, radiation, and evaporation (natural cooling) can be employed to achieve the required heat rejection to the heat sinks. According to Santamouris and Asimakopoulos (1996), during summer season, cooling plans should be designed according to the following three levels, in order that overheating is prevented, and thermal comfort preconditions in the interior of buildings are promoted:

- Adjustment of heat gains;

- Inhibition of heat gains in the building;
- Rejection of heat to heat sinks from the interior of the building (hybrid or natural cooling).

The following sections discuss the architectural design attributes that can benefit the reduction of cooling loads in buildings, without the deployment of mechanical systems.

2.2. Building orientation

The easiest approach for achieving thermal comfort in a building is the consideration of its orientation, or passive solar design, at the initial stage of the design process, in order to avoid the necessity for the additional inclusion of mechanical equipment to promote cooling (Morrissey et al., 2011). According to Bekkouche et al. (2011) and Hamdani et al. (2012), positioning a house in an appropriate direction is a central principle of architectural design. Such matters of directional alignment are of key significance in regions with a harsh climate, where considerable variations in temperature are generally the norm (Bekkouche et al., 2011). In regions where the temperature is well above the average temperature for thermal comfort, the cooling load is significantly affected (Krüger et al., 2010b). According to Haase and Amato (2009), the solar radiation to which the surfaces of a building will be exposed can be determined by its orientation, together with climate factors. However, Hamdani et al. (2012) claimed that the performance of a building is not greatly affected by its orientation, and that the most suitable method for achieving desirable temperature results is to consider thermal insulation and shading devices as depicted in Figure 2.1.

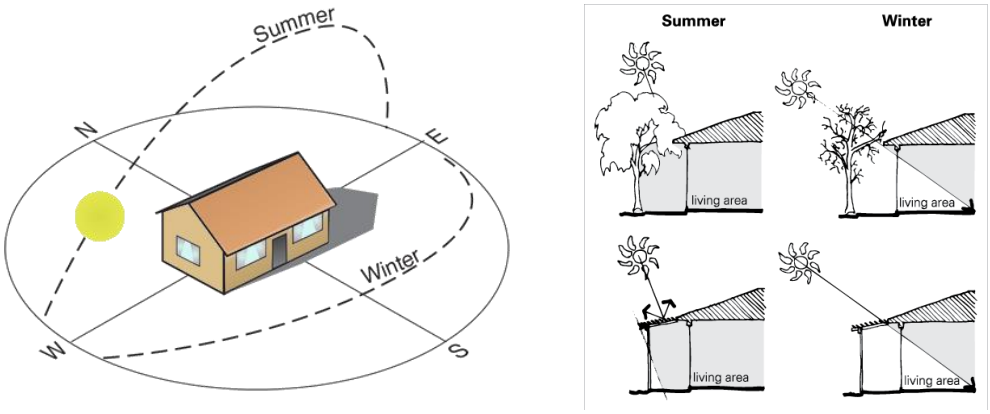


Figure 2.1 Orientation considerations for controlling exposure to solar radiation. Source: (Gromicko, 2014).

Nevertheless, Olgyay (2015) argued that a building's alignment should correspond directly to the local climatic conditions, in order that the maximum benefits from natural heating and cooling are exploited, thereby aligning the building's design with the local climate. The precise location of both the interior and the exterior spaces is determined by the shape of a building, and the position of the sun and prevailing wind direction, with different climates potentially requiring different combinations of outdoor spaces in building. In addition, the positioning of sustainable buildings that rely on passive lighting, cooling, and heating are also reliant on the local climatic conditions (Iyengar, 2015).

2.2.1. Building shape

In the design of a green building, the key factor that should be considered is its shape, owing to its substantial impact on the energy consumption and energy performance of the building (Ma et al., 2006). In addition, according to Lomas (2007) and Okeil (2010),

ventilation in a building is dependent on, and its success determined by, the building's shape, as this impacts on how the air movement inside and around the building is controlled.

In suitable building design for structures in hot dry, and hot humid regions, the natural ventilation, or air-conditioning mechanisms, are connected, as the cooling load and the heat gain on the cooling equipment can be reduced if the building is compact, with a minimum envelope surface area corresponding to the occupied space. However, a very compact shape is not the ideal design for a building designed to have maximum natural ventilation to reduce the need for air conditioning. The features of a specific optimal shape differ to some extent in hot humid and hot dry temperatures in this particular case (Santamouris and Asimakopoulos, 1996)

Significant differences in the total energy consumption of buildings in such regions are dependent on the total area of their envelope, and the total area of their external walls. Due to the significant differences between the indoor and outdoor temperature, external walls are one of the most important aspects affecting heat loss and gain. Moreover, the upsurge in the use of glazing has increased the degree of heat exchange with the outdoor environment. This fact was argued by AlAnzi et al. (2009), who claimed that there is a strong correlation between glazing and the form of a building.

Another method that utilizes a building's form for achieving energy saving is known as 'self-shading'. As illustrated in Figure 2.2, the cross section of a building can be increased to incorporate extra shading. This technique is useful in very hot conditions, as it

manipulates the high angle of the sun in summer, in order that the direct solar gain is reduced by the building itself. Nevertheless, self-shading is believed to possess limited applications, and in harsh condition, is only effective in the early morning and late afternoon (Capeluto, 2003).

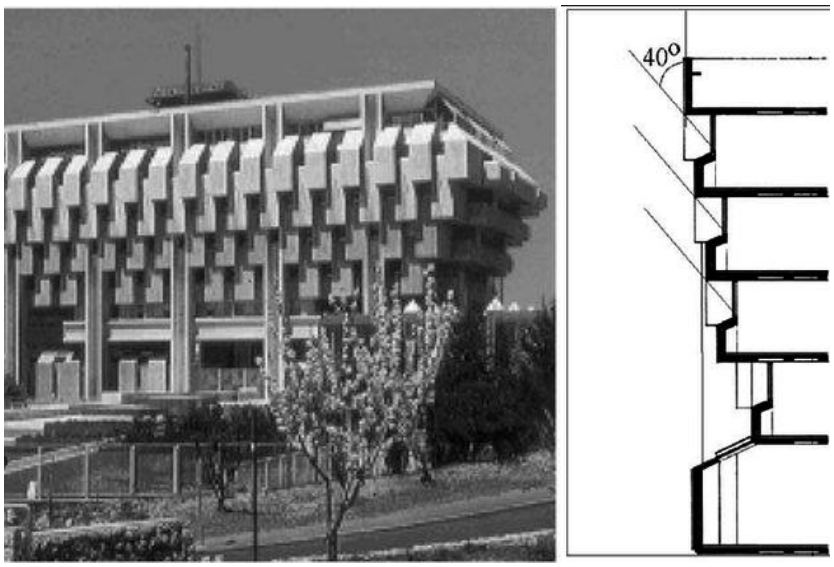


Figure 2.2 Building view and a cross section showing a self-shading design. Source: (Capeluto, 2003).

2.2.2. Building envelope

The components of a building, such as the windows, walls, floors, skylights, roof, and other features through which the living space is protected from the elements are referred to as the 'building envelope'. Certain supplementary facilities, for instance, shielding a building's structure from challenging climate conditions, blocking outside noise, and improving indoor air quality, are the services delivered by an effective building envelope. Presently, cooling or heating systems can be economized, or can be exchanged for low-energy substitutes, for the purpose of saving energy when using

passive thermal control, and buildings can also be adequately sealed to achieve this purpose (Iyengar, 2015). In addition to the operating period of a cooling system in summer, the factor that has the greatest effect on the total energy consumption of a building is the building envelope (Fang et al., 2014).

The interior climate conditions are determined by the envelope, which dictates whether the heating and cooling mechanisms demand more or less energy. There can be both positive and negative impacts on particular energy requirements, and other conditions can be determined by the actions of the elements originating in a building's envelope. As a result, evaluating the functioning and operation of a building as one is essential (Radhi, 2008).

The success of the steps taken to improve a building envelope's thermal performance is dependent on the type of building and its use. Residential buildings with a low window to wall ratio can have reduced energy demands, specifically in terms of heating, if an optimum level of insulation is employed in the building's façade (Lollini et al., 2006). However, the same approach is not suitable for buildings with a primarily glass façade, which is usually the case in commercial office buildings (Radhi, 2008). For such buildings, improvement in the U-value does not include a decrease in the outside heating gain, although the thermal performance can be improved by the type of glazing employed.

- **Walls**

Walls are the primary feature of a building's envelope, and should provide acoustic and thermal comfort, without compromising the building's aesthetics. One significant element of walls is their thermal resistance (R-value), since it strongly affects the building's energy consumption, particularly in high-rise buildings that have a high ratio between their walls and the total area of their envelope. The impact of thermal insulation is assessed according to the clear wall R-values, and the centre-of-cavity R-values, although this does not take into account factors such as the impact of the framing factor, and the interface links (Kosny et al., 2006).

In thermally insulated walls, the potential for surface condensation is greater if there is more than 80% relative humidity (RH) in the ambient air, given the small radiative and convective heat transfer coefficients of the exterior wall. This problem increases during the winter, and especially in regions with a cold climate and high levels of humidity (Aelenei and Henriques, 2008). When such moisture condensation occurs on the exterior walls of a building, it causes detrimental microbial growth that can engender the reduction of the wall's life, and also cause other adverse conditions for the building. The materials normally employed in a building's construction include different kinds of walling materials, such as masonry-based, metal-based, and wood-based. Meanwhile, other kinds of modern building wall design also exist that have been developed to improve comfort levels and energy efficiency, including double skin walls, passive solar walls, walls with latent heat storage, and Lightweight-Wood-Concrete walls.

- **Windows**

One of the significant loads that impacts on the cooling and heating energy utilization of buildings is the load entering through the building's envelope, particularly its windows and skylights. The cooling loads involved are overshadowed by the solar gains obtained through the windows, and the use of outside air for lighting loads and ventilation is also significant.

The presence of glazing within window apertures constitutes a thermally poor system that causes considerable heat loss and gain that can affect the overall energy consumption (Sadineni et al., 2011). Glazing is also considered to constitute a weak link between the outdoor and indoor environment. In terms of heating, 10 to 25% of heat loss is due to windows, whilst in terms of cooling, the heat penetrating glass can result in considerable heat gain, depending on the outdoor temperature (Pacheco et al., 2012). However, although glazing is more fragile than other opaque construction materials, windows can also assist in determining the solar gain admitted, and can be utilized for providing ventilation. Hence, a valuable area of study might concern an assessment of the impact of heat transmittance, the thermal bridging via glazing, and the direct solar gain (Ben-Nakhi, 2002).

As evidenced, windows and glazing are of considerable significance when modelling buildings for determining their thermal comfort and total energy consumption (Pal et al., 2009), and can promote the saving of a substantial amount of energy (Pacheco et al., 2012). Moreover, the window to wall ratio area can have a significant effect

on energy saving, in terms of the heating and cooling within buildings. This effect is due to the kind of glazing employed, since certain kinds of glazing, such as hollow glazing, or low-hollow glazing, have more impact than others. As the window to wall ratio increases, so too does the solar heat gain. Heat exchange also increases according to the heat transfer coefficient, since windows generally have a larger area than solid walls (Su and Zhang, 2010).

- **Roof**

Another significant element of a building's envelope that is extremely prone to solar radiation, and other changes in the environment, are roofs, which can impact on the indoor comfort conditions. Roofs are responsible for a considerable amount of heat gain and loss, particularly in buildings with a large roof area, such as auditoriums, sports complexes, and exhibition halls. According to building regulations in the United Kingdom (UK), in 1965, 1976, and 1985, the upper U-value limits for flat roofs were 1.42W/m^2 K, 0.6W/m^2 K, and 0.35W/m^2 K, respectively, while currently, all new buildings in the UK are required to have values of 0.25W/m^2 K or less (Gaffin et al., 2005). The importance of the thermal performance of roofs for improving the total thermal performance of buildings is indicated in this decrease in the U-value, over time.

Certain passive cooling methods can be applied in tropical climates through changes in roof architecture, since a small cellular roof layout has little solar exposure, and differs from mechanically or naturally ventilated roofs, domed and vaulted roofs, high roofs, micro-ventilated roofs, and double roofs. Approaches that have gained in

popularity include white-washed external roof surfaces that reduce their solar absorptivity; the use of high thermal capacity materials, such as concrete, to reduce the peak load demands; and roofs covered with vegetation to provide shade and humidity. One method of decreasing the effect of solar radiation on the surface of a roof is roof shading, using local materials such as hay, terracotta tiles, inverted earthen pots, and date palm branches to achieve economical roof shading. All of these methods can help to achieve around a 6 °C decrease in the indoor temperature (Chen et al., 2015), Another method that can be employed to reduce the effect of solar radiation on a roof is the use of roof coatings, while day- and night-time factors that determine the kind of roof coating include high solar reflectance and high emissivity, respectively. It is not appropriate to employ aluminium-pigmented coating, due to its low infrared emissions. However, the surface temperature of a white concrete roof can decrease by 4°C through cool coating in summer, and by 2°C during the night (Chen et al., 2015). Usually, compound roofing systems are employed to achieve the qualities required of a roof, according to the climate where the building is located.

- **Thermal insulation**

One of the most successful approaches for saving energy, relating to a building's cooling and heating load, is thermal insulation (Sadineni et al., 2011), which also facilitates thermal comfort during both summer and winter, and decreases undesirable heat loss. As Budaiwi (2011) explained, the appropriate density of the material employed for thermal insulation is connected with thermal conductivity, as when the insulation density is high, it possesses a lower thermal

conductivity (k-value), which signifies the insulation's beneficial performance.

A range of studies have assessed the optimal depth of thermal insulation in various climates, and also considered both the cooling and heating loads (Kaynakli, 2012), and Bojic et al. (2001) explained that the decrease in such loads is extremely reliant on the depth of the insulation employed. Meanwhile, An eQuest simulation was employed by Yu et al. (2008) to examine how the total energy requirement is controlled by the depth of insulation and placement of insulation on a building's front face that is exposed to natural heat. The authors observed a decrease of almost 25.92% in the overall cooling and heating demand when an integrated optimization strategy was employed for insulation, together with a glazing and shading system, and a consideration of the window to wall ratio. They also noted that once a specific insulation depth is exceeded, the reduction in energy continues, although at a reduced rate.

While there is a minimal impact in terms of the insulation layer's position, whether on the internal surface, the external surface, or within the wall, in terms of the annual consumption of electricity, there is a lower consumption if it is located on the inside wall surface. However, when the cooling energy consumption is taken into account independently, more electricity is used when the insulation is located within the wall, compared with other locations, as shown in figure 2-3 a different characteristic of thermal insulation layer position on vertical wall. In a study conducted by (Kolaitis et al., 2013), the lowest electricity consumption for cooling was achieved when the

insulation layer was 25mm thick, and for heating, the lowest value was achieved when the insulation layer was 100mm thick.

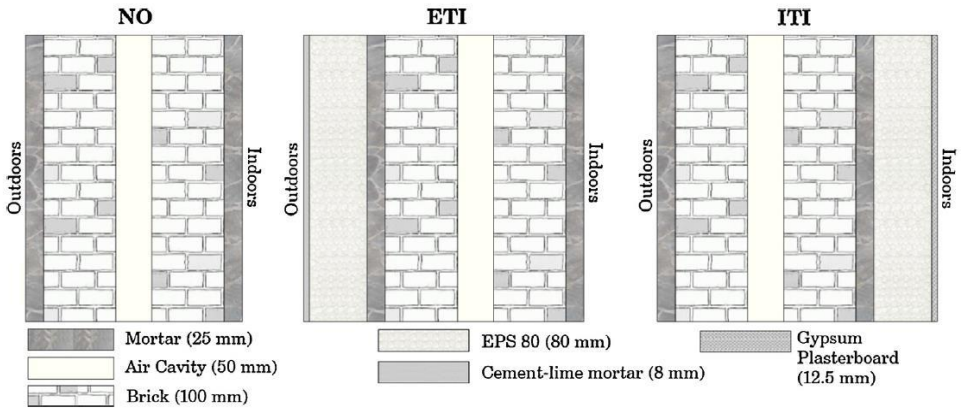


Figure 2.3 A selection of wall assemblages: no insulation (left), external thermal insulation (centre), and internal thermal insulation (right). Source:(Kolaitis et al., 2013)

- **Building colour (surface)**

Different factors affect the impact of a building envelope's colour on a building's thermal performance, such as the building's orientation, its modes of ventilation, the composition of the wall, and the attributes of its windows.

The amount of solar radiation on a building envelope's external surface is determined by the external surface's colour. Light colours usually possess a lower solar heat absorption, and the heat absorbed can be further reduced using an irregular external surface texture, which radiates the heat back to the environment as, due to the irregularities of the textured surface, there is a lower absorption area than the emitting surface. This also creates an increased surface area

for the purpose of convective heat transfer, engendering a more rapid cooling of the textured surface, compared with a flat surface (Santamouris and Asimakopoulos, 1996).

2.2.3. Solar controls (shading elements)

The solar radiation of a building can be regulated by shading on the building's façade, which can be a favourable approach when such shading is incorporated into the façade's cavities, as it promotes radiation inside the building.

Similar to other energy-saving approaches for buildings, the employment of shading devices can be helpful at specific times of the year, although it can be counter-productive at others (Chen et al., 2015). It is important that the shading is controlled if visual and thermal comfort within a building is to be ensured. Passive shading systems can decrease the heat obtained by a building, and lower the need to use other cooling systems. However, one disadvantage of this approach is a reduction in the availability of daylight (Tzempelikos and Athienitis, 2007), which increases the need to use artificial lighting. Such lighting is detrimental to the comfort of the building's occupants, compared with natural light, and is also costlier. Nevertheless, if the excessive use of shading mechanisms is avoided, thereby negating the need for an increased use of artificial lighting, there can be considerable energy and cost savings. Moreover, a reduction in use of artificial lighting also decreases the amount of heat generated within the building (Chen et al., 2015).

A number of other elements, and the inclusion of certain systems in a building, can also help to provide shading. The increased use of solar energy, such as solar panels, produces a need for standardization in the approaches employed, in order to account for the shading of buildings with respect to their proximity to other constructions. In addition, the energy gains of shading should be adjusted, according to the climate where the building is located.

According to Bouchlaghem (2000), shading devices should be developed in such a way that their position can be adjusted, depending on the season, in order that the building is shaded during the summer, but not during the winter. A study conducted by Florides et al. (2002), using a TRNSYS simulation, indicated that the use of an overhang produced an increase in solar protection, and a reduction in the annual cooling demand, since the heating demand increased. This was because the overhang obstructed a certain segment of the solar radiation. Both the negative and positive effects increased when the windows were positioned on the south side of the building, because they received a greater amount of the annual solar radiation. The study concluded that the use of long projecting horizontal overhangs could be useful, provided they could be removed, or folded back during the winter.

Figure 2.4 illustrates an example of a basic shading strategy for a south elevation, with this elevation allowing for the easiest control of solar energy. Shading devices are normally designed in the form of horizontal projections are installed on top of the windows. The length of projections depends on height of window and the angle of elevation of sun at its peak point. This not only helps to prevent absorption of

sun's heat during hot weather but also facilitates heat absorption during winter to ensure that the environment is warm enough.

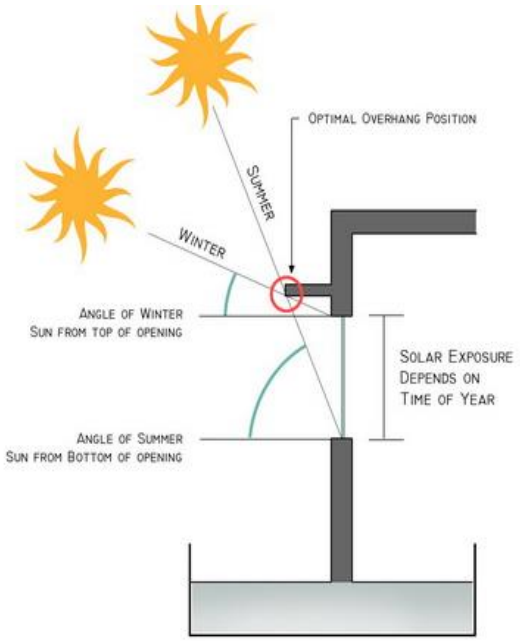


Figure 2.4 Basic shading strategy for a south elevation (Source: (Yao, 2014)

- **Vegetative shading**

Shorter buildings can be shaded from sun with nature. For this, usually deciduous trees are employed. These trees are giant flowering plants and are characterised by shedding of leaves in fall season, which serves the dual purpose of shading in summers from sunlight and exposure to sunlight in winters (as leaves are shed off allowing sunlight to be absorbed by building). This purpose can also be served by vines and their supporting trellises or other similar devices. Vegetative shading is a good option regarding temperature control during shoulder months or in winters. This works like deciduous trees which provide shade in summer and shed leaves in winter to allow

exposure to sun for a pleasant internal environment. Moreover, sufficient wind movement must be present near the external trees to facilitate the natural cooling process (Figure 2.5).

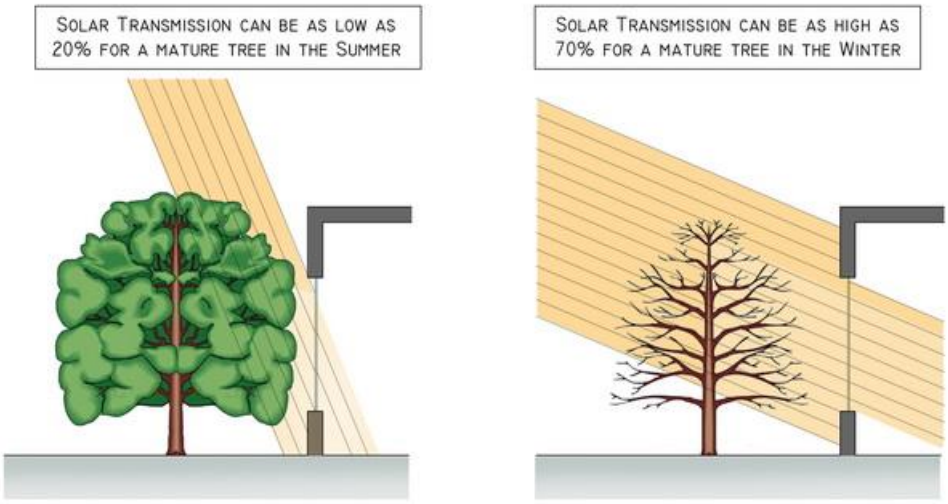


Figure 2.5 Low and high solar transmission affected by a tree in summer and winter.

In addition, a suitable building design can result in direct self-shading through the building itself, without any requirement for additional elements, which would be particularly useful for isolated buildings that receive excessive amounts of direct solar radiation. This is termed 'self-shading', in which the inverted pyramid is the most commonly applied building shape (Capeluto, 2003).

2.2.4. Thermal mass

Thermal mass, referred to as the heat capacity is the ability of a substance to accumulate heat. During hot weather, uncovered substances including the walls and surfaces of a building accumulate the heat they are exposed to until the point when the heat is finally

discharged. This mechanism assists with the maintenance of a stable internal temperature that prevents the overheating that may occur in the summer, as shown in Figure 2.6. Meanwhile, the property of heat capacity or thermal mass enables the substance to accumulate heat they are exposed to. This process slows down at night time when the sun is away. Similarly, during winters the heat from sun is absorbed and stored by surfaces during the day which increases internal temperature consequently lowering the use of heating system (Chris, 2013).

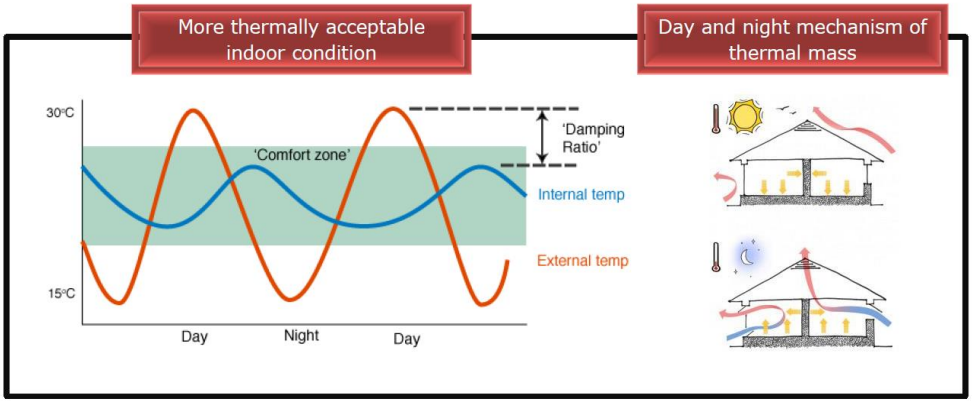


Figure 2.6 Thermal mass (Source:(Alwetaishi, 2015)).

The ultimate use of systems for heating and cooling is decreased due to thermal mass. Moreover, thermal mass also has a unique aspect namely the thermal storage capacity or thermal performance (Yang and Li, 2008). In locations with hot air, it is advisable to use thermal mass to moderate the internal conditions of a building in the presence of the considerable fluctuations of the outdoor temperature (Krüger et al., 2010a).

2.3. Natural ventilation

Over the last few decades, natural ventilation in buildings has become a focus of interest for researchers. The term 'natural ventilation' refers to the airflow from or into building via specifically designed apertures in the building's envelope, due to natural pressure differences owing to stack effects or/and wind. 'Building ventilation' systems can be mechanical or natural (Prajongsan, 2014), and include three thermally significant functions (i) maintaining healthy internal air quality (IAQ) by reducing the concentration of contaminated indoor air, (ii) providing a comfortable environment that protects against discomfort caused by moistened skin, and (iii) cooling building structures when the ambient temperature is higher than the indoor air temperature. A minimum function of natural ventilation is the removal of contaminated air via the exchange of the air between the inside and the outside of a building (Alwetaishi, 2015c), while it can also be employed as an effective passive cooling method that reduces the need for mechanical cooling systems in buildings in hot regions (Prajongsan, 2014).

In recent years, interest in combining passive cooling and natural ventilation strategies has increased, as these approaches can provide thermal comfort, and a suitable indoor air quality with a minimal energy consumption, compared with mechanical ventilation. Indeed, the findings of a recent study demonstrated that the energy cost of using natural ventilation in buildings is 40% lower than the energy cost for air conditioning in buildings (Khatami, 2014). According to Elzaidabi (2009), the main advantages of naturally ventilating buildings are:

- Reduced energy consumption and lower running costs;
- Reduced noise levels;
- Reduced installation and operation costs;
- The provision of healthy interior conditions that promote the physical well-being of the occupants;
- An increase in the value of the property, due to the reduced operating expenses and energy consumption.

However, natural ventilation strategies for buildings also involve a reduced controllability of the indoor climate, and are sensitive to variations in climatic conditions, which means that they are not suitable for all buildings, and the limited cooling capacity is dependent on the users' understanding of the method's correct operation.

2.3.1. Natural ventilation strategy systems for buildings

The thermal comfort and summer cooling potential of buildings is dependent on natural ventilation strategies (Schulze and Eicker, 2013), and the means of achieving RH levels and lower indoor-outdoor temperatures conditions have improved over time. Ventilation is important for IAQ, and to remove harmful chemicals and odours during times when the building is both occupied and unoccupied. In addition, it is also important for the removal of heat to prevent the accumulation of condensation within a building's fabric (CIBSE, 2005). The occupants' needs and the building's location play a major role in determining the essential ventilation rates (Cook, 1998).

Natural ventilation and cooling systems are defined as "all naturally evolving processes and heat dispersal and modulation techniques, as well as those associated with building design techniques and the prevention of overheating" without any supplementary input from

mechanical systems (Santamouris and Asimakopoulos, 1996). Natural, passive cooling can be attained by the use of solar protection and thermal techniques, for example in the building's layout, form, and solar control mechanisms that allow for heat dissipation and the modulation of heat gain, such as a building's thermal storage capacity (Santamouris, 2006). Moreover, the suitable application of bioclimatic architecture, such as the building's orientation, layout, and window specifications, can supply suitable indoor conditions that are typical of the external conditions, which therefore require natural cooling to decrease the indoor air temperatures (Givoni, 1994). A practical key of heat dissipation techniques that was created by (Santamouris and Asimakopoulos, 1996) and (Givoni, 1994) listed (air) natural ventilation, (sky) the radiant cooling, (ground) soil cooling, and (water) in direct evaporative cooling (DEC) or indirect evaporative cooling (IEC). The applicability of these is presented in Table 2.1.

Table 2.1 Natural ventilation strategies (Spentzou, 2015).

Strategies	Applicability	Applications
Comfort ventilation	Warm, humid regions; Small diurnal range (<10°C); At an indoor air speed of 1.5-2m/s; External air temperature should not exceed 28-32°C (Givoni, 1994).	Ventilation via openings; Wind-catchers; Atriums;

Night ventilated cooling	Regions with a large diurnal range; Higher than the comfort zone upper limit (air speed around 1.5m/s); Daytime temperature 30-36°C; Night time temperatures <20°C;	Solar chimneys; Dynamic façades.
Radiant cooling	Any area with a low degree of cloud at night; Non-dependent on RH (Givoni, 1994).	High-mass concrete roofs; Roof ponds; Roof externally insulated during daytime (Batty et al., 1991);
Evaporative cooling	Indirect: in areas with around 25°C WBT, and maximum DBT 46°C; Direct: in areas with 22-24°C WBT, and max DBT 42-46°C (Santamouris and Asimakopoulos, 1996).	PDEC towers; Water elements and features.
Soil cooling	Indirect: hot summers, cold winters; Direct: Hot, dry areas with mild winters (Givoni, 1994).	Earth-integrated buildings; System of underground pipes circulating air from the building.

Natural ventilation strategies were employed long before the development of mechanical apparatus, and included such widespread techniques as creating negative and positive pressure inside and outside a building, and stack driven pressure. The use of natural ventilation continues to be recommended in hot and humid conditions, where the outdoor temperature is very close to indoor thermal comfort levels during the winter, and at night-time (Alwetaishi, 2015c).

According to recent reviews of natural ventilation strategy, there are several methods that can be employed as a design strategy in mixed-mode ventilation, for example, zoned, contingency, changeover, and concurrent mixed-modes. While these approaches are suitable for occupancy and multi-purpose buildings, they are most applicable for domestic buildings where the mechanical cooling serves as backup ventilation, and the occupants are able to open the building's apertures according to their preference (Taleb, 2015). During the summer, the outside air temperature overrides the indoor temperature, which dictates the alterations in the impact of ventilation from cooling to heating, therefore indoor spaces may require a minimum of fresh air (CIBSE, 2005).

During the daytime, the use of natural ventilation serves three major purposes: (1) cooling the indoor air, assuming the outdoor temperature is lower than the indoor temperature; (2) cooling the building fabric; and (3) cooling the occupants' bodies directly, via evaporation and convection (Taleb, 2015). According to (Givoni, 1994), in areas with a daytime temperature above 36°C, the use of passive cooling strategies should be added to the night-time ventilation mechanisms. In addition, if natural ventilation occurs overnight, the building's thermal mass should be employed as intermediate storage, enabling the storage of the night's cool air. However, the efficiency of night ventilation is dependent on the airflow rates (Santamouris et al., 2010), therefore, a number of factors must be considered under such climatic conditions (Taleb, 2015), as follows:

- **Control of natural ventilation**

The setup of the control factors of natural ventilation is more important than the strategy itself (Schulze and Eicker, 2013), since natural ventilation is primarily affected by the surrounding environmental conditions, such as the humidity, temperature, wind direction, and wind velocity rate, therefore it is vital to provide a means of control in order to protect both the occupants and the buildings from undesirable conditions. Natural ventilation controls, in terms of opening and closing a building's apertures, can be automatic, manual, or both (Khatami, 2014), although occupants are often slow to control their levels of thermal comfort, and lack an awareness of the CO2 footprint as an indicator of indoor air quality. Therefore, relying only on manual control is not recommended. Many experimental studies and surveys revealed that the use of both classic and artificial intelligence control strategies, based on a set of rules, are effective for achieving indoor comfort (Santamouris and Wouters, 2006).

- **Natural ventilation and IAQ**

Poor IAQ, due to a low ventilation rate, produces a decrease in the building occupants' productivity and comfort, as demonstrated by recent studies. There is a high probability of Sick Building Syndrome (SBS) that is characterised by breathing problems and headache among people within the building due to improper ventilation and low indoor air quality (IAQ). This is especially true for packed spaces. However, automatic ventilation can eliminate this problem by improving the IAQ. Moreover, risk of SBS is usually decreased with diverse control options.

The assessment criterion for IAQ and thermal comfort, when evaluated both mechanically and naturally in ventilated buildings, require the measurement of the CO2 concentration in the occupied zones (Khatami, 2014). The European Committee for Standardization (CEN) classification of the ventilation air quality is illustrated in Figure 2.7, which shows that approximately 15 L/s.p and above are regarded as a high IAQ, whereas air quality rates of 6 L/s.p and less are considered to be a low IAQ. The range between 6 and 10 L/s.p is defined as 'moderate' air quality, and the range between 10 and 15 L/s.p as 'medium' air quality (Liddament, 2009).

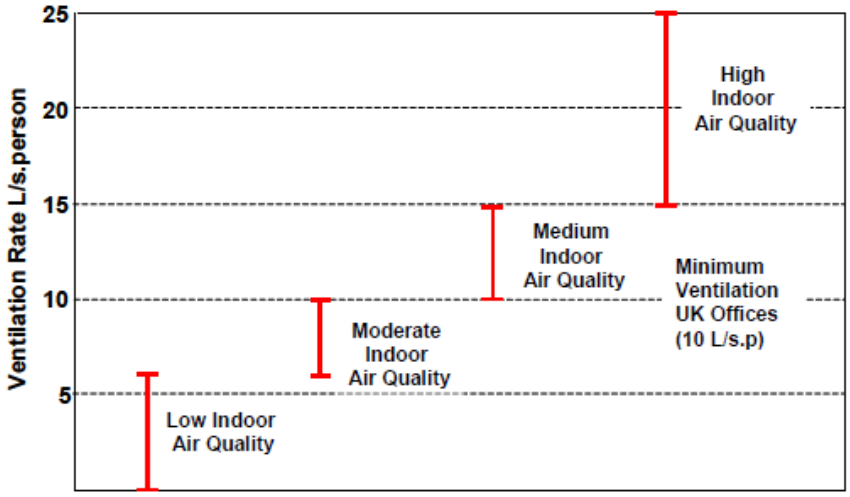


Figure 2.7 European CEN air quality classification (Source: CEN Standard 13779, 2007).

2.4. Natural ventilation mechanisms

The mechanism, or the energy, that drives natural ventilation in and around buildings is the pressure difference between the outdoor and indoor environment resulting from the stack or/and wind forces (Table 2.2) (Prajongsan, 2014).

Table 2.2 Natural ventilation mechanisms (Prajongsan, 2014).

Natural ventilation mechanism		
Methods	Description	Diagram
Wind force	- differences in the wind pressure; - influenced by wind direction, according to the building's orientation; - wind 'pressure zone' on the building's side is positive, while the leeward side and low pitch roofs are negative 'suction zones'; - the airflow distribution from positive to negative; - pressure difference between the building's apertures plays a central role.	
Stack or buoyancy force	- from the variation in air density, due to temperature differences between the indoor and outdoor across the aperture; - influenced by the size and location of the apertures, and the height of the internal space; - with one opening, the air is driven by the pressure difference in the upper and lower zones of the building's aperture; - with more than one opening, and with a chimney, the air is driven by the pressure difference in the different positions of the apertures; - the warmer air rises to the upper levels; - the stack air flows out of the room at the warm zone; - the air is replaced by cooler and heavier outdoor air, which is driven into the room at the bottom; - the opposite flow direction may occur when a building's indoor air temperature is lower than the ambient temperature; - the air enters a building through the openings that are lower than the neutral pressure level location; - the top opening should be as large and as high as possible, in order that the NPL will be at the highest possible position, and so that the external air can enter the largest possible amount of the building. This top opening should be on the leeward façade, so that wind and stack effect can drive the air in the same direction.	
Combined wind and stack forces	These combined effects depend on: - the position of the building inlet and outlet openings, with respect to the external wind direction; - air temperature differences between the indoor and outdoor environment; - the effective opening area.	

2.5. Thermal comfort

Thermal comfort is of crucial importance for three reasons: (1) for recommending and specifying relevant standards, (2) for regulating the consumption of energy, and (3) for providing acceptable conditions for a building's occupants (Taleghani et al., 2013).

The limitations by which building scientists estimate the level of cooling or heating of different buildings are referred to as the 'thermal comfort boundaries', and thermal comfort is described as "that state of mind through which satisfaction with the thermal environment is expressed" (Taleghani et al., 2013). Meanwhile, (Alwetaishi, 2015b) defined thermal comfort as "a state wherein no driving forces are there to rectify the environment by their behaviour". American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined the thermal comfort to be the disposition in which the level of contentment is determined by thermal environment. (Djongyang et al., 2010).

Researchers often evaluate thermal comfort according to the 'adaptive approach', and the 'heat balance approach'. As far as the evaluation of natural ventilation options for a building occupants' thermal comfort is concerned, the appropriate assessment tool to employ can be determined by identifying the different thermal comfort models (Djongyang et al., 2010).

The 'heat balance approach' relates to the thermal comfort achieved between the balance of heat lost and generated by the human body. Heat transfer by conduction, convention, evaporation, and radiation

causes heat loss from the body (Khatami, 2014), and there are six important factors involved in achieving thermal comfort and a heat balance equilibrium: the mean radiant temperature, the air temperature, the RH, the air velocity, the thermal resistance of clothing, and the amount of physical activity undertaken (Prajongsan, 2014). These factors are inter-correlated, and their effects on comfort cannot be considered independently. In addition, age, gender, state of health, and acclimatization are among the other factors affecting an individual's perception of atmospheric conditions (Prajongsan, 2014).

The major thermodynamic and physical attributes of humid air can be illustrated using a psychometric chart that depicts the interaction between the different properties, such as the RH and DBT, along with the moisture content. The fundamental characteristics of air that are crucial for the inhabitants of building usually define the comfort zone. Figure 2.8 shows the comparison of ASHRAE comfort zones for two areas; one where the temperature is automatically controlled and the other where evaporative system of temperature control is employed, in which the increased air flow is taken into account by the evaporative air conditioning comfort zone, which, on the basis of vapour compression air conditioning, is modified and compared with the ASHRAE comfort zone.

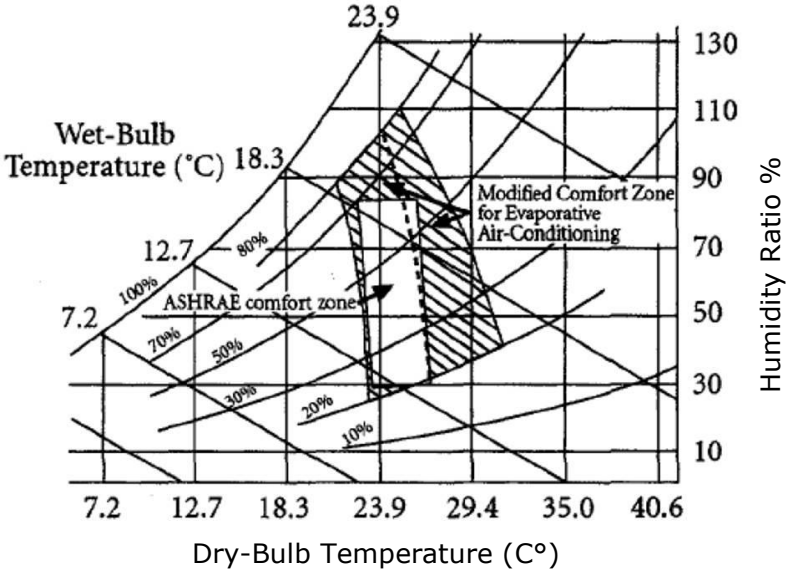


Figure 2.8 Modified evaporative air conditioning comfort zone, taking into account the increased airflow, compared with the ASHRAE comfort zone, based on vapour compression air conditioning (Source: ASHRAE).

The specification of personal parameters, in terms of aspects such as metabolism rate and degree of clothing insulation, together with the combination of indoor thermal environmental parameters (thermal radiation, temperature, air speed, and humidity) is the primary objective of the ASHRAE-55 standard for determining the thermal environmental conditions that are acceptable for the majority of a building's occupants (Taleghani et al., 2013). Since the environmental factors are those that have the greatest impact on human thermal comfort, they have been the subject of serious scientific interest, and even if one particular factor is of concern, it is important that all of the others are also considered. According to ASHRAE-55 Standard (2004) humidity, air temperature, air movement, and radiant temperature are the key environmental

factors that affect thermal comfort. Meanwhile, as noted previously, an individual's metabolic rate, impacted by activity and insulation in the form of clothing, is another factor that should be considered, together with factors such as a group's format, which necessitates that priority is lent to certain aspects of thermal comfort.

2.6. Evaporative cooling technology

The oldest, and some of the most effective, techniques that can be employed to achieve a decrease in air temperature to address temperature imbalance are those that employ water evaporation, or 'evaporative cooling'. In a perfect system, evaporative cooling is an adiabatic (constant enthalpy) process, with the latent heat of vaporization removed by water through the formation of water vapour, and an equal amount of heat provided by the air through a reduction in the DBT.

The process involves mass and heat transfer, and achieves a drop in the air temperature by allowing the transfer of large amounts of heat energy to water through the air. One of the primary uses of evaporative cooling is to decrease the temperature of buildings in two ways: directly, by facilitating water evaporation; and indirectly, by facilitating physical contact with a surface that has already been cooled using the DEC process (Musa, 2008).

Evaporative cooling is a simple, cost effective, energy efficient, and environmentally non-hazardous method that can be employed as an alternative to traditional mechanical vapour compression techniques. It is extremely power efficient, as it can operate on around a quarter

of the requirements for mechanical vapour compression. The technique is also defined as the simultaneous decrease in air temperature, and increase in water temperature, which increases the humidity content of the air, making it colder (Cuce and Riffat, 2016). As well as being energy efficient and environmentally friendly, it is also a novel technique that allows for the provision of cool air for a building's occupants.

Nevertheless, evaporative cooling possesses also a number of disadvantages, including the requirement of appropriate air characteristics for the process to work effectively. The main principle behind the process concerns the differential of the temperature between the dry-bulb and wet-bulb of the ambient air; as such, this technique is especially suitable for locations that are characterized by an arid climate and extreme temperatures (Rafique et al., 2015).

The capacity for cooling is hampered in regions that are characterized by a humid and mild climate, owing to the small temperature differential (Amer et al., 2015). However, evaporative cooling offers important advantages including, but not limited to: a) simplicity, arising from the low effort required for the construction and structure of functioning schemes; b) environment friendliness, compared with techniques for cooling that employ refrigerants, which are also pollutants, as it requires only water to function; c) energy efficiency, because the technique does not use any mechanical compressors, which also produces a reduction in the emission of CO2 (Duan, 2011).

2.6.1. Basic principles and types of evaporative cooling

In order to function, evaporative cooling requires the natural process of water evaporation, in conjunction with a system that regulates the air, forming an environment that cools effectively. This is achieved by regulating the warm and fresh air outside the area to be cooled. The air passes through a wet porous surface in the form of a pad, which gradually cools the air through the evaporation of the water (Chaudhari et al., 2015).

The temperature differential between the web-bulb and the dry-bulb is the driving force for the evaporation of the water, as well as being the process that facilitates the effectiveness of evaporative cooling, as the temperature differential causes an increase in the efficiency of the evaporative cooling. When employing evaporative cooling, any surface surrounded by air can be cooled effectively through the evaporation of liquid, and it also utilizes the heat content of the surface to cool the body, which also causes the conversion of liquid to vapour.

Figure 2.9 illustrates the process of evaporative cooling in the form of a psychrometric chart, depicting the resulting air having achieved a DBT of 18°C, and 79% RH, after being regulated through an evaporative cooling system. The air was initially characterized by 30°C DBT, and 20% RH, hence an overall decrease in temperature has been achieved, while also allowing for the increase in RH (Musa, 2008).

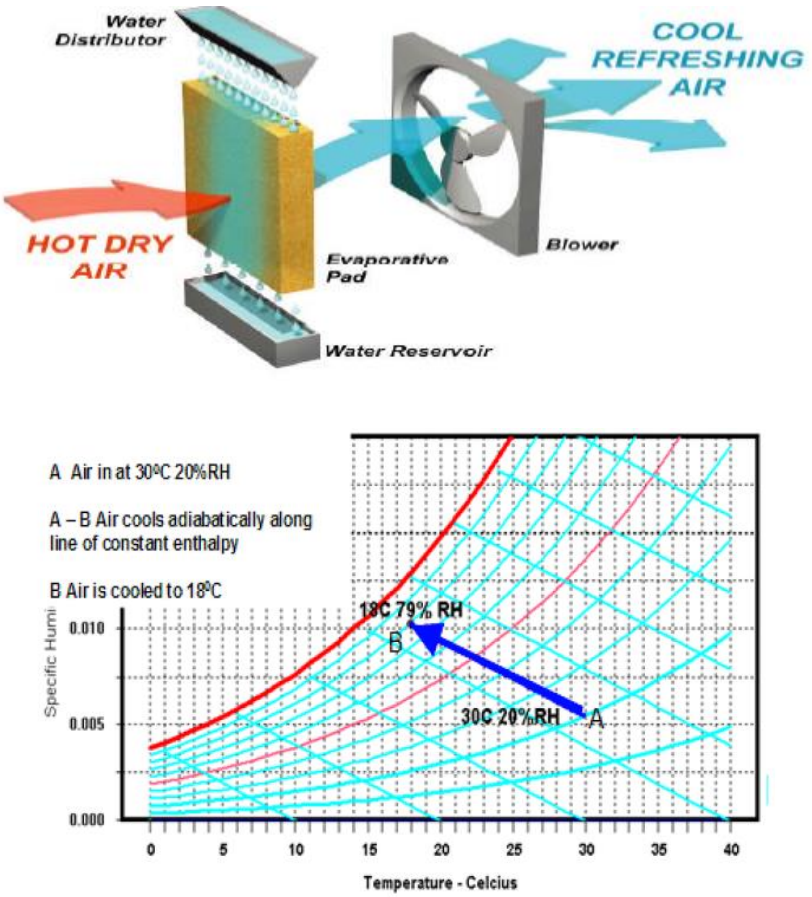


Figure 2.9 a) Basic evaporative cooling process (above), b) psychrometric of evaporative cooling (below) (Source: (Musa, 2008) p,6).

Figure 2.10 presents a psychrometric chart depicting the difference in the cooling techniques of DEC, compared with a mechanical cooling system, illustrating that, owing to the smaller enthalpy differential, the exact cooling load requires a greater amount of mass flux in the case of evaporative cooling, in contrast to the conventional air conditioning system. Moreover, the resulting humidity of the air will be much greater when using evaporative cooling, compared with conventional air conditioning techniques that maintain constant operating characteristics.

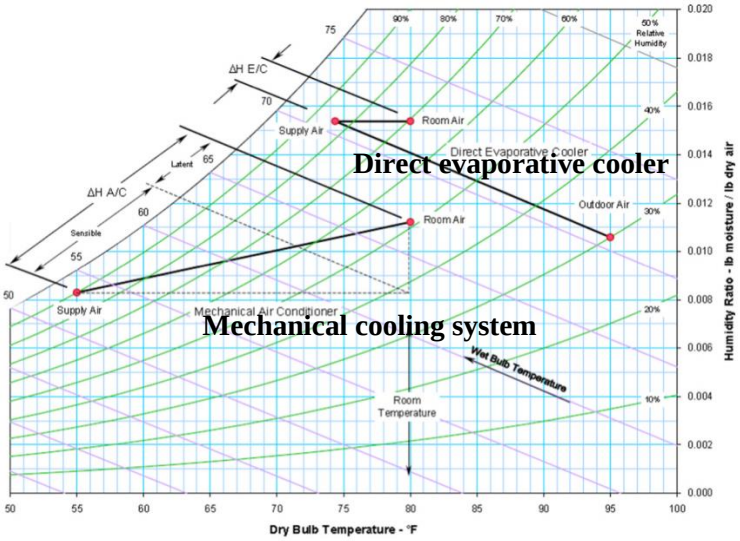


Figure 2.10 Psychometric chart showing the enthalpy change used to determine capacity.

Table 2.3 compares various kinds of evaporative cooling techniques, in terms of their performance and characteristics.

Table 2.3 Types and characteristics of evaporative cooling systems (Source: (Rafique et al., 2015).

Type	Technology states	Comfort impact	Energy saving potential (%)	Effectiveness (%)
Direct	Mature	humidity increase	70	80-90
Indirect	Early production	No humidity increase	50	About 85
Indirect- Direct	Early production	Slight humidity increases	80	110

In addition to direct evaporative cooling (DEC) systems, Indirect Evaporative Cooling (IEC) techniques also exist, in which the cooled air humidity does not increase. (Chaudhari et al., 2015), 1) direct evaporative coolers are characterized by direct physical contact between the functioning fluids, water and air; 2) indirect evaporative coolers that are characterized by the separation of the two

functioning fluids using a plate or surface; and (3) hybrid techniques that employ both direct and indirect cooling techniques, in conjunction with other cooling cycles (Amer et al., 2015, Kanzari et al., 2013). The IEC system involves the prior cooling of the air by heat exchange, after which it is passed through a cooling pad, or the reverse process, whichever is suitable for the situation, while a direct cooling system involves the passage of air directly across the humidifier to reach the cooling chamber (Chaudhari et al., 2015).

2.6.2. DEC system

The DEC process involves the direct contact of the incoming air with the cooling water, which results in the addition of moisture to the cooled air stream. It is an adiabatic (constant enthalpy) process, since it involves the decrease in air temperature, and the simultaneous increase in the humidity content. Therefore, this technique is especially suitable for locations that are characterized by an arid climate and extreme temperatures (Rafique et al., 2015), although it hampers the capacity and potential for cooling in regions that are characterized by a humid and mild climate, owing to their small temperature differential (Santamouris, 2007). Indirect cooling systems are preferable for regions with extreme temperatures, but already humid air. The performance of a direct cooling system can be most efficiently assessed by the WBT, since its temperature remains constant, while the DBT experiences a simultaneous decrease. In terms of effectiveness, DEC systems can achieve an efficiency of around 85%, if they are well-structured (Rafique et al., 2015, Kanzari et al., 2013). Figure 2.11 illustrates both the schematic and psychrometric process of the DEC.

(a) (b

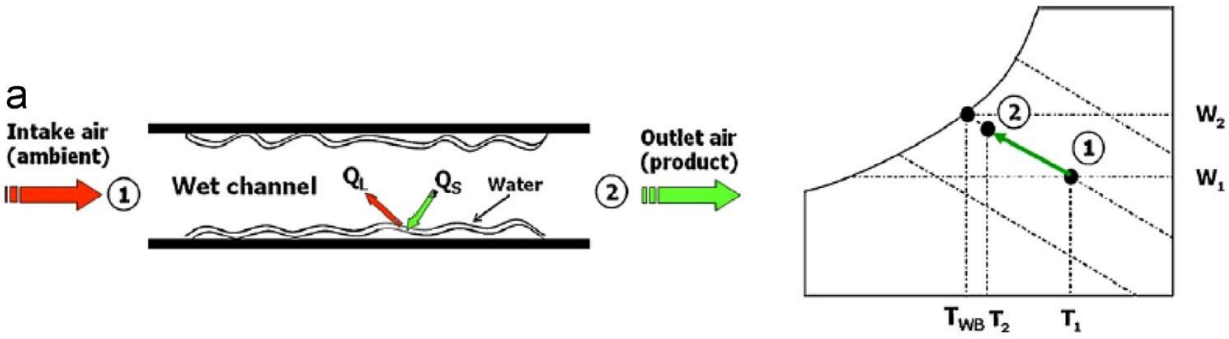


Figure 2.11 (a) Working diagram of direct evaporative cooling (Source: Cuce and Riffat, 2016(Duan, 2011, Cuce and Riffat, 2016), (b) the thermal process shown on a psychometric chart (Source: Duan, 2011(Duan, 2011, Cuce and Riffat, 2016).

As is evident from the psychrometric chart, the temperature of the incoming air is decreased, while simultaneously allowing for an increase in the moisture content of the air, since the ambient air comes into direct contact with the sprayed air. The figure also illustrates the functioning of a direct evaporative cooler, involving the transmission of heat and mass between the cooling water and the hot air (Rafique et al., 2015). The incoming air (State 1) transfers the heat to the water, which results in moisture as it enters the wet channel. The DBT of the incoming hot air decreases as a result, while the moisture content simultaneously increases as a result of the continued evaporation into the airstream along the wet channel (State 2). Consequently, while the latent heat from the evaporation is removed by the water, in the form water vapour, an equal amount of heat is given by the air, producing a reduction in the DBT. Moreover, regardless of the enthalpy content of the water

evaporated, the incoming air experiences an approximate process from State 1 to State 2, as illustrated in Figure 2.11(b) (Duan, 2011).

Taking into consideration the fact that the RH can increase up to a high of 80%, the use of DEC is not appropriate for buildings in moist climatic conditions, since this increase may cause rusting and warping, and also the mildewing of materials that are vulnerable to moisture (Amer et al., 2015). Finally, DEC systems can be further classified into two kinds: passive DECs that do not require power, as they are operated naturally, such as mashrabiya, wind towers, and roof-pounds; and active DECs that require electricity for their operation, such as random media, rigid media, and remote pad (Amer et al., 2015, Ford et al., 2010, Chaudhari et al., 2015).

2.6.3. IEC system

The IEC process does not involve the direct contact of the incoming air and the cooling water, as instead, the air is cooled sensibly. The psychrometric chart in Figure 2.12(b) illustrates the functioning of the indirect cooling system, depicting the fact that the secondary air flow is cooled using water, while the primary air stream is cooled using the secondary air stream, by employing a certain type of heat exchange mechanism that results in the decrease in the temperature of the air. As such, both the DBT and the WBT are decreased in an IEC system. In terms of effectiveness, the IEC system can achieve an efficiency of around 60-70%, if it is well-structured (Rafique et al., 2015).

Figure 2.12 provides both the schematic and the psychrometric process of the IEC system (Duan, 2011, Cuce and Riffat, 2016), depicting the working air entering the wet channel, while the incoming air enters the dry channel from the same source from which the working air has been extracted. The latent heat evaporation with the water results in the cooling of the incoming air, or 'primary air', while concurrently allowing sensible heat transfer using convection with the working air, or 'secondary air' of the adjacent wet channel. The psychrometric chart in Figure 2.12(b) illustrates the increase in the temperature of the working air from State 1 to State 3, while the incoming air (State 1) experiences a cooling effect, while maintaining the constant humidity ratio of the WBT of the working air (Duan, 2011). Such IEC systems are classified into sub-WBT IEC systems, and WBT IEC systems (Amer et al., 2015).

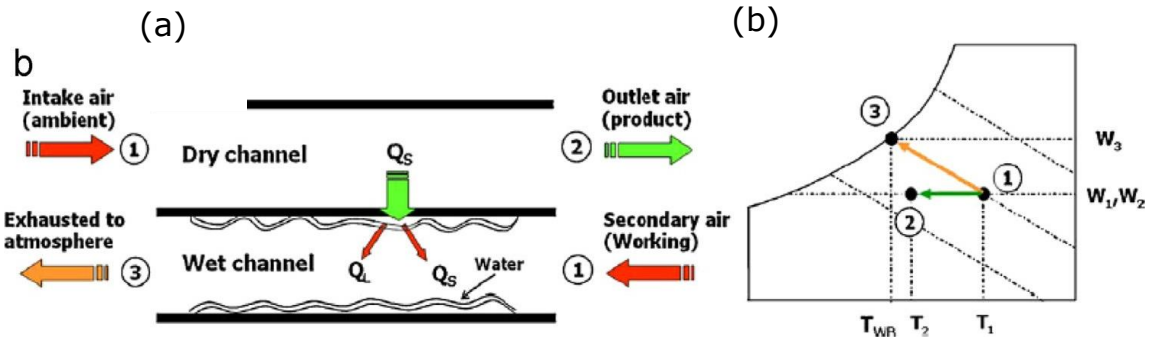


Figure 2.12 (a) working diagram of IEC (Source: Cuce and Riffat, 2016(Duan, 2011, Cuce and Riffat, 2016), (b) the thermal process shown on a psychometric chart (Source: Duan, 2011).

2.6.4. Indirect-direct evaporative cooling (IEC)

When DBTs lower than the temperatures that can be achieved by single-stage systems are required, IEC systems can prove to be

effective, as the conjunction of the indirect and the direct cooling systems allow for a reduction in the consumption of energy, owing to the decrease in the working time of the technique employed. Moreover, double stage coolers also create lower DBTs, compared with those achieved by a single stage process. As the psychometric chart in Figure 2.13 illustrates, the two-stage evaporative system employs the IEC system during the first stage, which is followed by the DEC. The air to be cooled proceeds from Point A to Point B, during which it is sensibly cooled using the technique of IEC. This is depicted in the line A-B, which is parallel to the DBT axis, showing the constant water content of the air. The air then reaches Point C using DEC during the second stage, which is depicted in the line B-C, which is parallel to the WBT line, showing a constant WBT.

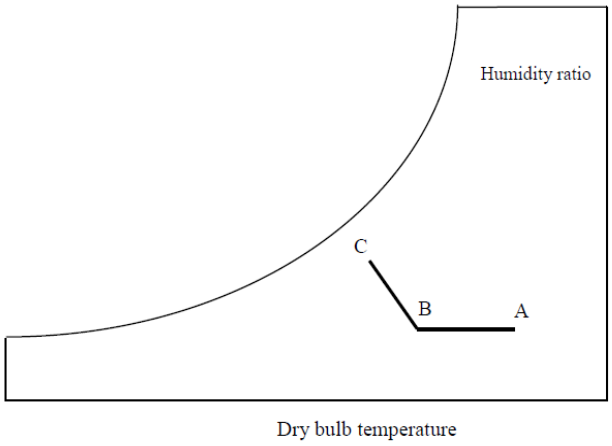


Figure 2.13 Two-stage evaporative cooling process.

2.6.5. Factors affecting evaporation rate

There are numerous factors that regulate and impact on the evaporation rate, through their interaction with one another, which ultimately affects the rate and degree of cooling. These

characteristics include air temperature, air movement, RH, evaporation surface area, and air pressure.

a) RH

The quantity of water vapour present in the air is referred to as the humidity of the air. There are three common measures that can be employed to quantify humidity: i) absolute humidity measures that are irrespective of the air temperature, and which concern the real moisture content, which is quantified in grams, in a predetermined volume of air, which is quantified in cubic meters; ii) RH, which is the most popular quantifying measure, and which quantifies the water vapour in the air as a ratio of the maximum quantity that the air could potentially hold at the given temperature; and iii) specific humidity, which quantifies humidity as the amount of water vapour, quantified in grams, contained in one kg of dry air.

A decrease in temperature results in a decrease in the ability of the air to contain water vapour, which results in greater RH, owing to the air being close to its saturation point. This process can be continued, without any decrease in the water content of the air, until the value of the RH reaches 100%, which is termed the total saturation, or the dew point. From this point onwards, the water vapour in the air converts back to a liquid state on any cooler surface. When the air contains only a very small amount of the total permissible amount of water vapour it can hold at a certain temperature, it results in an extremely low RH. Such conditions allow for a large drop in the air temperature, owing to the high potential for the evaporation of the extra quantity of water, which decreases along with the increasing

RH. This situation can be controlled effectively using a desiccant, such as silica gel, which serves to absorb the extra water vapour from the air, as a result of the passage of the air through the desiccant, where the air exchanges some of its moisture content for heat, released by the desiccant.

b) Air temperature

While the aforementioned factors can influence the evaporation rate, evaporation requires heat, with a higher air temperature causing a higher evaporation rate to keep constant the air content. This is due to the fact that as the temperature increases, the rate of evaporation increases, as a larger number of particles are able to break free of the liquid's surface, owing to the increased speed of the water vapour molecules. This process can be witnessed in the example of a wet street, which dries faster under a hot sun than it does under shade. Furthermore, the interdependence of the various aforementioned factors influencing the rate of evaporation is evident in the relationship between the air temperature and the RH. While they primarily affect the evaporation rate, these factors also interact simultaneously, and affect one another.

c) Air movement

Since the movement of air, whether it occurs naturally, or due to certain mechanical interventions, results in the replacement of the humid air above a wet surface with less humid air, the air movement can also be deemed to be a crucial factor affecting the rate of evaporation. This is due to the fact that the movement of air results

in a constant supply of drier air to the surface that requires evaporation, ultimately resulting in lower RH that enhances the evaporation rate. The movement of air assists in the increase, or at least in the maintenance of the constant evaporation rate.

d) Evaporation surface area

Since a greater surface area allows for more molecules and atoms to leave the evaporating surface, increasing the evaporation surface area enhances the rate of evaporation. This can be observed in the instance of the water in a cup that might not appear to evaporate, while the same quantity of water evaporates quickly when spilled on a surface, due to the fact that the greater surface area permits the wet surface to interact freely with the surrounding air.

e) Air pressure

Evaporation rate is also determined by the air pressure on the surface, since it dictates the speed of the diffusion of the water molecules above the surface of the liquid. This is due to the fact that atmospheric pressure compresses the water molecules near the surface requiring evaporation, so under higher pressure conditions, more energy is required to increase the speed of the water molecules that need to escape. Consequently, a higher air pressure tends to slow down the diffusion process, while a lower air pressure tends to increase the evaporation process. As this process continues, air pressure below the vapour pressure of the water results in the boiling of the water at the same temperature. This explains why water

molecules require less energy to boil at high altitudes than they do at sea level, even when the temperature and RH is constant.

2.6.6. Applications of evaporative cooling

As discussed previously, evaporative cooling systems provide an excellent alternative to conventional air conditioning systems, and their use is currently popular in the building sector. The choice of whether to adopt a DEC or an IEC system depends solely on the required moisture content in the air of a room, because the choice of system can provide either cooling along with high humidity in the case of a DEC system, or if cooling is required with a low RH, an IEC is more appropriate. The most widespread application of evaporative cooling is in the desert coolers, or swamp coolers, that are a component of the chillers installed in medium or large scale cooling plants for such offices and warehouses (Santamouris, 2007). Conventionally, evaporative coolers are installed on the rooftop, mainly for structural reasons, although they can be installed on any other predetermined surface. A considerable amount of work has been conducted regarding the application of DEC and IEC systems in buildings, including the utilization of porous components to enhance the cooling process in the system (Musa, 2008).

2.7. The integration of traditional passive evaporative cooling within a building

Archaeological evidence demonstrates that the Ancient Egyptians first employed evaporative cooling in around 2,500 BCE, using a system that achieved the cooling of air by employing water-containing porous jars. The use of this system in buildings ultimately

spread across the Middle East region, due to its year-round hot, arid climate. Alternative approaches, including porous water pots, ponds, pools, and thin water chutes, were later developed, which were integrated into a building's construction to provide a cooling effect (Duan et al., 2012, Rafique et al., 2015). Passive DEC is used widely for space and water cooling. The process employs a container made from watertight canvas, or porous clay, which contains water. These are preferably positioned in a well-ventilated, shaded location, although they can also be hung close to an opening, or in an open seating area. Since the containers are permeable, some of the water from them leaks onto the surface. The requirement of heat for evaporation is eliminated by presence of air-flow that promotes the evaporation of the surface water. As a result, the surrounding temperature, as well as the temperature of the water within the containers reduces (see Figure 2.14).

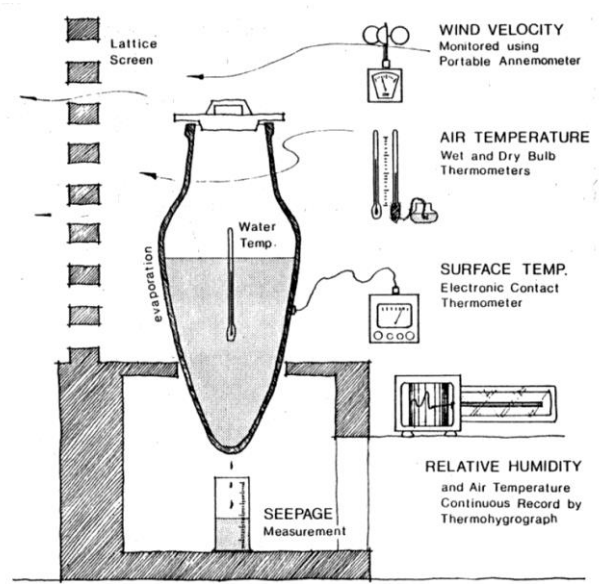


Figure 2.14 Egyptian water jar (Source: (Lechner, 2014))

Integrated building structures usually employ the following types of passive evaporative cooling systems:

Mashrabiya: 'Mashrabiya' is an Arabic word that means 'a drinking place'. Mashrabiya are a traditional element of Islamic architecture that is utilized for the evaporative cooling of buildings, for drinking water, and for natural ventilation (see Figure 2.15(a)). They consist of a wooden lattice opening, and clay jars in what is essentially a cantilevered space. In this system, as the water from the jar's surface evaporates, cooling occurs. The clay jars are not only used for cooling the water they contain, as they can also be used for cooling other items, such as medicine jars, soda cans, and fruit and dairy products, simply by placing the item to be cooled inside the water. A mashrabiya system, with permeable clay jars placed near the lattice opening for cooling and ventilation is depicted in Figure 2.15(b).

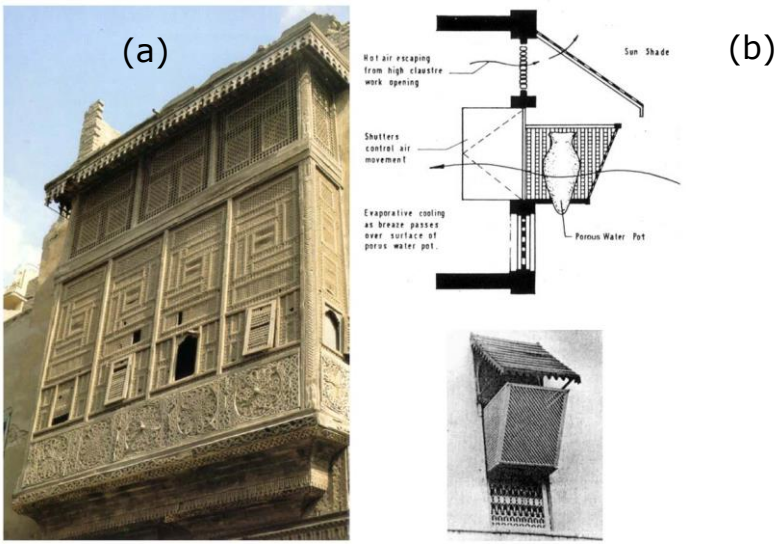


Figure 2.15 (a) The mashrabiya, (b) clay porous water jars (Source: (Lechner, 2014)).

Roof-pound: A roof pound is a type of passive indirect evaporative method used for IEC. In this system, a shaded pond is employed, and an un-insulated roof serves the purpose of a heat exchanger between the pond above, and the room below. In winter, the pond is either shaded, or kept open, and the roof is insulated (see Figure 2.16). The temperature of the water in the pond is maintained at ambient average WBT.

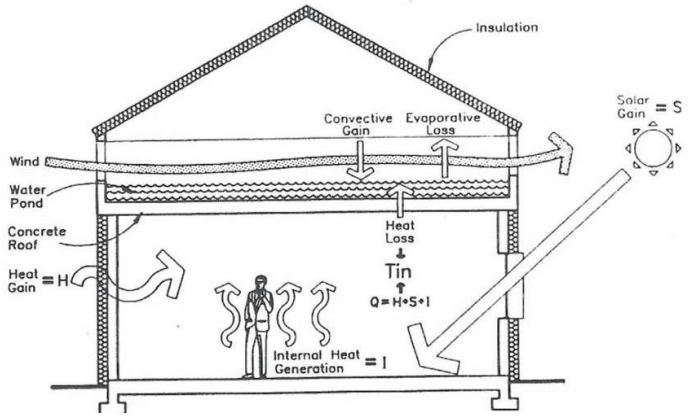


Figure 2.16 Roof-pound system (Source:(Lechner, 2014)).

Windcatcher with cooling: In the Middle East, 'windcatcher' is the name given to one of the oldest forms of a passive downdraught evaporative cooling tower (PDEC). In this traditional system, the windcatchers pass the air entering a space through wet mats, water-containing permeable jars, or an underground storage area, in order to achieve evaporative cooling. Before the air enters a room, it is channelled over the porous devices, where evaporation occurs, in order that the air reduces in temperature prior to entering the room space. This traditional technique of cooling was further developed in Egypt by the architect Hassan Fathy, who made certain improvements to the system, in order to use it for ventilating housing projects and schools (Figure 2.15).

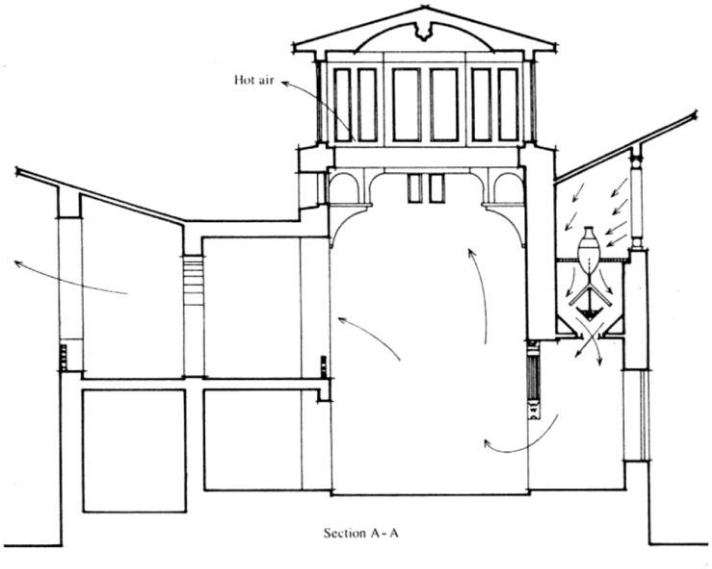


Figure 2.17 Windcatcher and maziara water jar system employed in Egypt in the 1970-80s (Source:(Lechner, 2014)).

Modern buildings continue to be equipped with traditional techniques for air regulation, such as permitting a downdraught for the purpose of cooling and ventilation, although slight improvements have been made to the methods. For instance, Bahadori (2014) and Fathy (1986) improved the old-fashioned windcatchers of Iran and Egypt. Other improvements included increasing evaporation by augmenting the surface area, or using traditional wind towers for improving the air flow rate by catching and altering the wind direction (Ford et al., 2010).

2.8. Integration of evaporative cooling within windcatchers

All around the world, and particularly in the Middle East, countries have used different forms of evaporative cooling for cooling and ventilation in buildings for centuries, and these techniques, such as

scented water jars placed in specific openings, and windcatchers, continue to be used effectively today. The main feature of all of the techniques is their ability to cool the air prior to it entering a space (Ford et al., 2010). There are many types of wind towers, and they can vary in terms of the tower height, the openings, and cross-section that provides passage for the airflow. The designs vary according to the desired airflow, the heat transfer area, the sensible heat storage capacity, and the evaporative cooling surfaces (Schiano-Phan, 2010).

In areas where the air moves too slowly, or that have a very low amount of air movement, a descending flow can be created using buoyancy inside a tunnel through which the air passes. This buoyancy also known as pressure difference is represented as ($\Delta\rho\ g\ h_e$), where ($\Delta\rho$) is difference in densities of internal channel and adjacent air, (h_e) is effective height of column and (g) is gravitational acceleration. In conventional designs, wet zone is located below the column, therefore, there is no significant increase in effective height of column and consequently buoyancy within the tunnel is negligible. But if the wet zone is located in the column or above it, then there is significant increase in effective height of column and buoyancy also increases allowing a rapid flow from upper to lower segment (Bahadori, 2014).

An additional system that can be employed within a windcatcher is known as a baudgeer (see Figure 2.19), a cross section of which, facing the wind, is depicted in Figure 2.18. Baudgeers are usually small, and their openings are covered with wet palm leaves that act as an evaporative cooler, cooling the surrounding air (Bahadori, 2014).

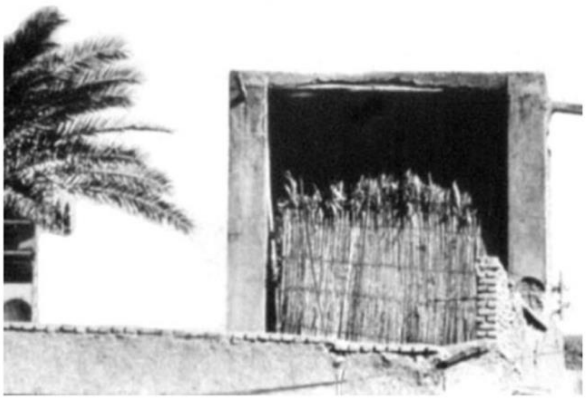


Figure 2.18 Wet palm leaves used to cool the air in a windcatcher (Source: (Lechner, 2014)).

Baudgeers can also be employed in other locations. For instance, a baudgeer system can be created with an underground tunnel across a courtyard to cool a specific space. The vegetation in the courtyard is watered regularly, and this water infiltrates the passage and causes a cooling effect on the air before it enters the building (Figure 2.19). The air entering the room flows first over a fountain and a small pool, which helps to reduce the air temperature (Bahadori, 2014).

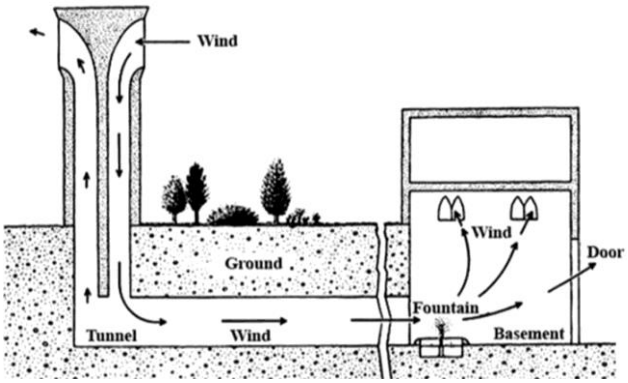


Figure 2.19 Cross section of baudgeer in with wet tunnel (Source:(Di Ruocco, 2014, p. 61)).

2.9. Conclusions

To maintain thermal comfort in the building through passive cooling strategies methods by controlling temperature, which has become an increasingly attractive solution for architects as the avoidance of mechanical cooling. In appropriate architectural design, the cooling load of buildings can be reduced by curtailing the direct heat conduction and solar gain through the envelope. Summer heat, in particular, imposes the most thermal stress on the envelope of buildings in hot regions, and the climatic design of the building must address its summer performance. Hence, a reduction in the indoor temperature of these buildings should be the primary focus of the design, alongside ensuring the inclusion of successful natural ventilation, when it is sensible. As well as traditional methods for evaporative cooling, which are green and low energy, cooling solutions include DEC, IDEC, and DPEC. However, the traditional DEC has the disadvantage of adding moist air into the building's living space. Meanwhile, Indirect Evaporative Cooling (IEC) systems allow the air to be cooled indirectly through a heat exchange surface, without adding moisture into the supply air. Currently, the most promising evaporative cooling technology is the Dew Point Evaporative Cooler (DPEC), which is capable of cooling the ambient air below its sub-wet bulb temperature, without adding moisture to the supply air.

Chapter 3. Energy Analysis of Mosques: Case of Hail, KSA

3.1. Introduction

The climate of KSA is characterised by higher temperatures with low RH. To achieve thermal comfort in mosque buildings, space cooling is essential for the majority of the year. Importantly, air-conditioners used for space cooling account for over 65% of all energy consumption in buildings. This chapter investigates and discusses a case study of typical energy consumption patterns in mosques, as they are affected by different climate conditions in KSA. The case study mosque buildings are located in cities of Hail, Dhahran, and Abha. For this purpose, Design-builder software is used to investigate and analyse the mosques' energy consumption, based on: a) actual monthly electricity bills; b) detailed energy modelling and simulation; and c) application of a series of energy saving strategies intended to improve and reduce cooling load.

3.2. Energy consumption in Mosques in KSA

A large proportion of primary energy consumption in the KSA is to provide thermal comfort for occupants. The available up to date data on energy consumption (SEC, 2014) shows over 77% of total electrical energy generated in the country was consumed by buildings. This was particularly influenced by the prevailing hot climate during the majority of the year, which creates heavy reliance on energy intensive air conditioning systems. This in turn directly

impacts on increased investment in the power generation infrastructure, higher costs from power generation, and environmental pollution.

To address energy sustainability in buildings, the KSA with the assistance of the King Abdul-Aziz City for Science and Technology (KACST) is initiating a number of measures to improve construction standards, energy efficiency, and raise public awareness about energy consumption. The research conducted to assist with this has focused on investigating energy use in buildings of worship (mosques), and the different techniques for reducing energy demand.

The architectural design of mosques has been the subject of many published studies. However, there has been little work on thermal comfort and sustainable environmental design. Interest in energy use in mosques was studied by Al-Homoud (2009) and Al-Hemiddi (2004), favourable indoor temperature was considered by Al-ajmi (2010), and usage of water by Manan et al. (2006). Similarly, research by Abideen (1996) discovered that various passive techniques can be employed to considerably decrease the cooling capacity of air-conditioned mosques located in Jeddah city. It was found the proposed passive cooling plans conserve 82% of air conditioning energy, 50% of financial costs, 28% of CO2 emissions, and 80% of CFC emissions in the city.

Al-Homoud et al. (2005) studied the energy consumption rates in different mosques situated in the Eastern Province of KSA. Their analysis examined utility bills and evaluated energy usage. The study showed air-conditioning systems are deployed throughout the year

to maintain comfortable indoor temperature, resulting in the consumption of considerable amounts of energy. Furthermore, Al-Hemiddi (2004) conducted a comparative analysis of the electrical energy consumption by mosques located in Riyadh and in Skaka (Al-Rahmanyah Juma), as shown in Figure 3.1. It is apparent that the two locations have very different climatic conditions, and in Skaka peak energy use is in wintertime for heating, in Riyadh energy is used during the summer months for space cooling.

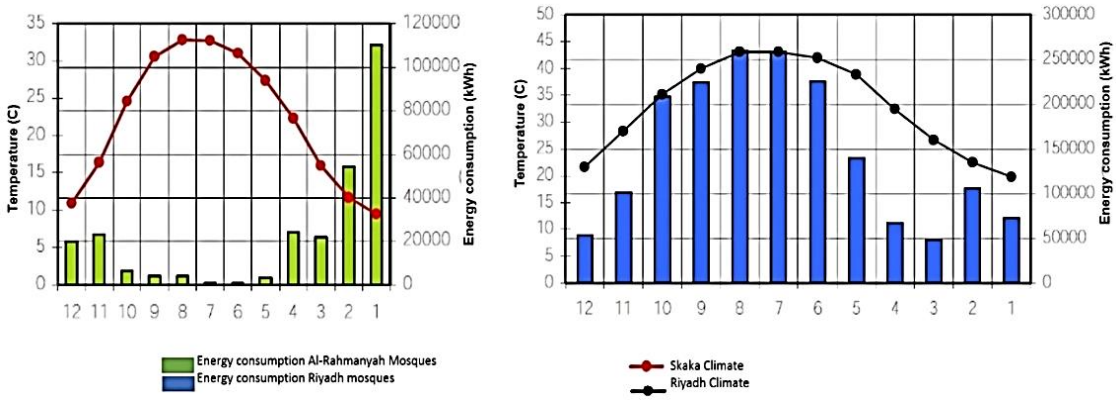


Figure 3.1 Energy consumption in mosques and outdoor temperatures in Riyadh and Skaka (Source: Al-Hemiddi (2004)).

In hot and dry climates, an effective alternative to traditional air conditioning systems is to adopt evaporative cooling systems. and integrate into key elements of buildings. Direct evaporative coolers, also known as desert coolers, are designed for dry conditions, and are extensively used for cooling at pilgrims' accommodations in the Holy sites of Mekkah (Alharbi et al., 2014). The authors conducted a comparative study of thermal performance, highlighting the environmental effect of various evaporative coolers. They found that evaporative cooling systems are employed for cooling in larger spaces, such as those intended to accommodate pilgrims, and in the

train stations, and can conserve over 70% of energy costs and decrease carbon dioxide emissions rates by 78% compared to mechanical vapour compression (see Figure 3.2). Moreover, evaporative cooling can effectively maintain favourable comfort levels by employing 100% fresh air. In addition, a significant reduction in peak electricity demand can thereby be achieved.

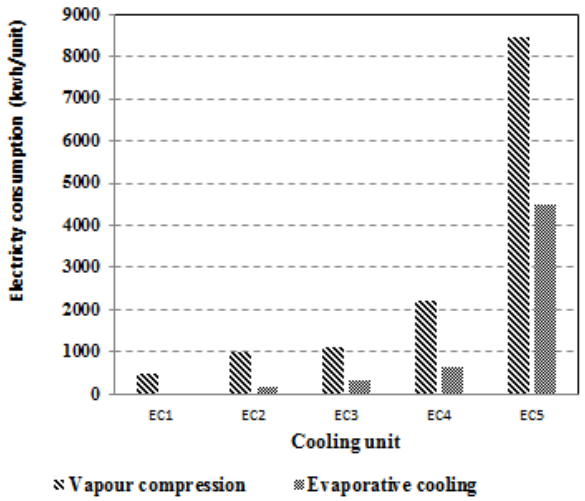


Figure 3.2 Comparison of electricity consumption between evaporative coolers and vapor compression (Source: (Alharbi et al., 2014)).

Further work monitoring energy consumption in mosques was carried out as part of the current research project. Ten mosque buildings were monitored in KSA, and their location can be seen on the satellite images for Hail city, and the energy data use is illustrated in Figure 3.3. Figure 3.4 shows the actual electricity bills for the mosques were obtained from SCECO (Appendices A for actual bills sheet). The data shows a large seasonal variation in energy consumption, with the summer months being the highest, when vapour compression and air conditioning system are used throughout the daytime. Where there

is a difference between all mosques due to several factors such as difference in the height of mosque ceiling, fabric building materials and insulation used, the type of cooling system and the behaviour of the users.

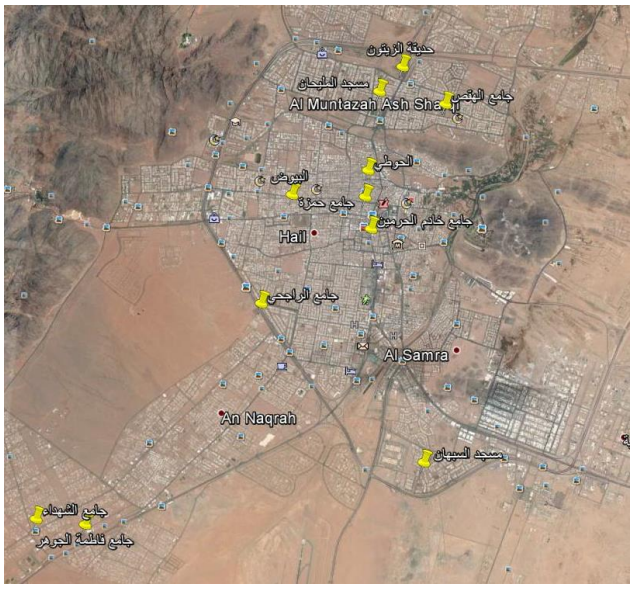


Figure 3.3 The location of the ten Mosques in Hail city.

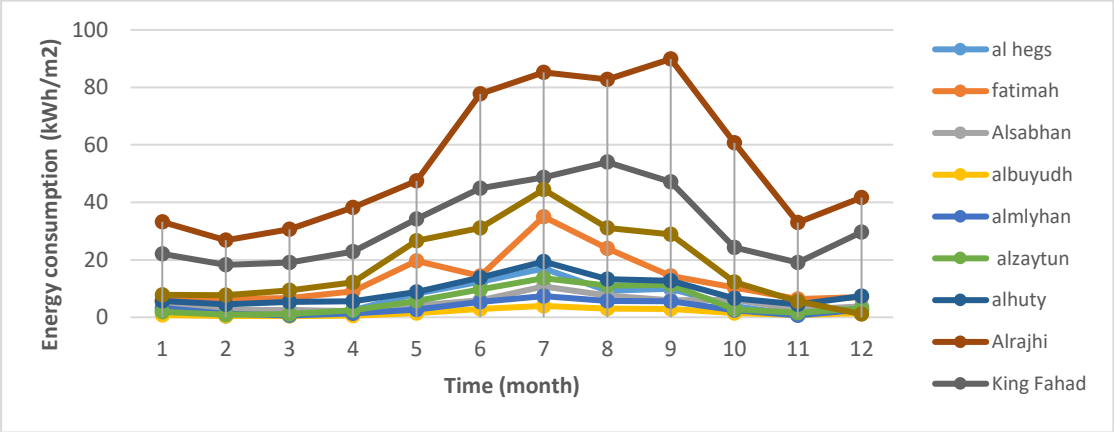


Figure 3.4 Electrical energy consumption monitored in mosques in KSA

3.3. Thermal comfort in mosques

Thermal comfort is generally perceived as affecting individuals' state of mind. It relies mainly on surrounding environmental conditions (temperature, RH, radiation and air velocity), level and type of activity (metabolic rate and clothes insulation) and other indirect parameters, such as state of health, age, etc. (CIBSE, 2006) specifies thermal comfort standards in places of worship, with recommended comfort ranges given in Table 3.1. The standards suggest a temperature range of 19 to 21°C for wintertime and 22 to 24°C in the summer time. It also indicates that adequate ventilation should be maintained at 10 Air Changes per Hour (ACH).

Table 3.1 Recommended Comfort ranges for religious buildings (Source: (CIBSE, 2006)).

Building Type	**Winter Operative Temperature Range for stated Activity and Clothing Levels**			**Summer Operative Temperature Range (Air Conditioned Buildings) for stated Activity and Clothing Levels**			**Suggested Air Supply Rate (L/s)**
	Temperature (°C)	Activity (met)	Clothing (clo)	Temperature (°C)	Activity (met)	Clothing (clo)	
Religious Buildings	19-21	1.3	1.15	22-24	1.3	0.65	10 ACH or 0.1 m/s

The above guidelines show general indoor climatic conditions in buildings; however, maintenance of those conditions in mosques will vary depending on building structure, design, materials, orientation, users' clothing, activities, etc. Occupancy density in particular is also

an important factor ensuring healthy and comfortable conditions, particularly during periods of high usage, such as in Ramadan. As spaces for worship, the buildings should aim to offer a serene and calm environment to worshippers (Ibrahim et al., 2014).

3.4. Climate of KSA and impact

KSA is a desert country located between 31°N - 17.5°N latitude and 50°E -36.6°E longitude. The total area it covers is 2.3 million square km^2. Thus, the geography of the kingdom is diverse and climate is considered to vary from one area to another.

The Saudi standards SASO classify climatic zones in the KSA according to daily temperature and rainfall levels, and are used to determine specifications and requirements for the thermal transmittance values of buildings within each area. Buildings are categorized according to their height, either low in the case of residential buildings, or high for commercial ones. They are further classified according to the three different climatic zones, according to their geographical location in the KSA, as shown in Figure 3.5:

- Zone 1- White (Riyadh, Makkah, AlSharkiyya, AlMadina, Najran, Gizan, Bisha)
- Zone 2-Yellow (Gassim, Hail, Tabuk, Al Jouf, the Northern border area (excluding Tarif and Guriat), Assir (excluding Abha, Khamis, Moshet, and Bisha), Al Taif, Al Baha),
- Zone 3-Red (Abha, Khamis Moshet, Guriat, and Tarif)

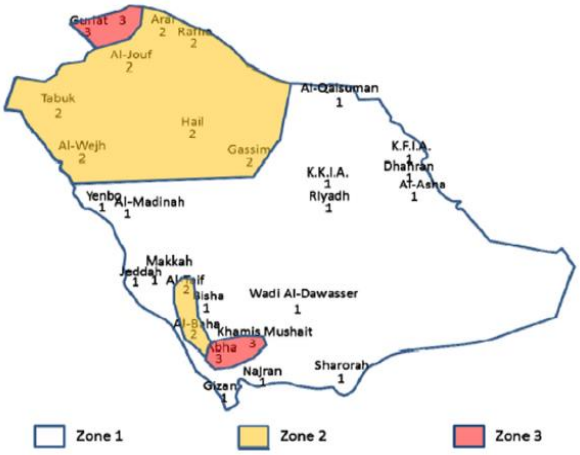


Figure 3.5 Climate zones of KSA (Source: SASO).

With the help of recent climate data obtained from the "world weather information service", by the world meteorological organization, table 3.2 presents the total monthly and average temperature data for three different cities in different climate zones in the KSA, namely: Hail, Abha and Dhahran.

Table 3.2 Average minimum and maximum temperatures in three different climate zones in KSA (world weather information service, 2018, Dec 3).

City	Hail		Abha		Dhahran	
Month	Mean Daily Mini Temp (°C)	Mean Daily Max Temp (°C)	Mean Daily Mini Temp (°C)	Mean Daily Max Temp (°C)	Mean Daily Min Temp (°C)	Mean Daily Max Temp (°C)
Jan	3.8	17.2	7.7	19.5	9.6	21.0
Feb	5.4	19.6	9.3	20.9	11.4	23.8
Mar	9.2	23.5	11.1	22.8	14.6	29.1
Apr	14.6	29.2	12.7	25.1	19.9	34.4
May	19.7	34.3	14.8	28.4	24.9	40.6
Jun	22.2	38.1	16.6	30.8	27.7	43.6
Jul	23.2	39.1	17.1	30.5	29.3	45.0
Aug	23.7	39.8	16.7	30.4	28.8	44.7
Sep	21.0	37.7	14.9	29.4	25.3	41.5
Oct	16.1	32.2	11.4	25.9	21.2	37.4
Nov	10.2	24.1	8.8	22.8	16.0	28.9
Dec	5.4	19.1	7.2	20.7	11.3	23.0

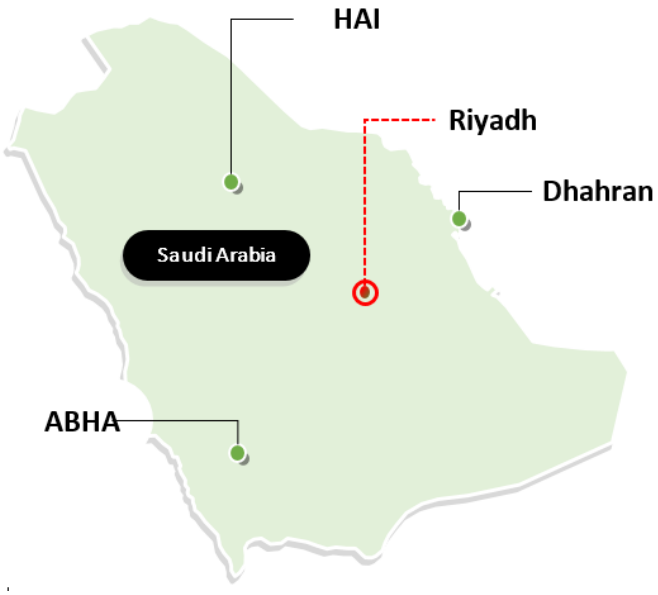


Figure 3.6 The locations of the selected cities.*6.*3 Figure

3.5. Selection of Case study and Location applied in (KSA)

Initially, the decision to locate the study in the KSA was made for a number of reasons; in particular, the fact that the KSA has a large number of mosques and there are few publications to date on the performance of mosques. In addition, this study can benefit other mosque buildings in parts of the world that share similar climatic conditions.

Selecting the case study of a typical mosque requires agreement regarding the size of mosque that is most common, but also access to a newly built mosque, for which the architectural drawings and specifications of the building are available as well as the electricity bills. An early visit to Hail city in KSA was undertaken to obtain all documents and to conduct a site observation. Three different regions in KSA were identified for this research. The original location of the

case study was Hail city (central region), which is the largest region in KSA, and includes the capital (Riyadh), which has a hot-dry climate in summer and a cold-dry climate in winter. A similar model was implemented in Dhahran and Abha. Dhahran experiences hot and moist climate during summers and moderate-moist climate in winters. Abha experiences moderate-moist climate during summer season and cold-moist climate in winters. Several different climatic zones were chosen to maximize the potential value of this research for future scholars, particularly in areas with similar climatic conditions.

3.6. Case Study for typical Mosque

The case study relates to mosque buildings located in Hail city, Lobdah district, KSA. The mosque was re-built in 2011 and used for the five daily prayers only. Figure 3.7 depicts the mosque. It has a rectangular plan form with dimensions of 17 x 23 m and a floor area of 391 m2. It is a small mosque, and consists of one storey offering capacity for around 375 people. The mosque has two entrances, a main entrance for people to congregate in, and a small entrance for the Imam. It has a dome-shaped attic with vertical skylights (located at the top of the central zone of the main prayer hall), and a tall minaret located at the South East corner of the mosque, as shown in Figure 3.8. For further information, the remaining drawings can be found in Appendix B.



Figure 3.7 Different photos showing the inside and outside of the Hail mosque.

The current study investigates energy consumption inside a typical mosque in a region with three different Climatic conditions, and pertinent to three cities in KSA (namely, Hail, Dhahran, and Abha) Hail (central region) is the representative case for a hot-dry climate in summer and a cold-dry climate in winter. Dhahran (Eastern region, by the Gulf Sea) is the representative case for a hot humid climate in summer and a moderate-humid climate in winter. Abha (south-western high inland region) is the representative case for a moderate humid climate in summer and a cold-humid climate in winter. The prevailing concerns associated with the buildings in these three cities are heat gain through the buildings' fabric and components, due to the fiercely hot and humid climate during the summer months. Therefore, the principal aim of this section of this research is to conduct a comparative study and investigate the issue of thermal comfort as it relates to energy demands for cooling in mosques in these three cities.

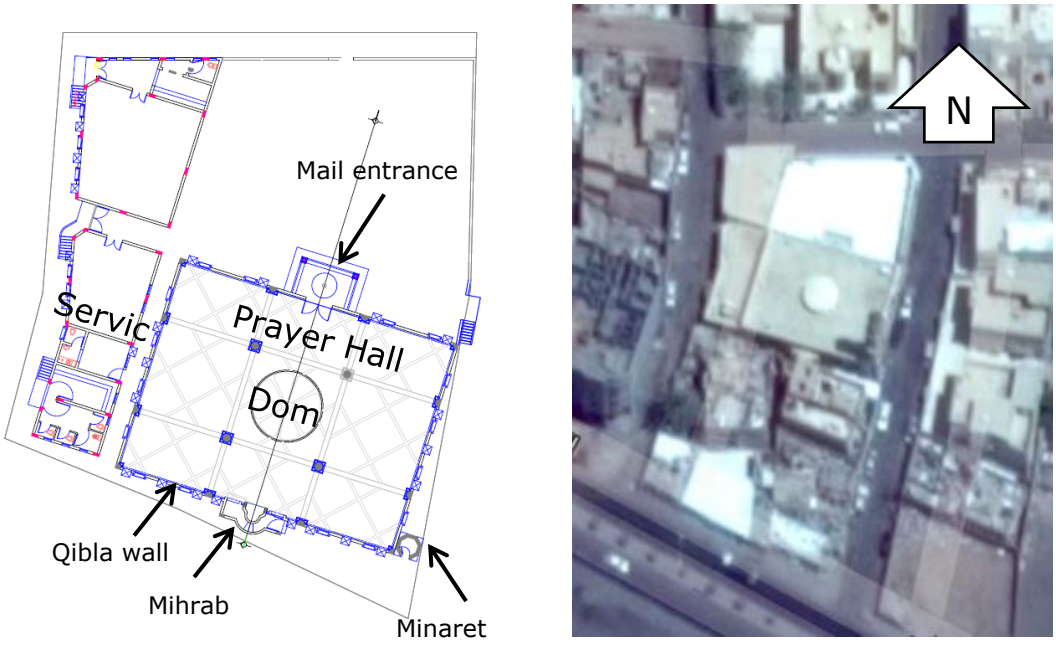


Figure 3.8 Site Plan for the Hail mosque building.

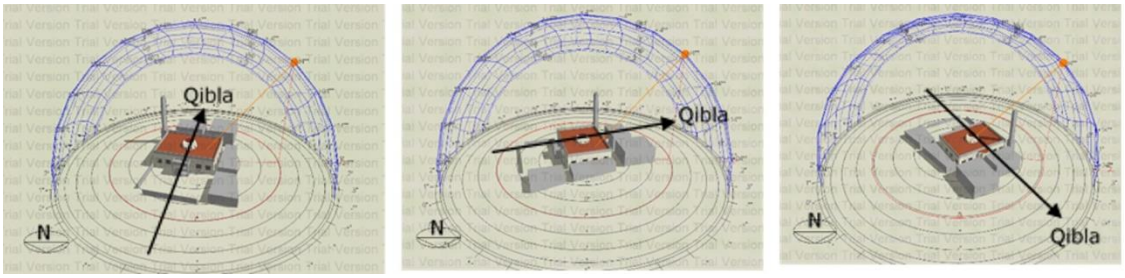


Figure 3.9 a) Hail b) Dhahran c) Abha

The orientation of the building is set out according to Qibla, as each city faces a different direction, which a consequent effect on solar gain, see Figure 3.9.The case study will investigate the mosque's energy performance in three selected cities in KSA. To evaluate thermal comfort in each, climate consultant software was used to highlight a suitable design strategy on a Psychrometric chart, as seen in Figure 3.10 the design strategy zone data which create a list of guidelines for each city through a year.

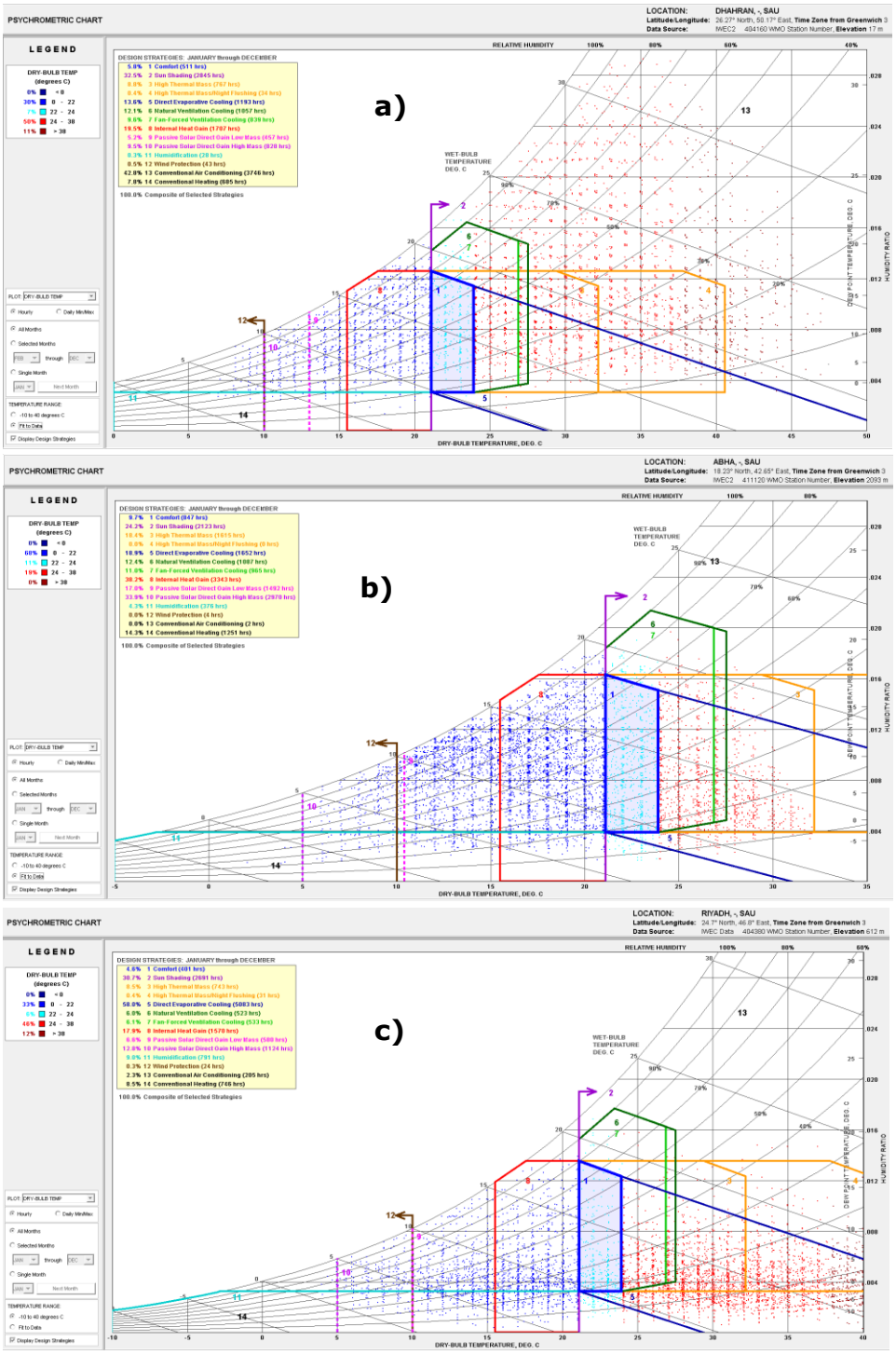


Figure 3.10 Thermal comfort zones for a) Dhahran b) Abha and c) Hail

3.7. Energy modelling simulation tool

Diverse design arrangements can be efficiently tested with computer simulation method which saves time and cost. This method is useful to evaluate efficiency of a building at each phase from the designing phase to the utilization phase .This method eliminates the need to conduct analysis of structure of building and estimation of cost for model .Moreover, the method is preferred by architects since it does not involve complex calculations.

At the present time, simulation programs and energy modelling software are widely available to the market, some of these are simple and straightforward to use, but others are more complex. In addition, some programs have been especially designed and created to suit a specific type of building. However, there is no specific programme tailored to mosque buildings. Examples of simulation software are the IES virtual environment, TAS, ECOTECT, Design Builder and Energy Plus.

Each tool is characterised by certain form of restriction and hence all of the design and performance variables cannot be exploited for simulation purpose. The selection of appropriate tools for design and performance variables is imperative in this regard. Table 3.2 summarises the design and performance variables for the selected simulation tools (Lim, 2012).

Table 3.2 Summary of design and performance variables for various simulation tools (Lim, 2012).

Simulation Tools	Climate zone	Graphical Interface	DESIGN VARIABLE												PERFORMANCE VARIABLE										
			External Shading			Internal Shading			Building Geometry						Thermal				Visual				Other			
			Horizontal	Vertical	Egg-crate	Louvers	Blinds	Glazing	Depth	Width	Angle	Window-to-wall	Spacing	Colour	Solar radiation	Solar transmit	Temperature	Ventilation	Illuminance	Luminance	Daylight Factor	Glare	View	Energy	HVAC	Free License
DOE-2.2	W		•	•				•	•	•	•	•	•		•	•	•		•			•		•	•	•
Ecotect Analysis	W	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•		•		•		•	•		
Energy Plus	W	P	•	•			•	•				•			•	•	•	•	•			•		•	•	•
e-QUEST-3	W	•	•	•			•	•	•	•	•	•	•		•	•	•		•			•		•	•	•
IES <VE>	W	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	
Design Builder	W	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•		•	•	
Radiance	L	•	•	•	•	•	•	•	•	•	•	•	•	•					•	•	•					•
VELUX DV	L	•	•	•	•	•		•	•	•	•	•	•	•					•	•	•					•

W = Weather file; L=Location; P = Plug-in available

It is difficult to choose a specific program from among the many highly advanced and accurate tools used worldwide. However, a choice must be made to implement all the required simulations.

In addition, Energy Plus is one of the many suitable building simulation tools, however it requires a high level of knowledge, which is dependent on a high technical format as a means of defining energy performance. In addition, it requires additional time for training and simulation implementation, as this aspect of the research simulation will be repeated several times for the purpose of investigation. In fact, Design Builder was initially launched as a more user-friendly version of Energy Plus. For these reasons, we will cover only Design Builder here.

3.7.1. Design Builder (DB)

Design Builder is a newer version of Energy Plus that uses its own simulation engine via Energy Plus accounts. It can be classified as an environment modelling program, covering multiple aspects of environmental performance, such as indoor comfort data, types of air-conditioning, natural ventilation, and controlling daylight with advanced solar shading.

The tool is designed to be simple; accordingly it has found a large audience of engineers, architects, and academic researchers. It is a useful educational tool intended for the purposes of learning; in addition, it encourages the student to focus on energy performance instead of consuming additional time learning how to use the software. Nevertheless, The program's outputs are comprehensive and cover all areas, highlighting aspects that are frequently sought, including the most important in this research; i.e. assessment of cooling load.

3.8. Case study: mosque building model

The DB user interface showing a 3D view of a typical mosque building is shown in Figure 3.11. The details for the prayer hall zone show a typical mosque layout, lighting, equipment, HVAC, and number of occupants (see Table 3.3).

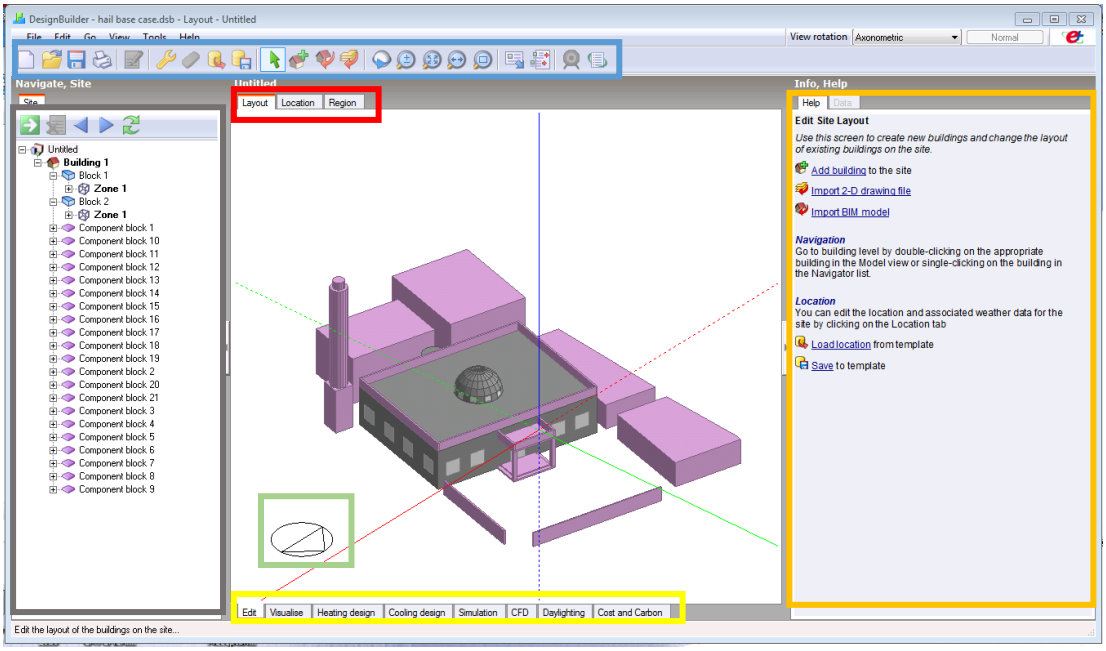


Figure 3.11 Mosque building 3D view in Design Builder's

The input data, once collected via observation, and entered into the DB simulation software (as presented in Table 3.3), identified the envelope, fabrics, materials, windows, doors, internal gain (occupants, lighting, and equipment) and HVAC systems. The operational uses determined by mosque occupancy, lighting, and A/C operation, are directly determined by the fixed five times daily prayer schedule, as a one hour duration is assumed per a day. In this existing mosque the maximum occupancy density is about 375 while by observation was assumed a minimum of 75 person per each prayer time. The thermal properties for base case mosque buildings, such as types of insulation and thicknesses of walls etc. were obtained from the Ministry of Islamic Affairs (MOIA) by (Shohan, 2015), and other architecture agencies (see Appendix C). In addition, the actual electricity bills for the mosque buildings were obtained from the SCECO.

3.8.1. Input data, assumptions and situation of the mosque

Table 3.3 Base case input data

Building Component			
floor area (m^2)	391 m^2		
Window to Wall area (%)	30 %		
Floor-to-ceiling height (m)	5.5 m		
Wall U-value ($W/m^2\ ^0C$)	1.592		
Thermal insulation placement	Un-insulated		
Roof U-value ($W/m^2\ ^0C$)	1.815		
Window type	Single glazing		
Window U-value ($W/m^2\ ^0C$)	5.778		
Window shading	Un-shaded		
Door type	Wood		
Building service			
Lighting power density (W/m^2)	5.0		
Air infiltration rate (ACH)	0.8(Minimum) 1.0(maximum) (during occupied periods)		
Maximum occupancy (person)	375		
Minimum occupancy (person)	75		
Type of HVAC system	Split (heating (CoP) 1.500 – Cooling (CoP) 1.830)		
Cooling set-point temperature (^0C)	27.0		
Heating set-point temperature (^0C)	21.0		
RH Humidification set-point (%)	60.0		
RH Dehumidification set-point (%)	80.0		
Weather Data	**Hail**	**Dhahran**	**Abha**
Dry-bulb temperature (Tout)	41.8 °C	44.7°C	30.4
Relative Humidity (RH)	29.2 %	52.5 %	23.8 %
Wind speed (Vout)	14 km/h	19 km/h	17 km/h



Figure 3.12 a) Type of HVAC system b) Door type c) Window

3.9. Base case energy consumption

Base case: The base case represents the standard practice for the mosque buildings constructed with the standard building materials. In terms of the construction of a mosque building and its thermal properties, the external walls are constructed from concrete blocks without any insulation, thereby rendering it a thermally lightweight building. In addition, is the mosque building has no thermal insulation of the roof, although it has water insulation. It should be mentioned here that the materials described in Appendix C are considered as the typical materials that are used in each mosque building (Shohan, 2015). However, there are some small alterations in some these materials depending on individual mosque building's design and specifications, including some alterations in the materials' thicknesses and colours.

The modelling of electrical energy use in the existing mosque was performed using the data from 2002. To validat the simulation data in Figure 3.13 showed the simulation and the actual bills for the existing mosque which clear that the different about 2%. Figure 3.14 shows the total energy consumption for the baseline case, with the highest energy consumption being 3606 kWh noted on the month of July. Figure 3.15 reveals that cooling load constitutes the highest amount of energy consumption, with maximum cooling load occurring in August. At this point, the cooling load covers 100% of total energy demand, with the highest outside air temperature being 36.4^{o}C, as identified.

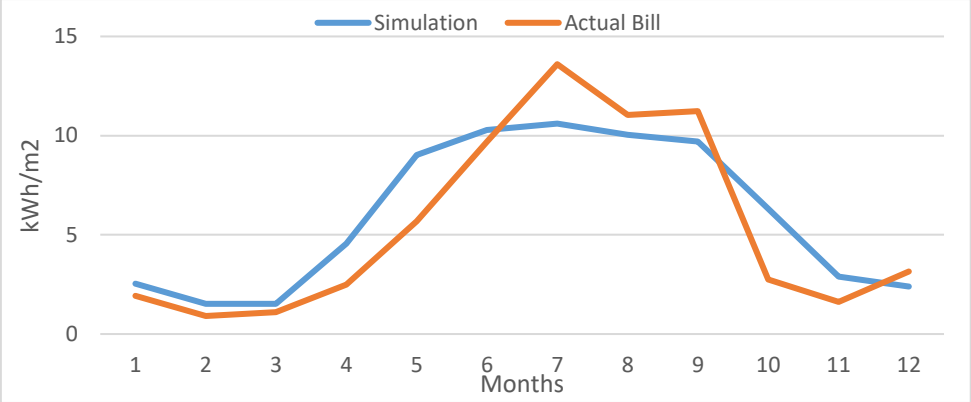


Figure 3.13 total electricity consumption for Simulation data compere with the case study Actual bill

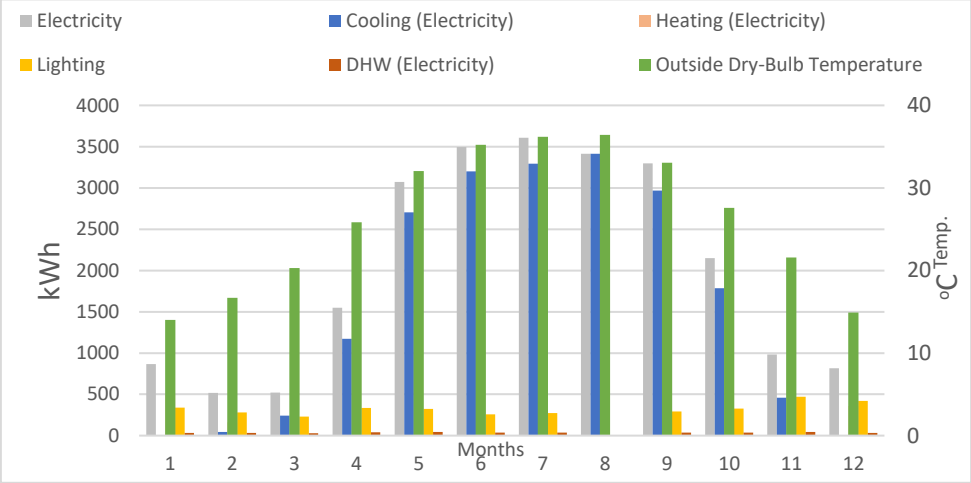


Figure 3.14 Hail base case - Electricity Consumption.

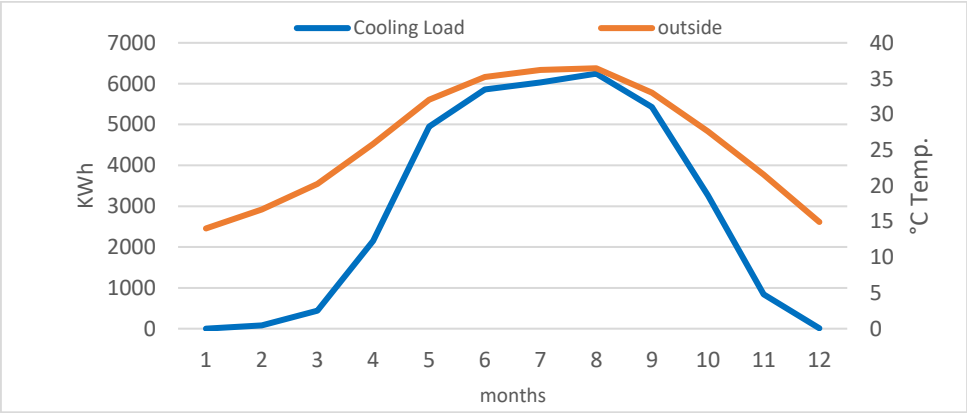


Figure 3.15 Hail base case – Cooling load and temperature

The simulation analysis was carried out for the base case (Hail) and then the data applied to the two other locations with different climatic conditions. Figure 3.16 represents solar heat gain, which definitely had the most impact on building energy consumption. The highest solar gain is observed in Hail, with the lowest in Dhahran. This trend is reflected in energy consumption for cooling, as shown in Figure 3.17

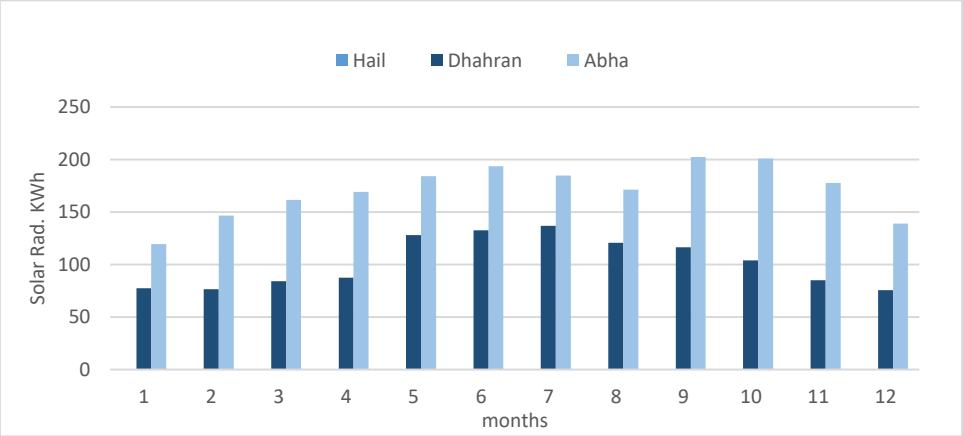


Figure 3.16 Direct normal solar (Hail, Dhahran and Abha)

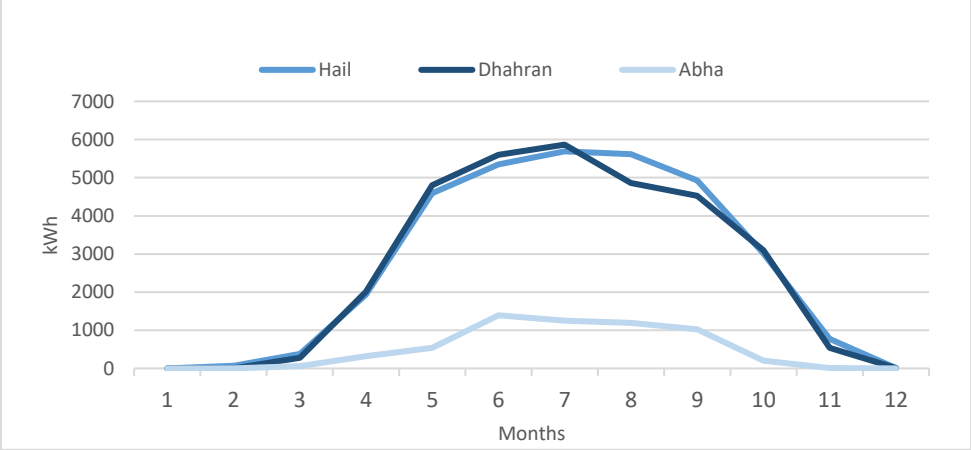


Figure 3.17 Cooling load (Hail, Dhahran and Abha).

Figure 3.18 Shows the wind speed for the base case, as applied to the three different cities; Hail, Dhahran and Abha. The highest wind speed was 5.64 m/s, and this was observed in Dhahran in June, followed by Hail and Abha at 4.25 m/s each in July and January respectively. The lowest speed of 1.11 m/s was seen in November in Hail. However higher speeds were witnessed in Dhahran and Hail during the summer months; whereas Abha experienced the highest wind speed during the winter. As indicated in Figure 3.19, RH is less in the summer months than in winter. In summer (July), Hail experienced lower RH at 17.23%, while in Dhahran and Abha, it was about 35% and 41% respectively.

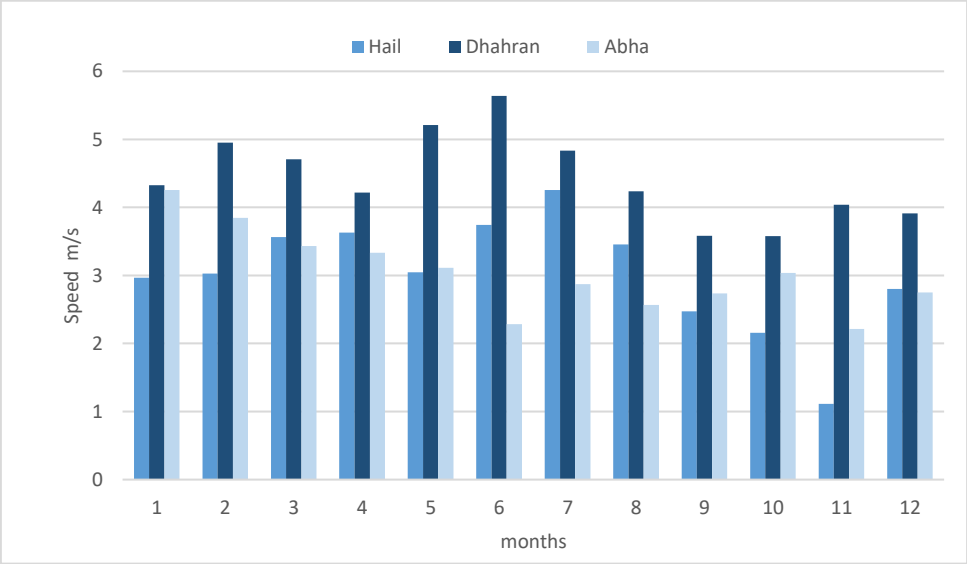


Figure 3.18 Wind speed (Hail, Dhahan and Abha)

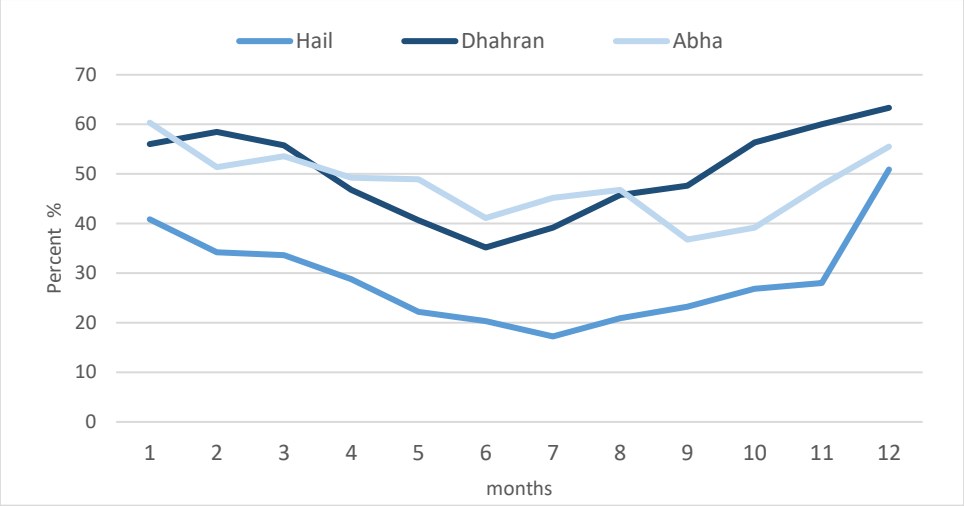
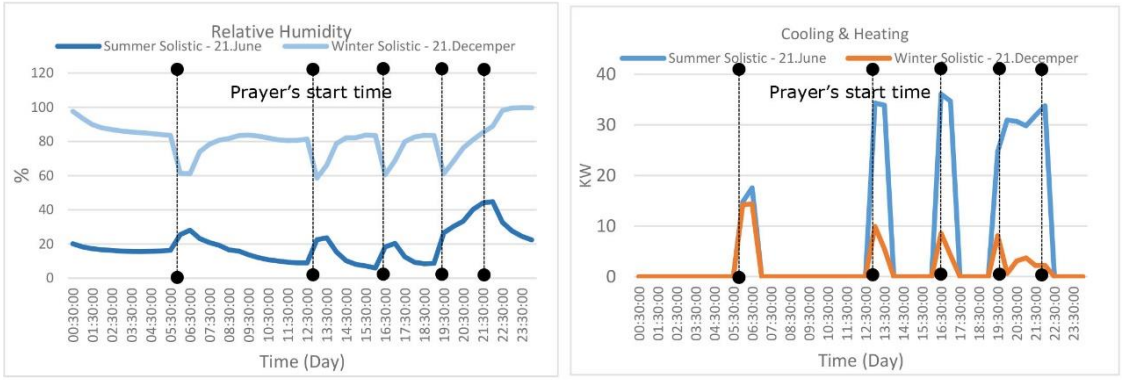


Figure 3.19 RH (Hail, Dhahran and Abha).

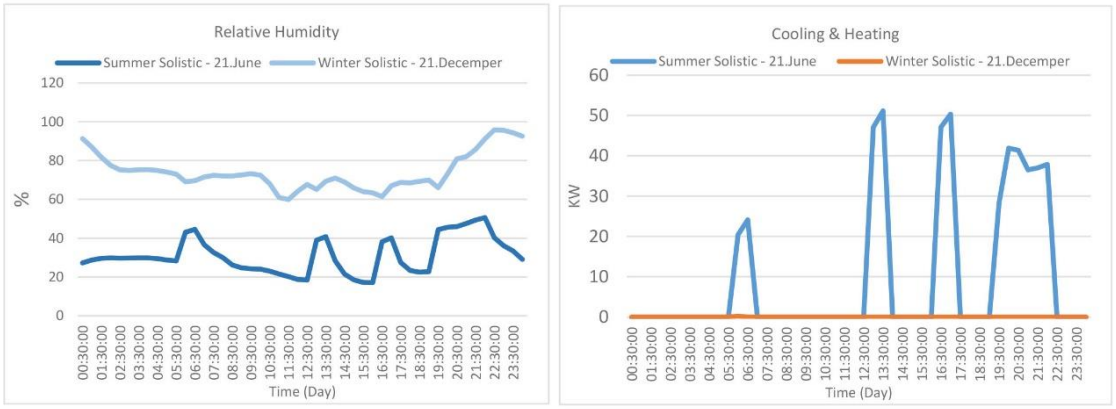
Figure 3.20 presents the RH measurements and cooling and heating load for all the three cities on the days of the summer and winter solstices.

In Figure 3.20(a), for Hail city, it is indicated that the RH on the summer solstice had a low of 9%, while at prayer time, when the air conditioners (A/Cs) are turned on, the RH increased to about 23%. On the winter solstice day, RH peaks at 99%, reducing to 60% at prayer times, with a cooling load of 36KW.

In Figure 3.20(b), the RH for Dhahran city in summer reaches 17%, but when the A/Cs are turned on, it increases to 50%, with a cooling load of 51KW. In figure 12c, for Abha city, the RH in summer is 13%, although it rises to 51% during prayer times, when a cooling load of 15KW is observed.



a)



b)



c)

Figure 3.20 Base case a) Hail b) Dhahran c) Abha

3.10. Proposed improvements strategies

In the literature review in Chapter 2, various elements of green-building design strategies were discussed; for example, orientation, shape, building envelope, openings-windows and natural ventilation. Each of these can have vary in effect when applied to buildings. For example, applying insulation to a building envelope requires consideration of orientation, insulation thickness, positioning on or within the building envelope. Likewise, window openings and shading have a strong impact on building performance in hot conditions. It is difficult to apply natural ventilation to buildings in hot and particularly humid regions, although this is possible at night time, when external temperatures become cooler falling below the level of internal thermal comfort.

3.10.1. Passive cooling solutions

In order to reduce the cooling load, several options were given for each of the three different climate cases (hot/cold-arid, hot-humid, and moderate/cold-mountainous). The potential for reducing energy consumption, and the impact of applying different passive techniques on the existing mosque are analysed as follows:

i) Wall insulation: Currently, the thermal conditions inside a building are improved with insulated exterior walls. By using thermal insulations, resistance of building against heat exchange is enhanced which consequently prevents heat absorption and heat loss. This method has been applied in the mosques experiencing each of the three different climatic

conditions, with upgraded insulation materials having better U-values according to the result of integrated within the mosque building envelope by (Shohan, 2015) as shown in Table 3.4. The simulation for this case has been carried out by incorporating roof and window insulation.

ii) Roof insulation: In this method, the insulated roof is used to improve the thermal environment of indoor spaces, most importantly in the summer. This technique has also been applied in three different climatic conditions using the same materials, as described in the first method, and as demonstrated in Table 3.4. Similarly, the simulation was carried out to test without wall and window insulations.

iii) Window-Double Glazing: This insulation method has also been tested at the three locations, considering the double-glazed windows with much better U-values, rather than the single glazed type; as indicated in Table 3.4. Likewise, the wall and roof insulation were being considered during the simulation of this case.

Table 3.4 Construction types of insulation cases.

		Base case	Wall insulation	Roof insulation	Window Double Glazing
Wall	R-Value (m2-k/W)	0.628	2.414		
	U-Value (W/m2-k)	1.592	0.414		
Roof	R-Value (m2-k/W)	0.55		2.337	
	U-Value (W/m2-k)	1.815		0.428	
Window	U-Value (W/m2-k)	5.778			2.665

iv) Envelope-shading: Shading devices are used rather than insulation materials in this case. This informs the solar gains

via the roof, external walls and windows, as shown in Figure 3.21. Physical, vertical, and horizontal shading devices block the passage of solar radiation through the building envelope and glazed windows into the indoor prayer halls, thereby improving thermal comfort.

v) Combination of wall, roof, window insulation and shading devices: This insulation configuration combines all the methods explained above to allow for the examination of the effects of envelope insulation and shading.

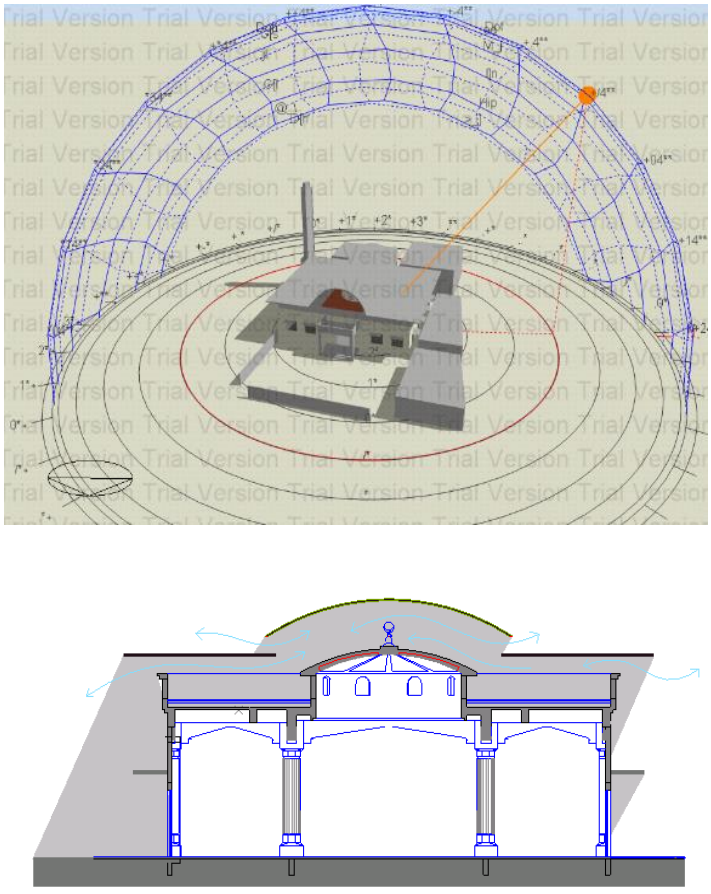


Figure 3.21 Building envelope shading

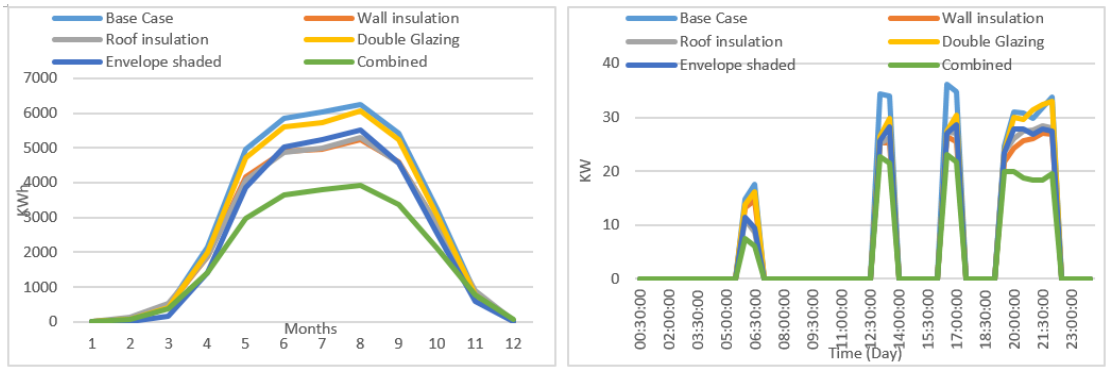


Figure 3.22 Cooling load by applying different strategies - Hail City

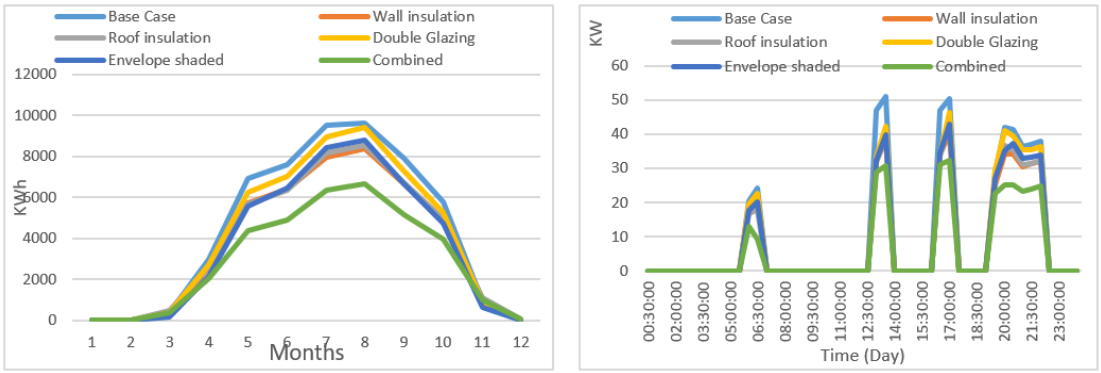


Figure 3.23 Cooling load by applying different strategies – Dhahran

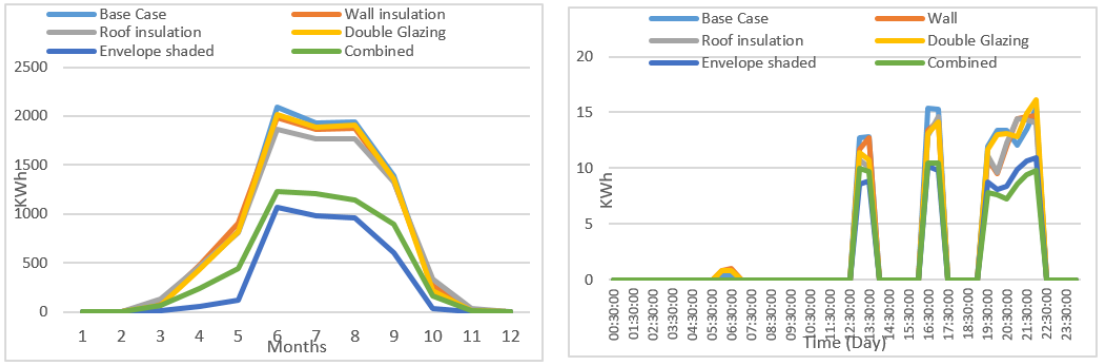


Figure 3.24 cooling load by applying different strategies - Abha City

Table 3.5 shows the potential of each method to reduce the cooling load. Figure 3.22 shows that in Hail city (Hot-Dry), the total annual cooling load is reduced by 37% due to the application of wall, roof, and double-glazed window insulation, in addition to the full envelope shading method. Likewise, the cooling load on the day of the summer solstice reduced from 34KW to 21KW. Figure 3.23 shows that for Dhahran city (Hot-humid), the total annual cooling load fell by 30%, due to the application of a combined strategy. In addition, the cooling load on the summer solstice reduced from 51KW to 30KW.

Table 3.5 the potential percentage of each case.

Reducing the cooling load (hottest day - summer)						
	Base case	**Wall Ins.**	**Roof Ins.**	**Double G.**	**Env. Shading**	**Combined**
Hali City	100%	15.9 %	15.1 %	3 %	11.9 %	37 %
Dhahran	100%	13.1 %	11 %	2 %	8.6 %	30 %
Abha	100%	3.4 %	9 %	1.7 %	50 %	40 %

The combination of roof and wall shading with conventional fabric insulation on walls as well as the roof, and double-glazed windows, reveals potential for exploiting the design and construction features of the combined strategy, as a means to improve the environmental and energy performance of existing mosque buildings. Consequently, the reduction in the cooling load in Hail, Dhahran and Abha is about 37%, 30% and 40%, respectively, as compared to an uninsulated and unshaded base case mosque. This is a direct reflection of the reduction in wall, roof and glazing insulation heat gain.

3.11. Active approach using evaporative cooling system

Employing a passive approach, Table 3.5 shows a summary of results for the cooling load reduction for the mosque building in the three cities; Hail (hot-dry climate), Dhahran (hot humid climate) and Abha (moderate humid). With regard to the active approach, the literature review reveals that evaporative cooling is a suitable method of cooling the building, and RH is observed to be low for the majority of the year. Consequently, Hail and Abha cities qualify as apply evaporative cooling methods. In contrast, Dhahran has the highest RH, and is not suited to this type of cooling which excluding as shown in table 3.6. In particular, Hail and Abha cities are ideal areas in which to implement evaporative cooling, due to the nature of their climates. According to Boukhanouf et al. (2013), sub-wet bulb temperature evaporative cooling systems can achieve cooling capacities of 225 W/m^2 of floor area.

This work focuses on adapting the design of a minaret to successfully deliver thermal comfort in mosques. The structure of a minaret lends itself well to providing energy efficient and passive cooling. Previous research has shown that evaporative cooling as integrated as a building element has been practised for centuries in the Middle East region.To implement the sub-wet blue temperature cooling system, as an indirect evaporative system, with cooling a capacity of 225 W/m^2, for the Hail case with a cooling load of 23067 W, a wet surface area of about 102 m^2 is needed to meet the cooling load demand for the prayer room. Whereas in Abha, about 46m^2 of wet surface area is required to meet the 10465 W of cooling load demand. Consequently, minaret size, according to wet surface area needed for each city (Hail, Abha) is detailed in next chapter.

Table 3.6 Mosque cooling load on typical summer day.

	Mosque Cooling Load (W)	cooling capacity of porous ceramic (w/m^2)	wet surface area (m^2)
Hail	23067	225	102
~~Dhahran~~	~~32385~~	~~225~~	~~144~~
Abha	10465	225	46

3.12. Summary

Evaporative cooling is a traditional method, which has been intrinsic to Middle East architectural heritage for many centuries. It provides thermal comfort in buildings for occupants undergoing the harshest of weather conditions, with minimum impact on the natural environment. Building on this, the current research attempts to apply the principle of evaporative cooling using up to date advancements in knowledge and materials science to adapt an important building element of mosques- the minaret- to extend its functionality and capacity to provide cooling. Both sub-wet bulb evaporative cooling and use of optimising porous ceramic structures within a minaret have the potential to advance design and thermal comfort, while minimising energy consumption in mosques in those regions that experience hot and dry climatic conditions. The results for the simulation performed using KSA as a case study, show potential for exploiting design and construction features to improve the environmental and energy performance of existing mosque structures. For example, it was noted that on the hottest day in summer, the cooling load in Hail, Dhahran and Abha fell to about 23067 W, 32385 W and 10465 W, respectively.

Chapter 4. Design and integration of evaporative cooling into a mosque's minaret

4.1. Background

This chapter discusses the design and integration of an evaporative cooling system into the envelope of a mosque, specifically the minaret, highlighting the construction forms, the purpose and location of various aspects of the mosque, and the evolving function of the minaret in modern mosques. The contemporary architectural challenge is to create new concepts and designs for minarets that incorporate its traditional function of a landmark for the mosque with its potential role of enhancing the environmental and thermal comfort of worshippers. This chapter discusses the adaptation of the minaret as a multi-functional element of the mosque, including serving as a passive air cooler, using an integrated windcatcher/evaporative cooling system. The proposed design considers the cooler configuration, and the cooling specification of the building, together with the construction materials of both porous ceramic and synthetic grass mats. The ceramic materials are compatible with integration into the structure of the minaret, while the synthetic material offers a modular design and flexibility for integration in the structure.

4.2. The minaret

The minaret is an integral part of a mosque. It is a tall, vertical architectural feature that is utilized for the call to prayer (adhan). In spiritual terms, alongside the dome, which signifies the arch of

heaven, the minaret represents the assertion of the Islamic faith. The minaret is an outstanding structure that offers an apparent focus and serves as a landmark. It may be either independently placed or may be longer than its supporting constructs. Traditionally, the call to prayer was performed from the gallery encircling the shaft of the minaret, however it is now conducted from the prayer hall, via an external loudspeaker mounted on the minaret. However, modern architects continue to view the elements of mosque architecture, such as the minaret, in a traditional way, without seeking to innovate, and redeploy them as a construction element. Therefore, many aspects of mosque buildings have become examples of environmental disfigurement. The minaret typifies this, as it is no longer required for the purpose of advertising and the call to prayer.

The earliest mosque, the Prophet Muhammad mosque in Madina, was built with a flat roof and no minaret, and the Muslim community of Madina was called to prayer from the roof of the house of the Prophet. The Umayyad dynasty were the first to incorporate minarets as an architectural feature of mosques, in Syria (Creswell, 1926).

4.3. Type and structure of a minaret

In contemporary mosques, minarets are built in a range of geometrical shapes and sizes, distinguished by the period of construction, and by regional characteristics. For example, they can be conical, square, cylindrical, or polygonal, as illustrated in Figure 4.1.

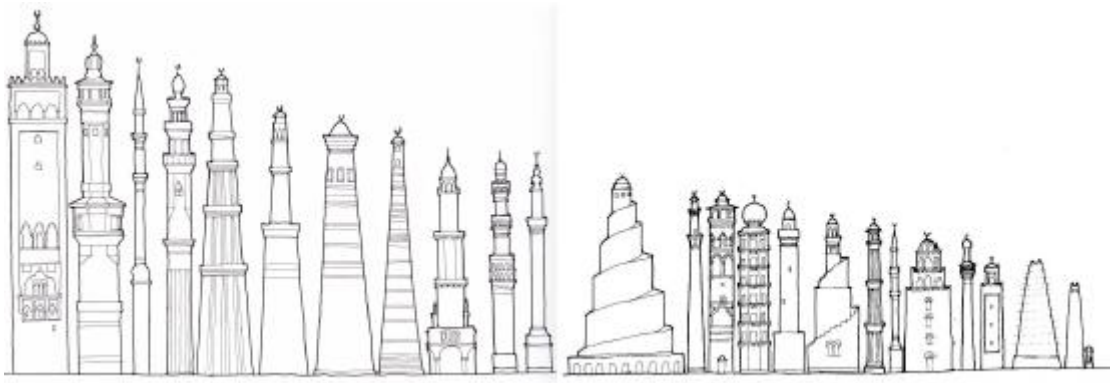


Figure 4.1 Minaret shapes and sizes (Adams, 2017).

The basic minaret structure is constituted of a base; a shaft, or long vertical hole; and a balcony. A staircase within the shaft provides access to the top, and is used to support the structure, while the balcony or balconies are located around the shaft. Generally, minarets are topped with a curved roof, and decorated with different materials and architectural features, such as cornices, arches, and inscriptions. The gradient from the shaft to the balcony is delineated by muqarnas decoration, and the degree of luxury decoration determines the minaret's origin and period (Creswell, 1926).

Recently, Alenazi (2017) studied the type and characteristics of mosque minarets, and identified three main shapes of historical minarets. Figure 4.2 shows the main categories of these, and the period and location of each, illustrating the fact that old minarets are found in three basic architectural configurations: 1) Square-shaped, with the base, body, and neck of a square plan; 2) Mixed shapes, with differences in the plan of the base, body, and neck, which might be square, octagon, and circular in plan, for instance; and 3) Circular, or with a base, body, and neck of a circular or octagonal plan, with each shape representative of a different historical style.

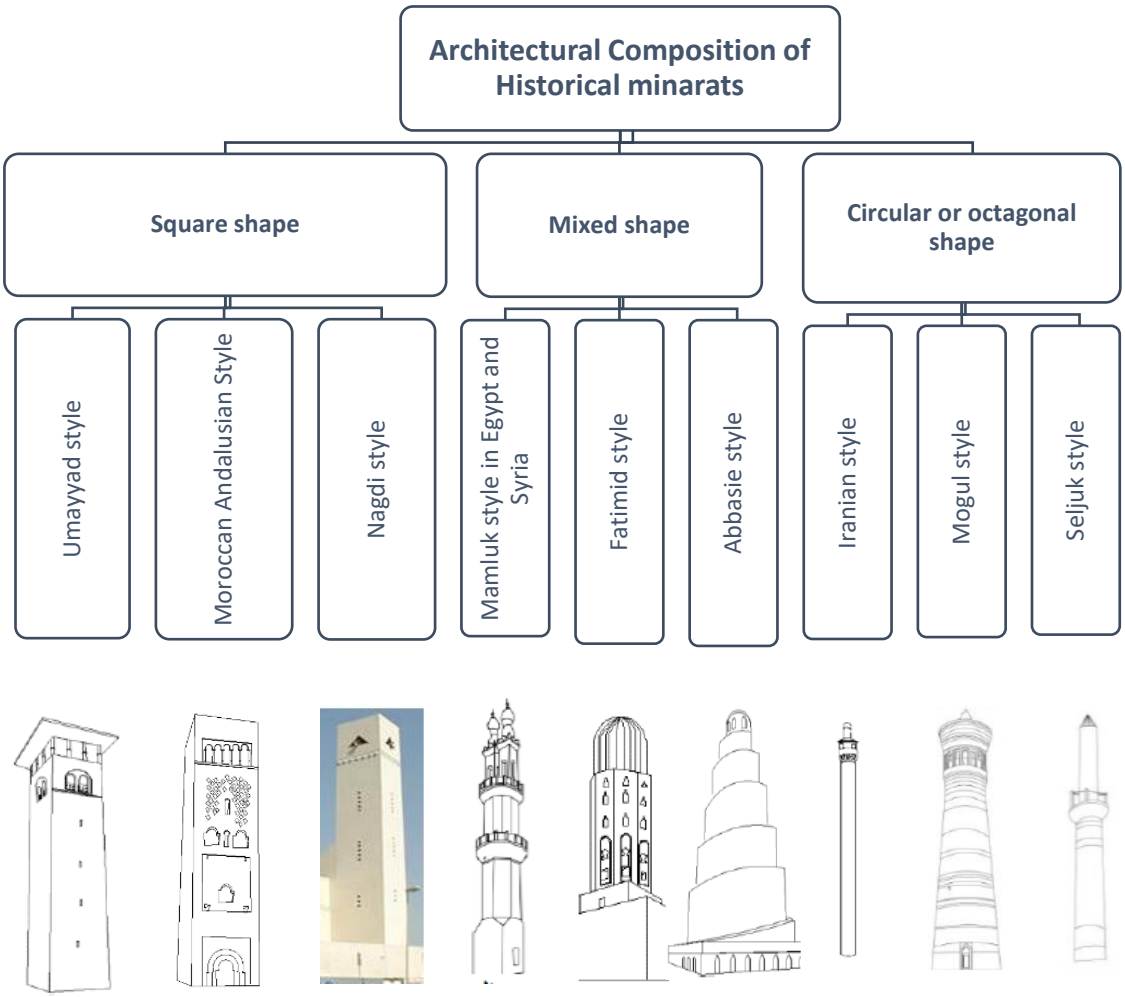


Figure 4.2 Historical styles of minarets (Source: Alenazi (2017)).

Figure 4.3 displays a representation of an Egyptian minaret from post-Fatimid era. The minaret has an intricate and distinctive structure. Every tower is designed to have three distinct segments; a square segment at its base, an octagonal segment in the centre and a dome on the upper segment. Muqarnas were used to decorate the area joining the different sections of tower.

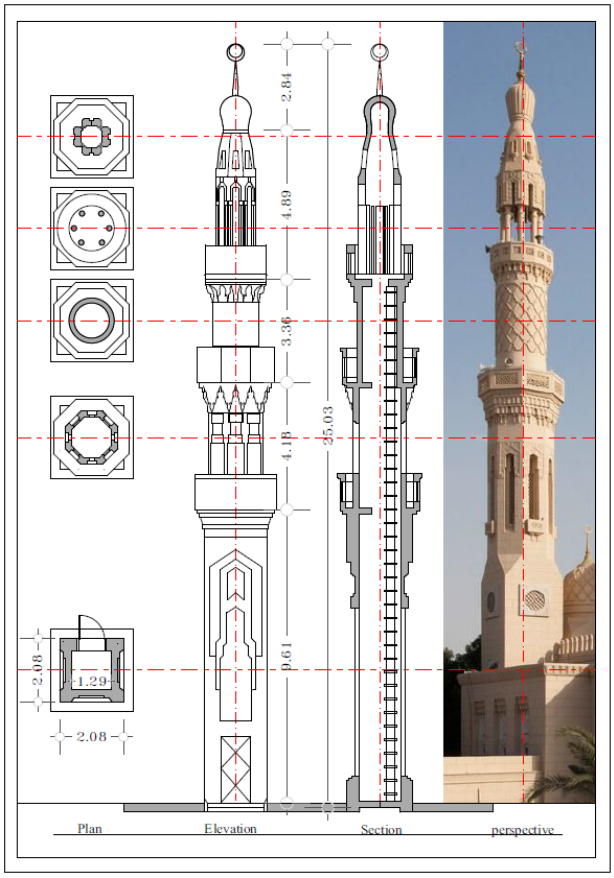


Figure 4.3 Minaret design from the time of Fatimid Egypt

Over time, the architectural design of minarets evolved from the typical designs found across the Muslim world to hybrid forms, and to the specific designs of modern mosques found in cities.

Along with his general study, Alenazi (2017) also studied the architectural style of minarets in the city of Riyadh, KSA, classifying them into the following four categories (see Figure 4.4): 1) Minarets copied from historical minarets, in 'that the minaret is reproduced only as architectural form but with differences in ratio, structural system and materials; 2) Hybrid minarets that 'Combine the old with modern or combine two different styles; 3) Minarets that translate

historical elements in modern ways; and 4) Modern minarets that are in a new form that is not related to historic styles.

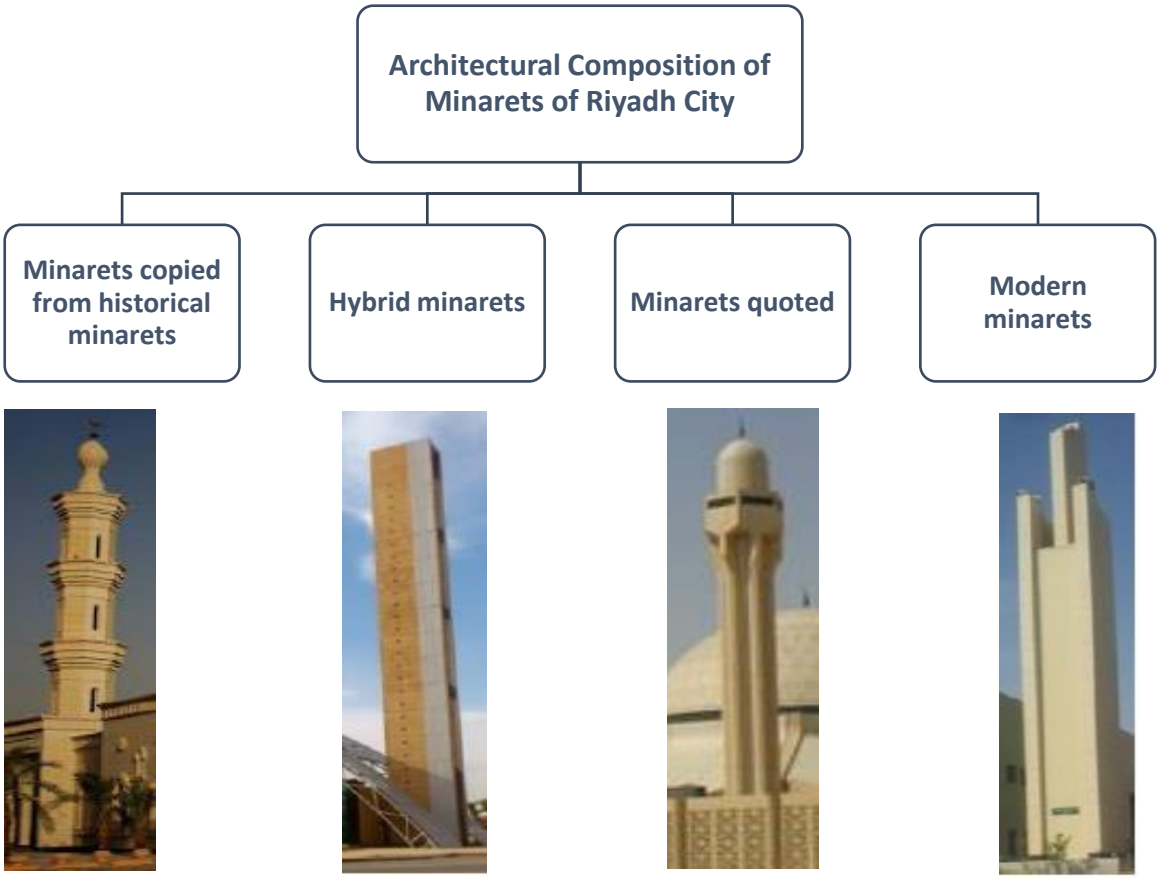


Figure 4.4 Types of mosque minarets in the city of Riyadh, KSA (Source: Alenazi (2017)).

Figure 4.5 provides an example of a contemporary minaret of a traditional form in the KSA, together with detailed construction drawings. The minaret was designed by the architect Rasem Badran for the Great Mosque of Riyadh, using a local style of Najdi architectural form, in order to create a connection between the past and the present. It was constructed using modern materials, and has a square cross section of 3.5 x 3.5 metres (m), and a height of approximately 29m. The walls of the minaret incorporate triangular

and rectangular openings at the top, conforming with the vernacular form of building practices for minarets.

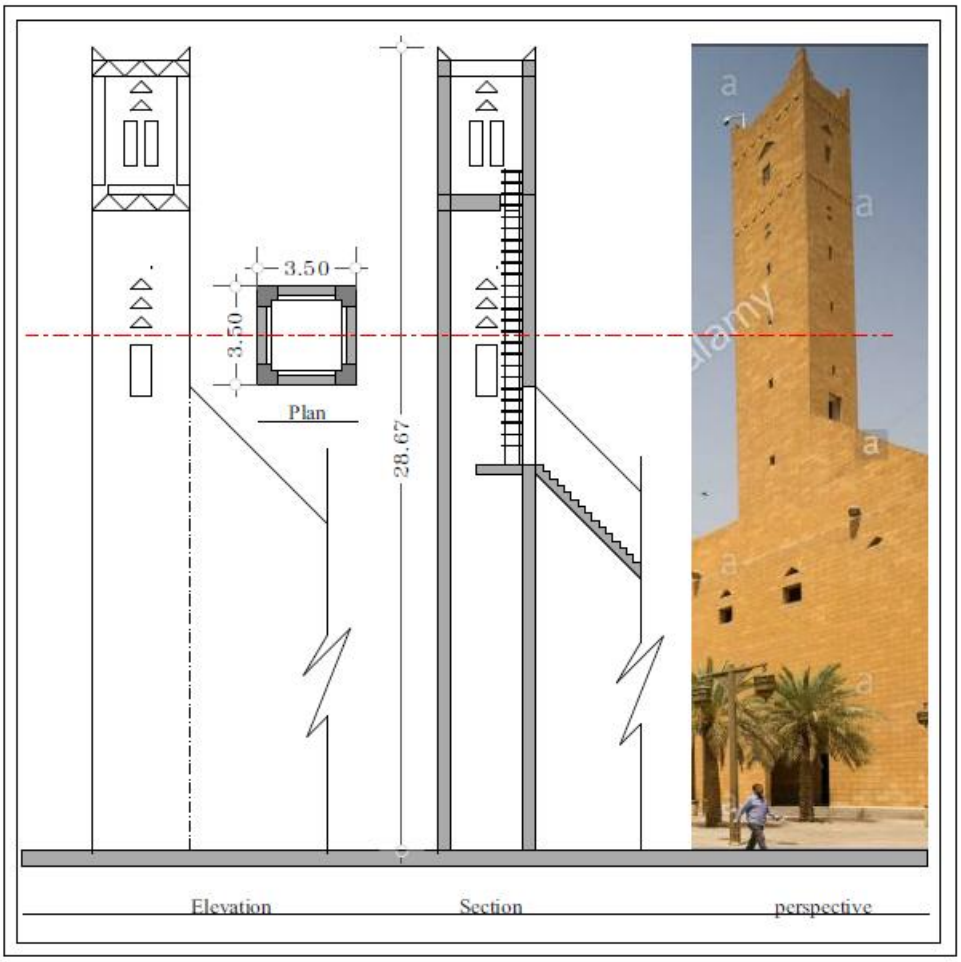


Figure 4.5 Contemporary minaret design from Riyadh, KSA The minaret's position in relation to the prayer hall

Minarets are usually self-standing elements within mosques that are either attached to the mosque's envelope, or separate from it. Even in contemporary mosque architecture, at least one minaret is included to project the presence of the mosque, although there can be four or more minarets in total. Figure 4.6 illustrates the position and number of minarets in a typical mosque.

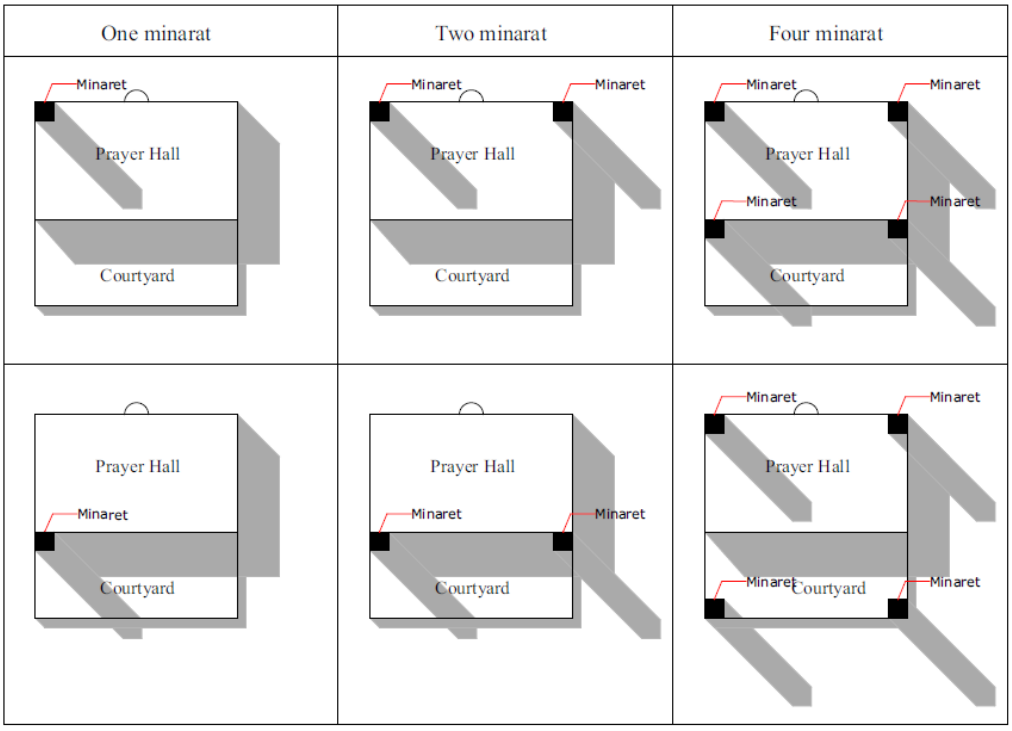


Figure 4.6 Examples of the position and number of minarets in a mosque

In order to extend the role of a minaret in a mosque to include the provision of thermal comfort, its position with respect to the prayer hall is important. As Figure 4.5 illustrates, the minaret is normally located at one of the corners of the prayer hall, with a direct connection to the inside space.

4.3.1. The minaret as a windcatcher

The top opening of a minaret can be employed to capture and channel fresh air from outside the building into the occupied space below, in the form of passive cooling. This traditional architectural design technique, known as a windcatchers, has been practiced in the Middle East for centuries, as windcatchers allow the prevailing wind to be

directed into a building's living space, usually forcing it to circulate over wet mats, water containing permeable jars, or an underground canal to cool the entering air. This technique of cooling has been applied to ventilate housing projects and schools in Egypt (Fathy, 1986), as shown in Figure 4.7.

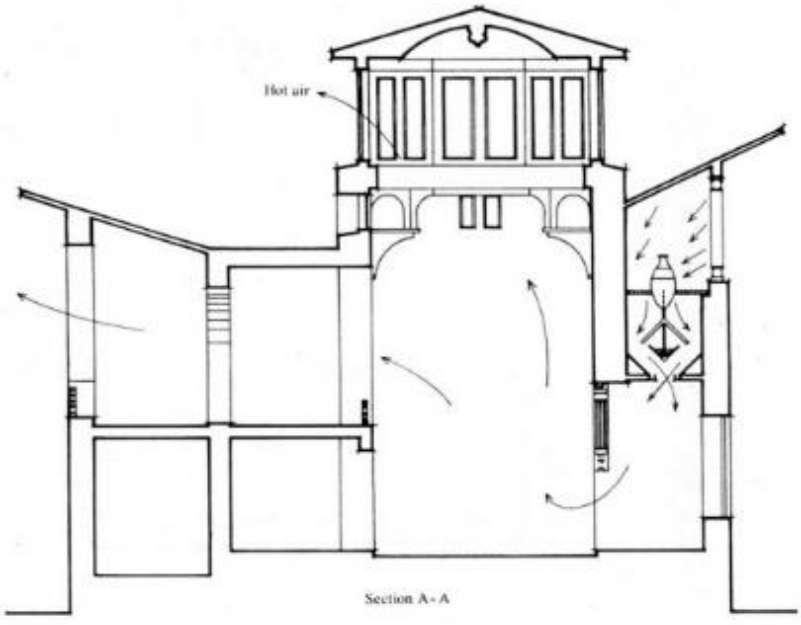


Figure 4.7 Windcatcher and Maziara water jar in Egypt (1970-80) (Source: :(Lechner, 2014)).

In addition, Imam (2003) assessed the ways in which a minaret can be employed to enhance the natural ventilation in a mosque, especially in warm-humid climates. Figure 4.8 illustrates various designs of minarets that exploit the prevailing wind direction and enhance airflow through the occupied space.

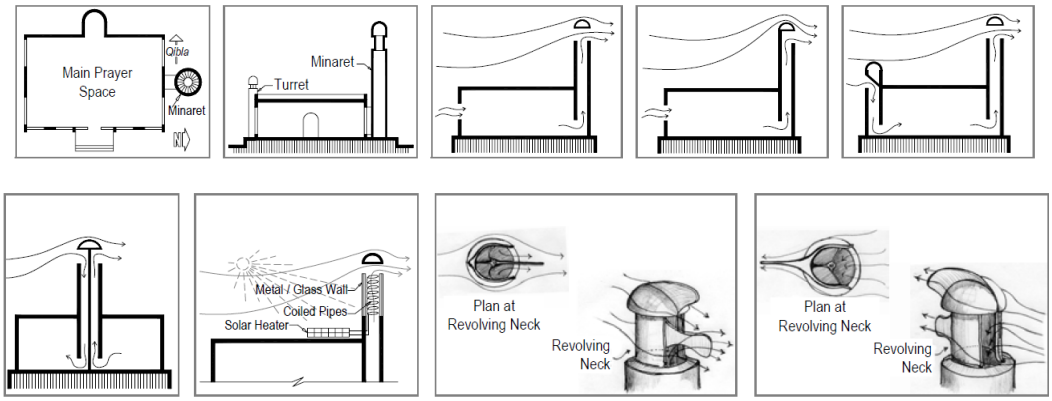


Figure 4.8 . Different concepts of minaret for ventilation: a) wind tower/wind scoop/'badgir'; as a solar chimney/revolving neck for a wind tower (Imam, 2003).

Moreover, Al-Tassan and Bahobail (2006) studied the Al Ruhmaniah mosque, in Al-Jouf, KSA (Figure 4.9). The building is equipped with twelve cooling towers, which enables the smooth flow of cold air through the building. Perforated evaporating pads are used for evaporative cooling in the towers. The mosque, a rectangular structure, is covered with a dome above the Mehrab area, and has a courtyard (surhaa) at the front.



Figure 4.9 Al-Ruhmaniah mosque (Al-Hemiddi, 2004).

4.3.2. Types of windcatcher

The use of a windcatcher, or tower, has evolved from a simple one-sided opening to more complex shapes. The following are examples of windcatchers that can be found in many modern buildings in many parts of the world.

i. One-sided wind towers (Figure 4.10a): These are designed with air openings facing the seasonal prevailing wind direction. When the wind direction changes, this type of wind catcher has a limited effect;

ii. Two-sided wind towers (Figure 4.10b): These are small in size, and fairly simple from an architectural perspective. The performance of two-sided towers is reportedly high, and they are more efficient than one-sided wind towers for circulating airflow. This type of windcatcher allows air circulation both into and out of the building;

iii. Four-, six-, and eight-sided wind towers: These are usually of a larger structure, and are more complex. The height, number of openings, and their size, depends on the prevailing climatic conditions. Figure 4.10c shows a two-story windcatcher with multiple openings;

iv. Cylindrical wind towers: The structure of a cylindrical windcatcher allows air to be collected from all wind directions, thereby offering a better performance than other types of

windcatchers. Figure 4.10d shows an example of a circular windcatcher.



(a) (b) (c) (d)

Figure 4.10 Types of windcatchers: (a) One-sided wind tower; (b) Two-sided wind towers; (c) Two story wind tower; (d) A cylindrical wind tower (Source: (Dehghani-sanij et al., 2015).

4.3.3. Windcatcher integrated passive cooling

The design of windcatchers, or towers, for passive cooling in buildings depends on their location, functionality, and appearance. When Schiano-Phan (2010) studied different designs, she found that they varied in terms of the desired airflow, heat transfer area, sensible heat storage capacity, and evaporative cooling surfaces, which in turn determined the height of the tower, number of openings, and cross-section of the airflow passages. Cooling in buildings using windcatchers mainly takes the form of passive downdraught evaporative cooled air, including the following (Ford et al., 2010):

i) Shower towers: This type of windcatcher incorporates a water spraying mechanism, whereby the air stream into the building is sprayed with water droplets. A showerhead in the form of water nozzles is located at the top of the tower, through which

water pumped at high pressure is sprayed in fine droplets that combine with the incoming air. Figure 4.11 shows an early example of this system by Fathy (1986) that uses water flowing over charcoal in an Egyptian 'Malgaf';

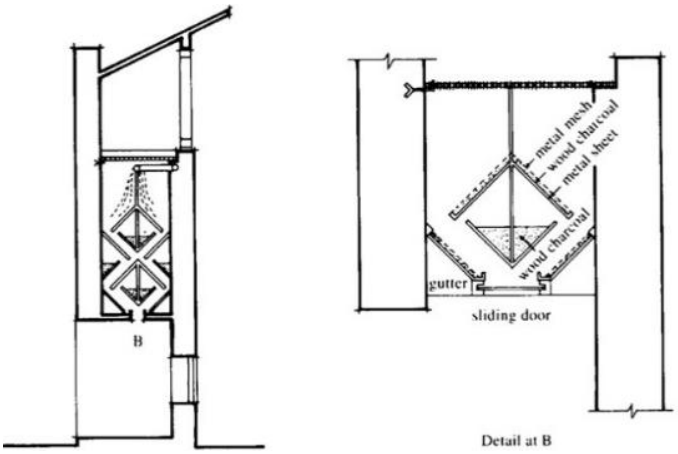


Figure 4.11 Type of shower tower: 'Malgaf', Egypt (Source: Fathy (1986)).

ii) Misting towers: These are similar to shower towers, as the incoming air into a building is sprayed with mist, using water nozzles that are also employed in food processing, botanical gardens, and the chemical industry that produce a very mist, which improves the evaporative cooling when combined with air. An example of this type of system can be seen in the Stanford Ecology Centre, United States of America (USA), where the downdraught tower was installed with misting nozzles to cool the reception area, using evaporative cooling (see Figure 4.12).



Figure 4.12 Type of misting tower: The Stanford Ecology Centre (Source: (Ford et al., 2010)).

iii) Wet media: Evaporative cooling can be enhanced using porous media to increase the surface area contact between the saturated media, and the air flow. This can take the form of dampened porous ceramic bricks in the tower for creating a cool downdraught, or clay water jars placed on windows, or at the bottom of wind towers (Schiano-Phan, 2010). Wet media, such as construction materials, are a good example of instances in which passive evaporative cooling systems are integrated into building elements. Figure 4.13 shows an example of the use of a clay water jar in a windcatcher in a courtyard house in Iraq, with a series of windcatchers placed on the roof to provide natural ventilation for the building's basement rooms. The incoming air undergoes direct heat transfer when it comes into contact with the cold inner surfaces of the duct walls, and its absolute humidity is increased as it collects water moisture from the wet porous water jars, before being discharged into the basement. Similar evaporative cooling techniques are found in the Sind region of Pakistan.

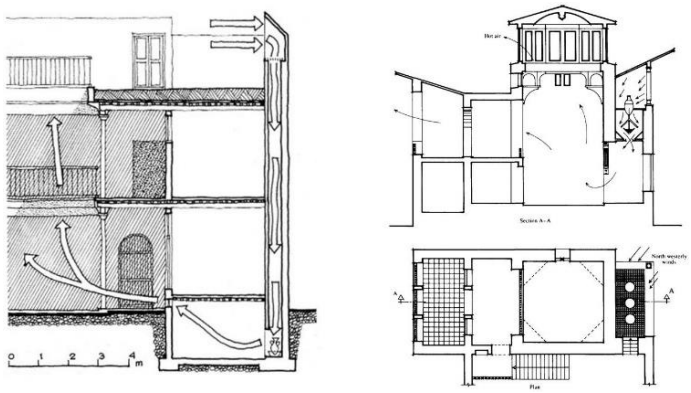


Figure 4.13 Integrated windcatcher evaporative cooling, using water jars (Lechner, 2014)).

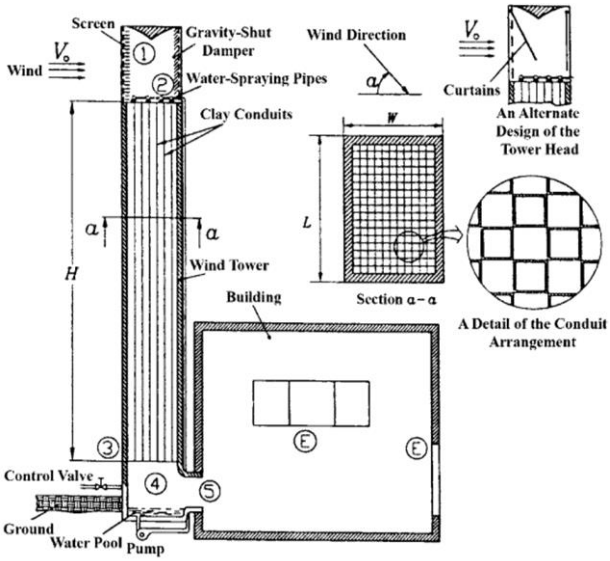


Figure 4.14 Cross-section of baudgeer with a wetted column (Bahadori, 2014).).

Traditional water jars are incorporated into modern buildings using modular clay bricks that divide the tower into a multitude of wet conduits by uniformly spraying water, as depicted in Figure 4.14, using a sump located at the bottom of the tower to collect excess water, which is recirculated over the wet clay material (Bahadori, 2014).

4.3.4. Active evaporative cooling system

Evaporative cooling integrated into buildings has been practised for centuries in the Middle East. However, traditional DEC has the disadvantage of adding moist air into the building's living space, and has a low cooling performance, with the temperature limited to the prevailing outdoor wet bulb temperature. In contrast, research concerning sub-wet bulb temperature evaporative cooling systems as an indirect source (Boukhanouf et al. (2013), demonstrated that it can achieve cooling capacities of 225 W/m2 of the floor area of a building. The arrangement of sub-wet bulb temperature evaporative cooling-system airflow is split into two segments; a dry channel for air supply and a wet one for releasing used air .The heat of the supply air is transferred to working air in wet channel .This heat exchange is facilitated by a thin non-porous channel wall and helps to lower down the temperature of dry supply air. The desired sub-wet bulb temperature is attained by directing some of the cooled air of the dry channel towards the wet channel to bring about the evaporation process in wet channel as evident from figure 4.15.

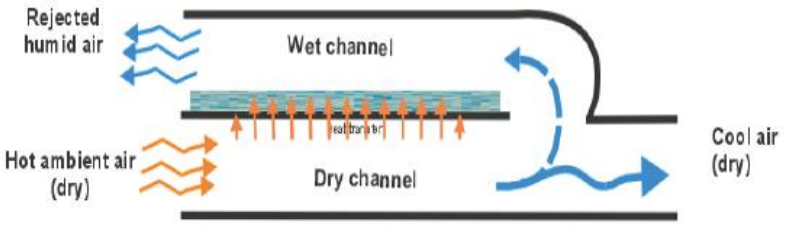


Figure 4.15 Sub-wet bulb temperature evaporative cooling arrangement (Boukhanouf et al., 2013).

The porous ceramic panels can be constructed with hollow structures to hold water, and to enable them to be interconnected. The wet side

of the panel, constituted of the wet channel, is water permeable, with a controlled porosity, while the side forming the dry channel is waterproof. Examples of ceramic panels are shown in Figure 4.16.

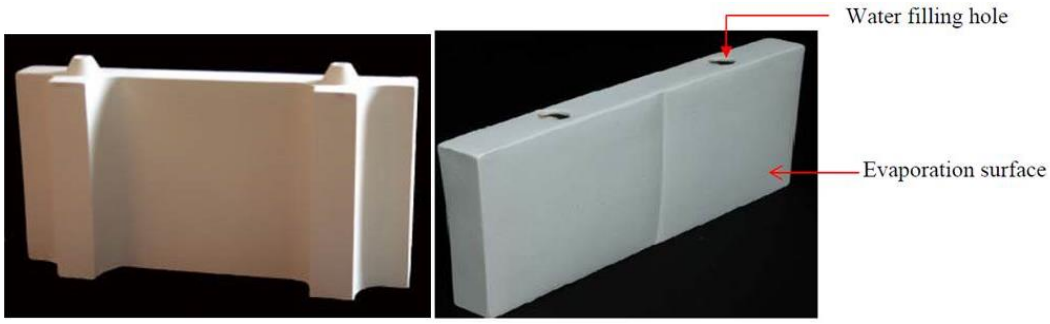


Figure 4.16 Porous ceramic panels. (Schiano-Phan, 2004).

Research conducted by Boukhanouf et al. (2013) demonstrated that evaporative cooling is effective in hot, arid climates, as the experimental results using the porous ceramic as a wet media material for evaporative cooling showed that the ambient temperature could be depressed by as much as 12.5^{o}C, at a low relative humidity (see Figure 4.17).

Moreover, the cooling capacity as a function of the exposed porous ceramic panels' evaporation surface was very high at a low air moisture content. Figure 4.18 illustrates that the cooling capacity was over 200W/m^2 for the ambient air with a relative humidity lower than 40%. Therefore, the total cooling capacity that can be achieved is scalable with the size of the porous ceramic panels.

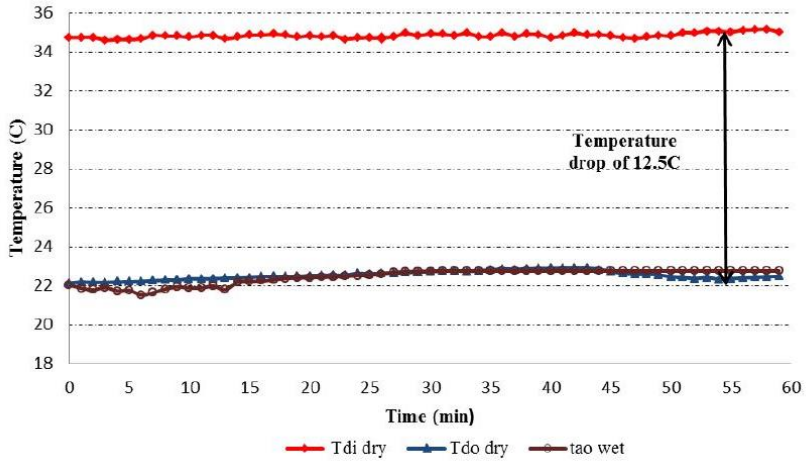


Figure 4.17 Temperature profile recorded in the wet and dry channels (Boukhanouf et al., 2013).

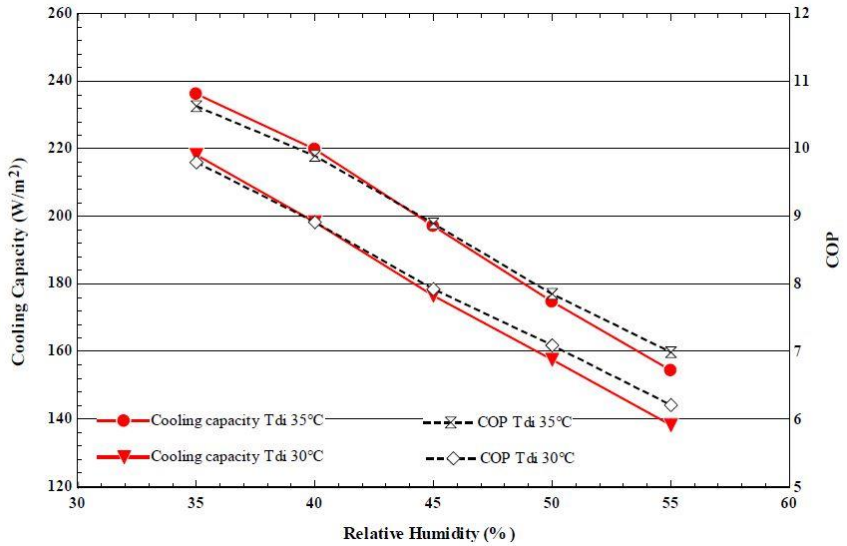


Figure 4.18 Effect of relative humidity on cooling capacity and coefficient of performance (COP) (Boukhanouf et al., 2013).

4.4. Proposed concept and design of a cool minaret

This section provides a detailed explanation of two proposed designs for a cool minaret that integrate the concept of air cooling.

Conventional DEC systems, such as those used in minarets, are affected by the prevailing weather conditions of the supply air at the tower inlet, in terms of factors such as its temperature, relative humidity, and air velocity. Traditional DEC also has the disadvantage of adding moist air into the building's occupied space, and demonstrates a low cooling performance, with the temperature limited to the prevailing outdoor wet bulb temperature, which can affect thermal comfort.

In the proposed design, the supply air was cooled without adding moisture. Figure 4.19 presents a diagram of a square tower minaret with ambient air entering through the upper portion of the tower, on top of the tower shaft. The form of the inlet was an important consideration for this project, and the majority of the examples of this form of air cooling in the extant literature had a cube form of inlet, with diagonal baffles on the inside, although other forms included cylindrical and triangular shapes. The material used as the wet media for holding the water, and forming the wet air channels, occupied the middle section of the minaret. The cool air was supplied at the lower part of the minaret shaft, with air openings at ceiling level, or at the ground level of the prayer hall. Two wet media materials were considered for evaporative cooling: porous ceramic materials, and synthetic grass matting.

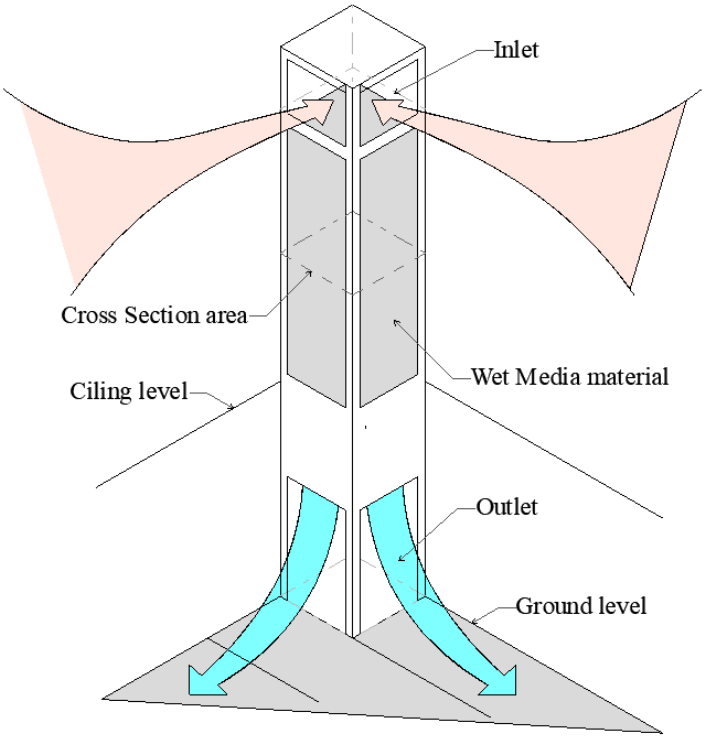


Figure 4.19 Diagram of a square tower minaret.

4.4.1. Ceramic materials

The structure of a minaret is well suited for playing an important role in providing energy efficient and passive cooling. One of the designs considered by this project employed porous ceramic material in the form of wet panels for cooling the air as it flowed along its surface. Ceramic materials have a stable structure, and can be incorporated and moulded in the minaret. These panels were designed to be arranged in a way that provided air channels in which the air could be cooled indirectly below the wet bulb (sub-wet bulb), in order to achieve the required cooling, without adding moisture into the supply air. The separation of the air channels into wet and dry, formed by the porous ceramic block, could be arranged into rectangular, square, triangular, or more complex structures. The ultimate aim was to

maximize the direct contact surface area between the dry and wet channels to facilitate both the heat transfer, and the transfer between the air and the wet surface in the wet channel. Figure 4.20 is a generalized sketch of the proposed configuration of the interposition of the ceramic panels within the minaret. In this design, the incoming hot and dry air is circulated through the dry channel, and is cooled indirectly by the exhaust air in the adjacent wet channel. The water evaporation in the wet channel causes the exhaust air to be cooled to its wet bulb temperature, and rejected through the outlet of the minaret opening as saturated air.

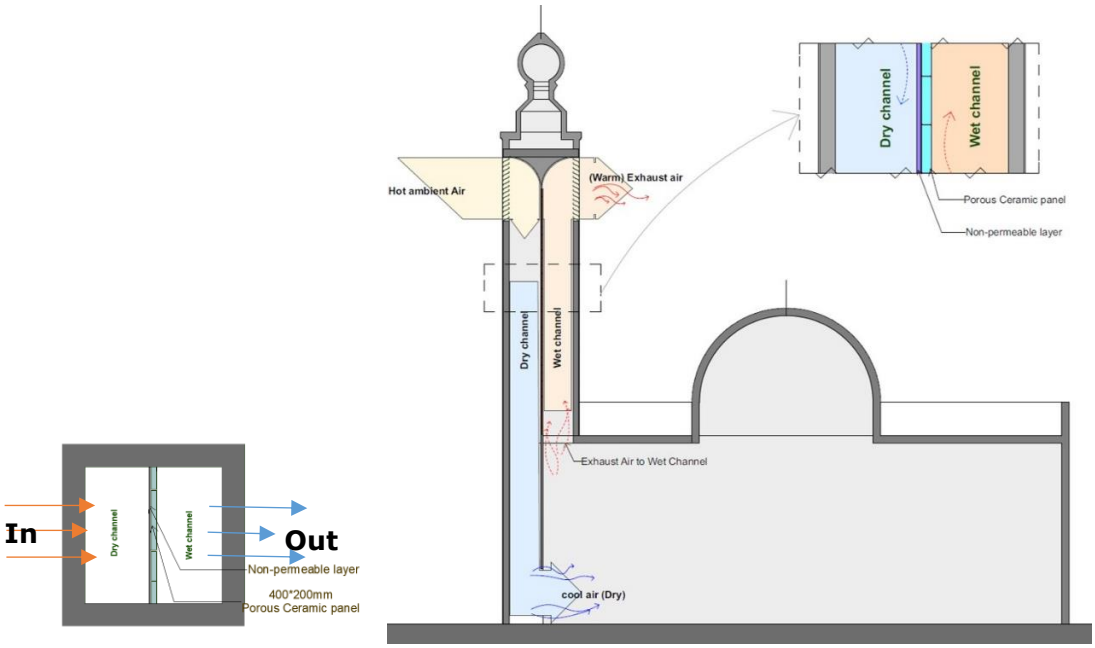


Figure 4.20 Diagram of the arrangement of a cool minaret.

Another arrangement of the integrated IEC system is shown in Figure 4.21, which illustrates the way in which the cool air can be dispensed at the ceiling or ground level of the prayer hall through overhead delivery diffusers, or a chilled ceiling type cooling method, such as those detailed in Option 1 and Option 2, respectively.

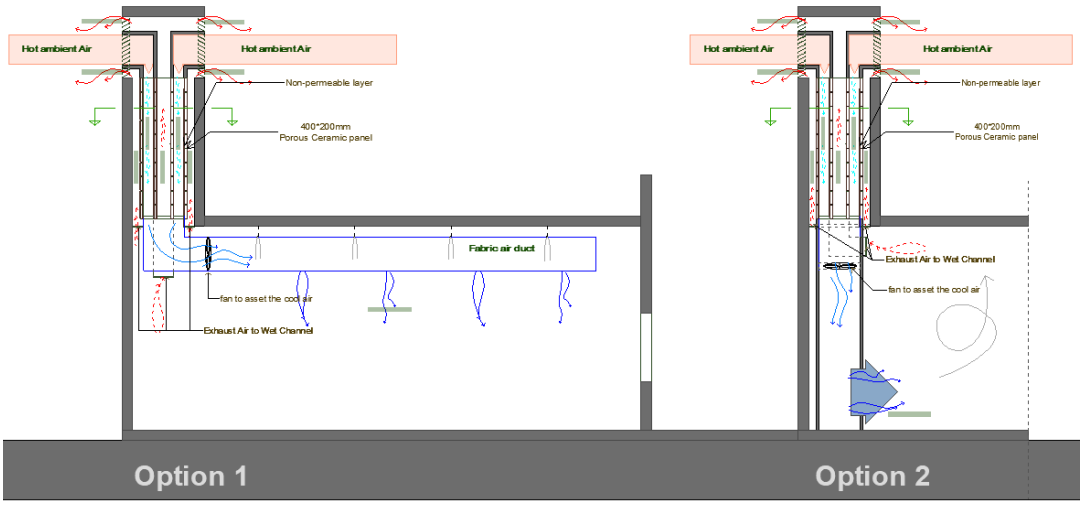
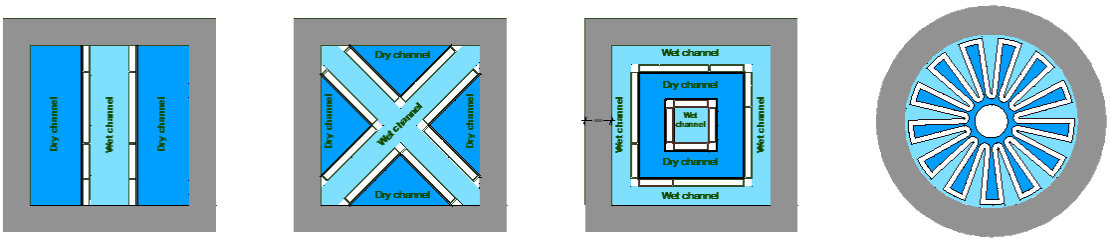


Figure 4.21 The proposed system components with two distribution option.

The arrangement of the ceramic blocks within the minaret can take the form of a number of configurations that create alternating dry and wet channels. In these various arrangements, the ceramic blocks form a multitude of dry and wet channels through which the supply and rejected air are circulated. Figures 4.22 a), b), and c) show the blocks arranged into rectangular, triangular, square, and circular channels. The main goal of each arrangement is to maximize the cooling performance of the minaret structure as a whole.



a) Rectangular b) Triangular c) square d) circular

Figure 4.22 Cross-section plans of different dry and wet channel configurations.

Meanwhile, Figure 4.23 presents a detailed three-dimensional (3D) drawing of a proposed cooling design for a cylindrical minaret with a windcatcher and cooler system, comprised of the following components:

Head: When the wind blows through the external louvered grille at a high level, from different sides, the dampers designed in a star shape funnel the air only to the dry channel, and the wet channels are closed. The rejected air, assisted by an extraction fan, withdraws the exhaust air to the outside of the building.

Evaporation cooling panels: The minaret void is divided into separate air ducts to form dry and wet columns within. The ceramic panels are mounted in the form of a wall, and are filled with water, which is supplied from the top, to flow from one panel to the other, and to permeate the outer surface of the ceramic wall. The porous ceramic wall is a sandwiched between two channels, with two narrow air gaps to the front and back of the ceramic wall.

Dry channels: The inlet air can be pulled into the building through the windcatcher shaped opening grid via the dry side of the ceramic material, and the air is then cooled by transferring its heat to the ceramic panel, without increasing its moisture content. The cool air is delivered into the building via a chilled ceiling level, as well as through radiation, directly into the occupied space.

Wet channels: The evaporation of water from the porous ceramic panel surface in the wet channels carries away the heat added to the

ceramic panels from the building space, which is rejected to the outside by an assisted fan.

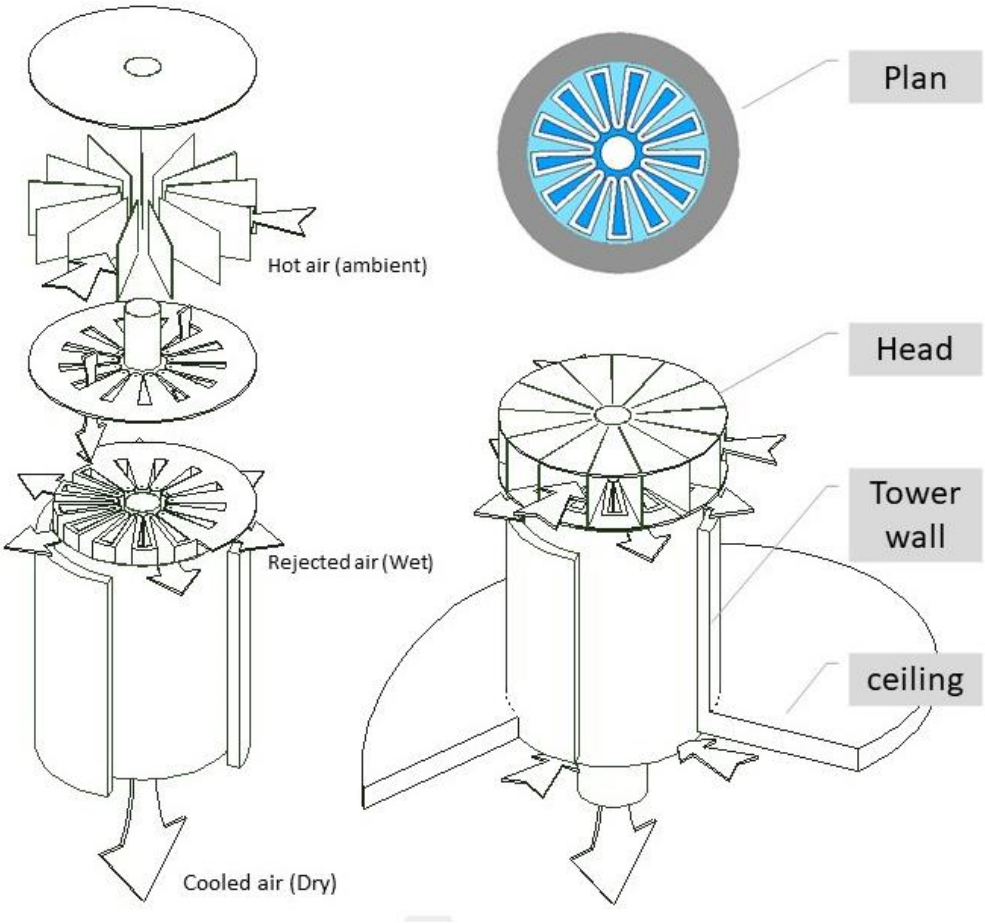


Figure 4.23 3D Module components of the proposed circle cool minaret

Figure 4.24 shows a detailed section of a wind cowl, or 'revolving neck' that can be integrated into the top head of the minaret to enhance the expulsion of exhaust air from the wet channel to the outside.

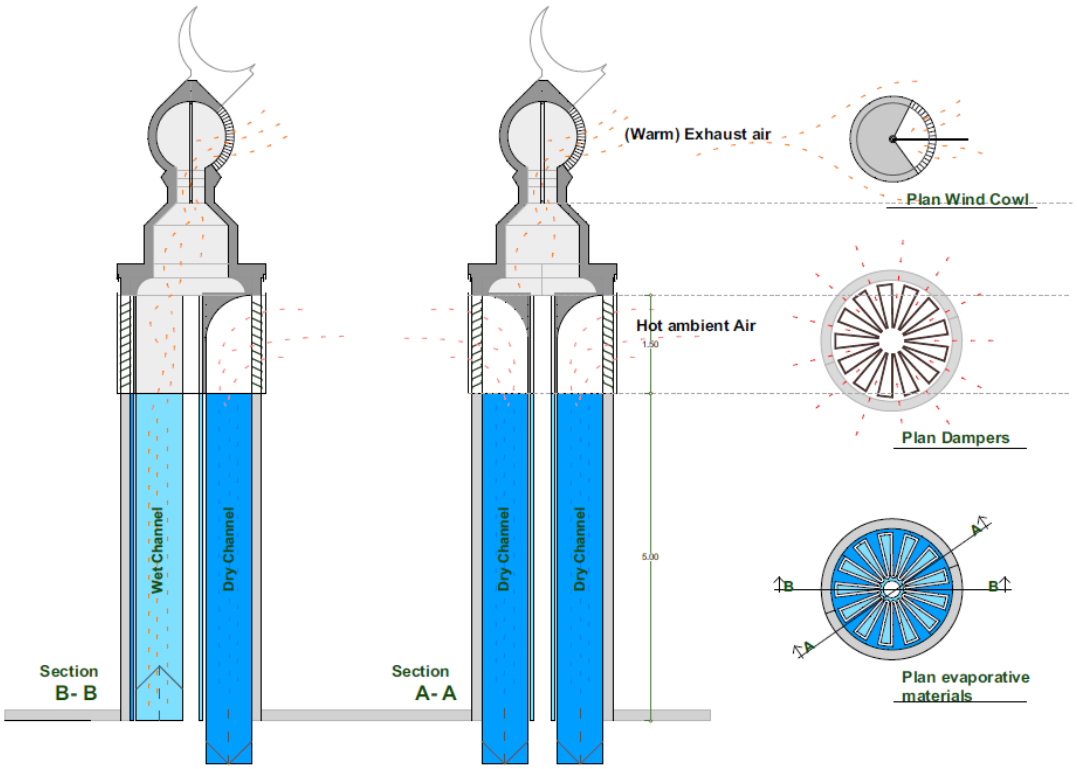


Figure 4.24 Circle configuration with revolving neck.

It was decided to implement the sub-wet blue temperature cooling system as an indirect evaporative system, with a cooling capacity of 225w/m^2, according to the results discussed in Chapter 3, and with reference to Boukhanouf et al. (2013) research regarding cooling capacity, which confirmed that each m^2 requires 225w/m. The highest minaret, according to the size of its cross-section, was the Hail case, with a cooling load of around 23000/225 m^2 = 102 m^2 of wet surface materials required, consequently the highest minaret with cross-section 2 x 2m was 3.10 m, with a cross-section of 1.5 x 1.5 m, and a tower height of 5.7 m, as illustrated in Figure 4.25.

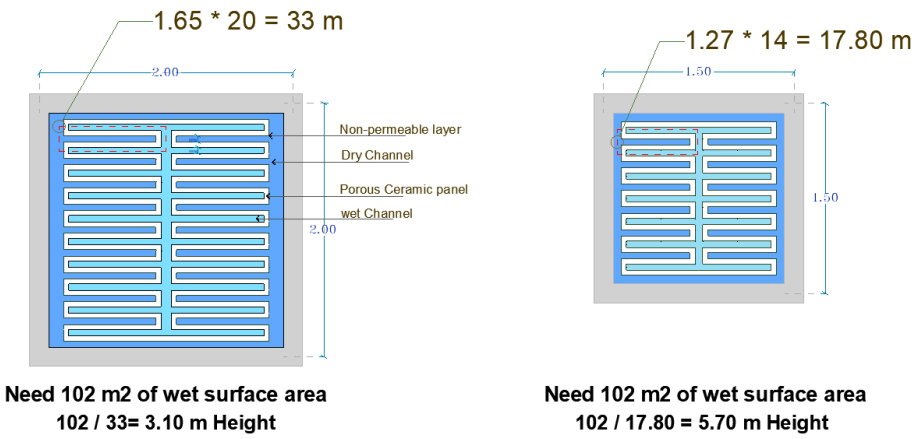


Figure 4.25 Contact surface area required, according to the size of different cross sections (2x2 and 1.5x1.5 m).

The results provided in Table 4.1, which were obtained from Chapter 3, demonstrate that the cooling load in the Hail case was 23067W, therefore a wet surface area of around 102m^2 was required to meet the cooling load demands of the prayer room, whereas in the Abha case, around 46m2 of wet surface area was required to meet 10465W of cooling load demand. The subsequent minaret size, according to the wet surface area required in each case, is shown in Figure 4.26.

Table 4.1 Mosque cooling load on typical summer day.

City	Mosque cooling Load (W)	Cooling capacity of porous ceramic (w/m2)	Wet surface area required (m2)
Hail	23067	225	102
Abha	10465	225	46

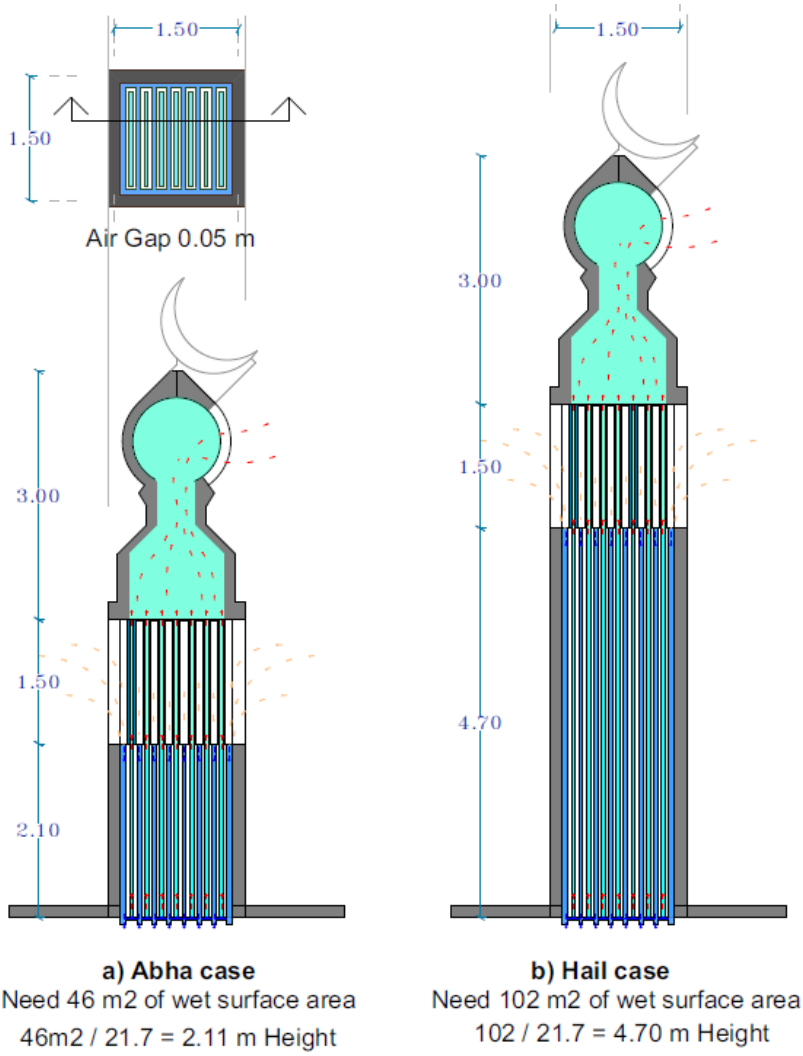


Figure 4.26 The minaret height, according to the cooling load required for a) Abha, and b) Hail.

4.4.2. Synthetic grass material

The second wet material that was considered for this project was synthetic material in the form of artificial grass that is constituted of fibres. It is primarily manufactured as an alternative to natural grass, and therefore has the appearance of a semi-natural artificial turf

structure that is generally used for sports grounds, and in landscaping in the built environment. This project proposed that such a synthetic material could be employed as a wet sheet that serves to hold the water for cooling the air as it flows along the turf's surface. Synthetic materials are flexible, and can be integrated and shaped in the minaret. Figure 4.27 illustrates a sample of a turf sheet, with a depth of 6mm.

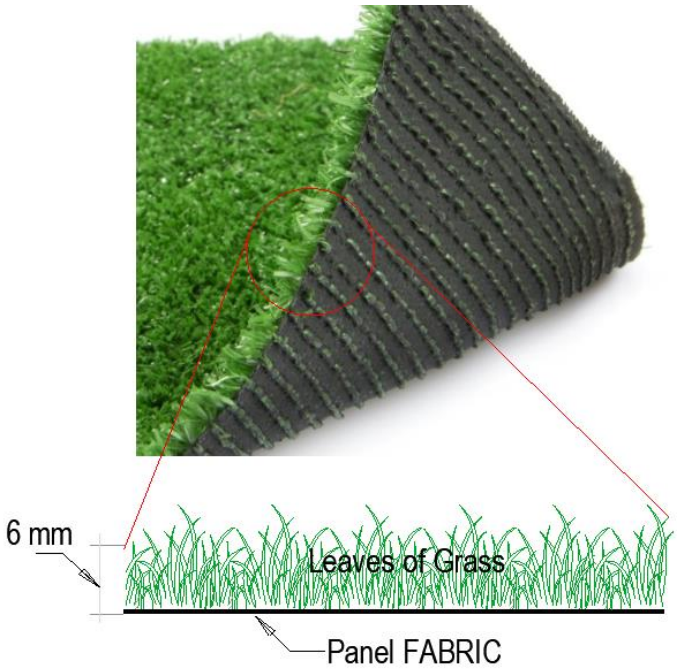


Figure 4.27 Sample sheet of synthetic grass.

Meanwhile, Figure 4.28 illustrates a sheet of synthetic turf employed in a way that provides air channels in which air can be cooled indirectly, below the wet bulb (sub-wet bulb), thereby achieving the required cooling, without adding moisture to the supply air.

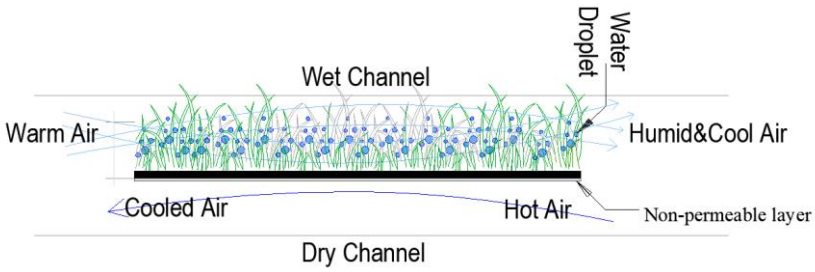


Figure 4.28 Synthetic grass sheet arrangement, showing dry and wet channels.

As shown in Figure 4.29, as a result of the small size of the synthetic material, when it is placed between the dry and wet channels, in an arrangement of multi-channels, the total of one unit size is approximately 12mm, which offers a large contact surface area within the structure of a minaret.

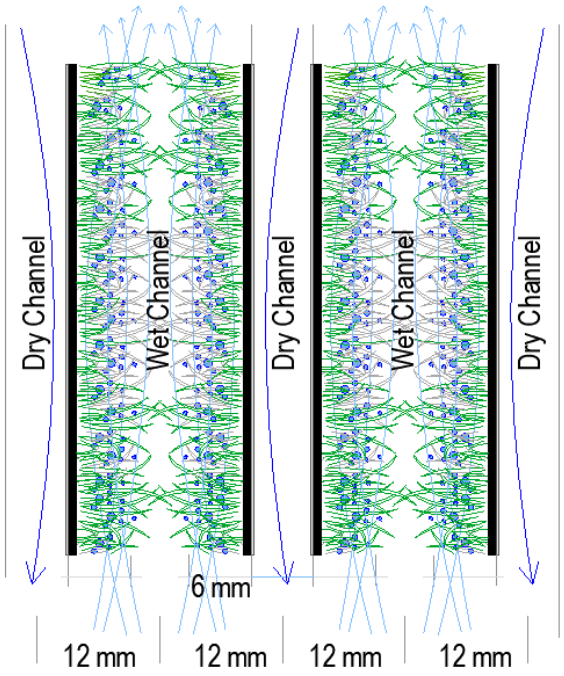


Figure 4.29 Multi unit configuration of dry and wet channels using synthetic grass.

Figure 4.30 shows the synthetic grass integrated into the tower, including multi-unit wet and dry channels formed by the material, which can be employed in any required shape. When using the grass sheet, the cross-section of the tower is divided into separate air ducts to form dry and wet channels, with two narrow air gaps at the front and back of the grass, framed by a very thin sheet of aluminium to support the grass unit. The ultimate aim is to maximize the direct contact surface area between the channels, and to facilitate both heat transfer and transfer between the air and the wet surface in the wet channel.

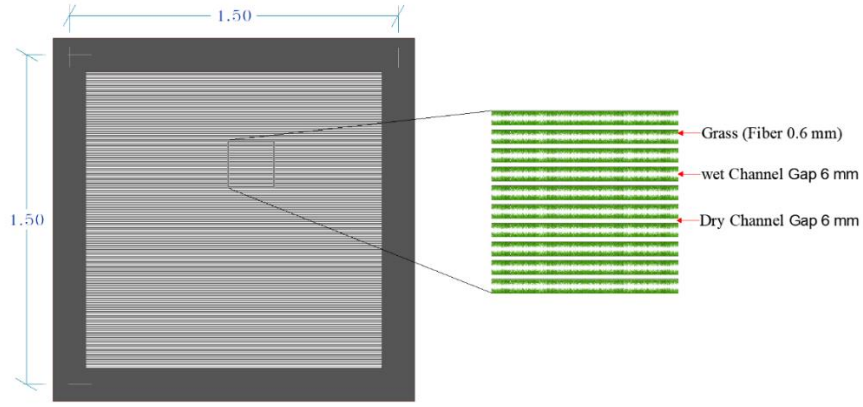


Figure 4.30 Square section plan of a minaret measuring 1.5x1.5m, incorporating the synthetic grass.

A cross-sectional plan of both a square shape and 3D section of a minaret tower that integrates this synthetic material demonstrates how it can be configured to include dry and wet channels The air flow is permitted by means of constricted narrow ducts .These ducts are created by separating the channels with panels as shown in figure 4.31.A thin non-permeable membrane covering is used to cover the surface of the panel in the dry channel. Conversely, in the wet

channel, the air has an immediate interface with the wet surface of the grass resulting in direct evaporation of water consequently cooling down the panel and decreasing the volume of the water. This causes the temperature of the air in the dry channel to drop. The air in the dry sections then transfers its heat to the wet channel by means of the thin non-permeable membrane covering, in this step, no more moisture content and only heat is transferred. In the meantime, the heat released by dry channel into the wet channel stimulates the evaporation process when it comes in contact with water and as a result of evaporation; this heat is carried away as humid air and rejected ultimately.

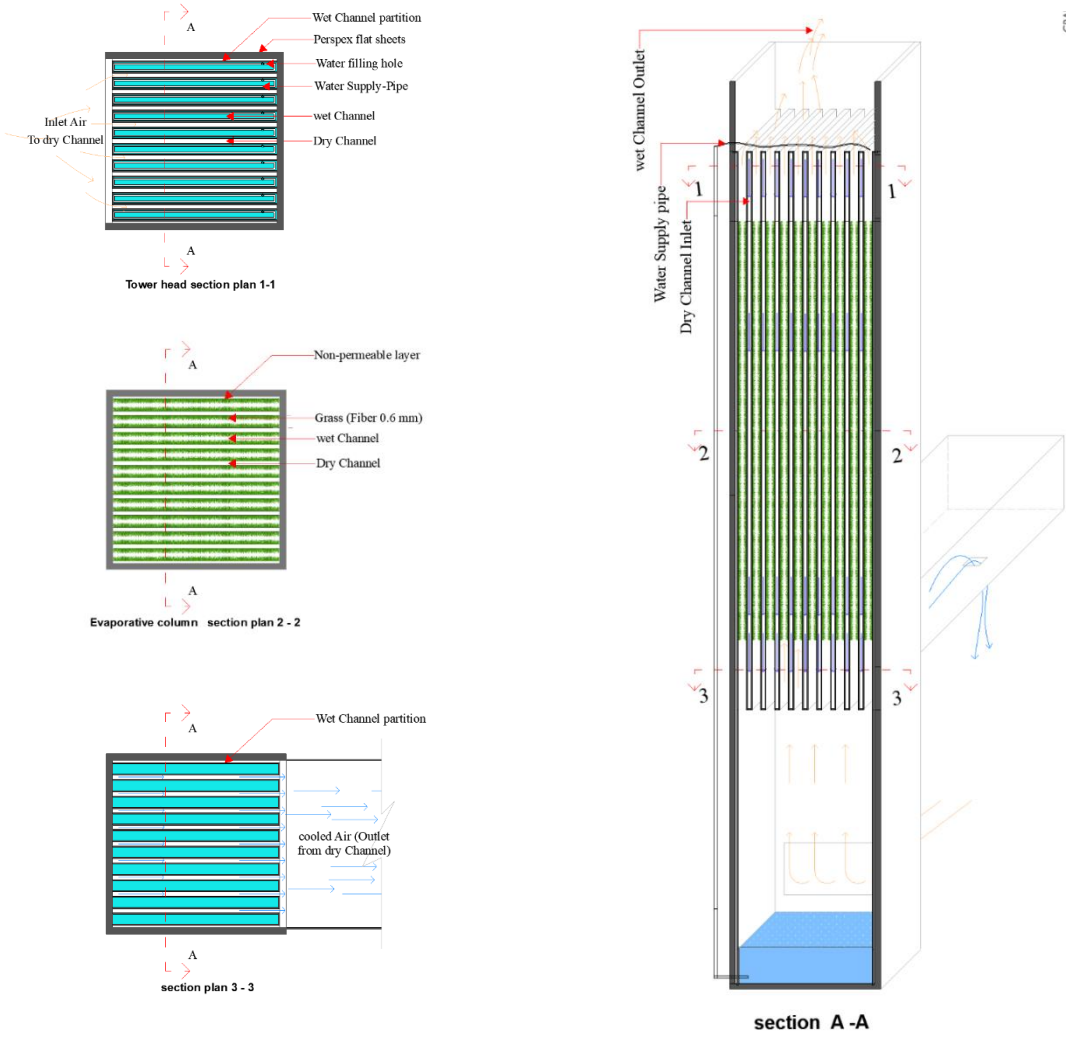


Figure 4.31 Detailed drawings of the tower components when employing synthetic grass.

The configuration of the minaret cooler system using synthetic grass Therefore operates in different three cooling modes: (1) DEC; (2) IEC; and (3) DPEC.

4.4.2.1. The properties and heat transfer qualities of synthetic materials

Artificial grass made from synthetic materials has been developed over a number of years, and is now a high-quality product. As illustrated in Figure 4.31, the green turf of synthetic grass is composed of a solid polyethylene material, in a plastic form. The content of the polyethylene is melted down by heating it, and colour is added to make it resistant to ultraviolet radiation. The supporting layer beneath the turf is made of polypropylene, polyethylene, or nylon, which provides an additional safety layer that increases the life and durability of the grass.



Figure 4.32 Constituent parts of synthetic grass

The plastic materials that form the basis of synthetic grass are able to absorb and retain heat (Sawafta and Bruner, 2018, Tetrault et al., 2018). This fact, combined with the depth of the material about (6mm) means that when it is placed between the wet and dry channels, it is able to facilitate an effective degree of thermal

transfer, and the water film distribution on the surface of the turf provides a greater contact surface area that enhances the evaporation in the wet air channels, which further improves the heat transfer.

4.4.2.2. Shape and type

Synthetic grass is available in several colours, and a number of blade heights and forms. Figure 4.32 illustrates 'W-fiber', 'U-fiber', 'V-fiber', and 'S-fiber' turf blade shapes.



Figure 4.33 Shapes and types of synthetic grass

4.4.3. Advantages and disadvantages of porous ceramic materials and synthetic grass matting

The porous ceramic proposed in this project has the potential to provide comfortable conditions, and possesses a number of additional advantages that other spray water evaporative systems cannot claim. However, it suffers from the fact that when integrating a porous ceramic evaporator into a building, a large ceramic contact surface area is required to meet high cooling loads, which therefore causes a potential loss of floor space. Moreover, designing a new configuration of porous ceramic with a small shape and components is challenging and requires time and experience, which is a critical limitation of the material, as is the fact that it is not possible to install a long vertical panel with more than ten ceramic components on top of one other.

In contrast, there are numerous advantages to using synthetic grass matting as an evaporator system, including: 1) It is not an organic material, therefore it does not decay, and has a long life; 2) It is of a low cost and ready availability; 3) Its small depth (6mm) provides large contact surface area; 4) The material weighs less than ceramic, and therefore requires less of a support system; 5) It is available in different types and shapes, and is flexible and therefore easy to adapt to any form required; 6) It is low maintenance; and 7) It does not attract bacterial growth. Meanwhile, the most significant disadvantage of the material is that it is hydrophobic, and therefore does not absorb the water from material's surface. In addition, the heat transfer properties of the material are unknown as it was designed for use in locations such as playgrounds.

4.5. Summary

In summary, seeking to provide thermal comfort for the occupants of mosques in the harshest of weather conditions, with a minimal impact on the natural environment, this chapter discussed the application of the principle of evaporative cooling using up-to-date knowledge and material science adapted for the purpose of providing cooling to the interior of a mosque by incorporating new designs into the fabric of the minaret, thereby extending the functionality of this building element. The chapter discussed two proposed designs for a cool minaret, the first using porous ceramic structures, and the second, synthetic grass matting. The cool minaret structure has the potential to advance design technology, and to provide thermal comfort, while minimizing energy consumption in mosques in regions with hot and dry climatic conditions.

Chapter 5. Construction of a small-scale proof-of-concept evaporating cooling tower

5.1. Introduction

This chapter describes the main stages involved in developing the proof-of-concept laboratory prototype of the cooling tower proposed by this project. The main laboratory rig includes a Perspex tower, a wet media material in the form of synthetic grass matting for the purpose of water distribution, and air inlet and outlet ducts. The instruments employed to measure the performance and modes of operation of the evaporative cooling system as DEC, IEC, and DPEC, are described in detail.

5.2. Prototype concept

The small-scale prototype 'cool minaret' model was designed to integrate evaporative coolers, and to demonstrate the feasibility of the concept. Figure 5.1 shows a sketch of the prototype tower, produced to a scale of 1:10, consisting of a square tower, connected to the roof of the test room below, in the form of an open box. The tower had one upper air inlet opening on the side, in the form of a windcatcher, and the air outlet was located at the top of the tower. The inlet air was channelled through a multitude of narrow air channels supplying cool air to the occupied space below, through overhead diffusers. The stale air was circulated from an opening situated at the bottom of the tower, along a set of alternating wet channels in the cooler that promoted water evaporation, and was

then rejected to outside at the top of the tower. The air circulation in the evaporative cooling channels could be accommodated to operate in various modes: direct, indirect, or sub-wet evaporative cooling.

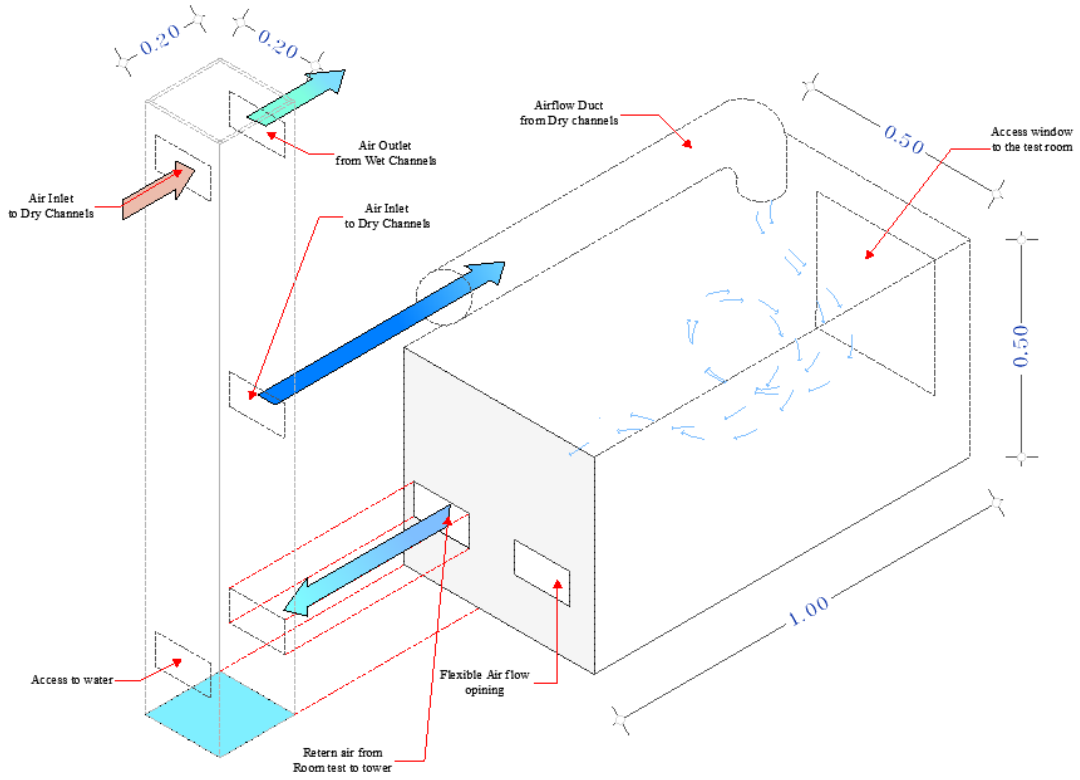


Figure 5.1 *3D sketch of the laboratory prototype*

A cross section of the tower using an evaporative cooling material in the form of synthetic grass mat, which formed the wet and dry channels, is shown in Figure 5.2.

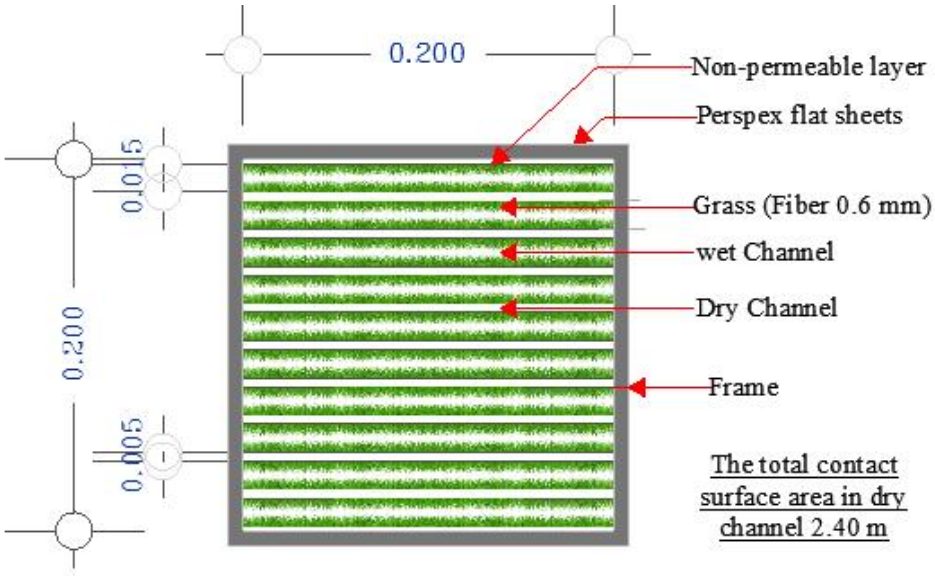


Figure 5.2 *Top view section of the tower.*

The grass mats were supported in situ by thin aluminium sheets that formed narrow waterproof channels, or dry channels, through which the supply air was cooled. Meanwhile, the narrow channels formed by the grass mats were sprayed with water, and the air rejected from the building caused the water to evaporate and indirectly cool the supply air in the dry channel.

The main purpose of the grass mats was to distribute the water, and maximize direct contact between the wet grass surface and the airflow, which enhanced water evaporation in the wet channel, and hence created a temperature gradient with the dry channel. This allowed the primary air in the dry channel to be cooled by transferring its heat to the panel through the thin waterproof membrane, without

increasing its moisture content. Meanwhile, the evaporation of water in the wet channel carried away the heat removed from the dry channel airflow, rejecting it as humid air at the top of the tower. Figure 5.3 provides a schematic representation of the top section of the tower, highlighting the dry channels, wet channels, and water spraying system.

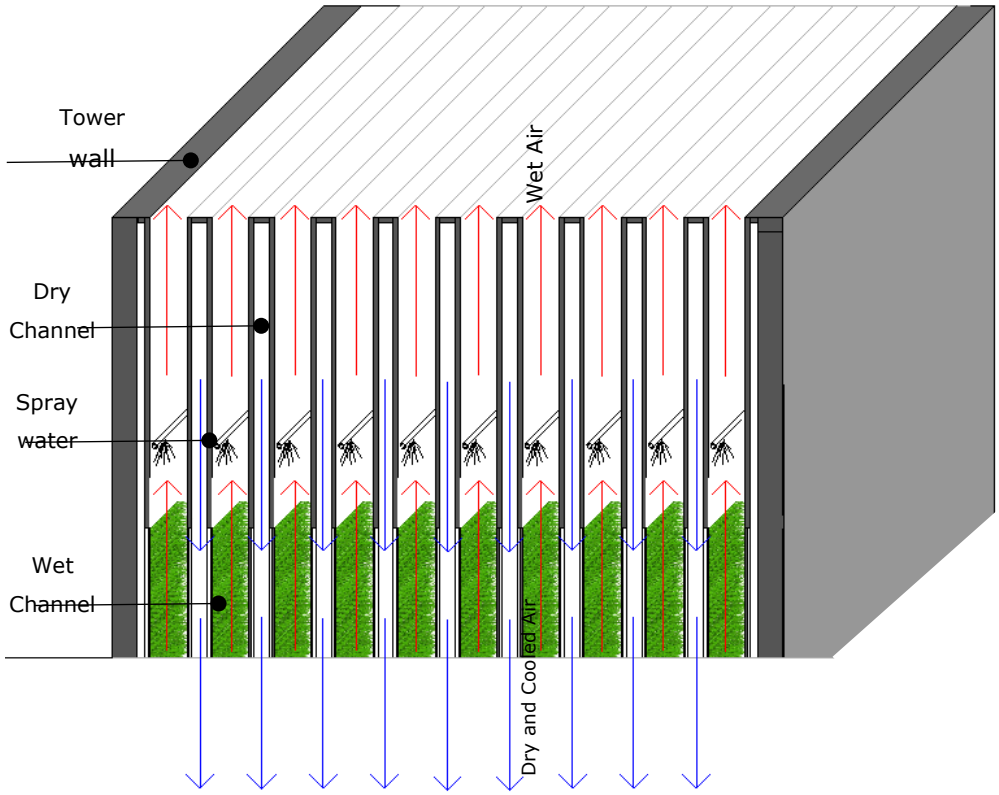


Figure 5.3 *Structure of the top section of the cooling tower*

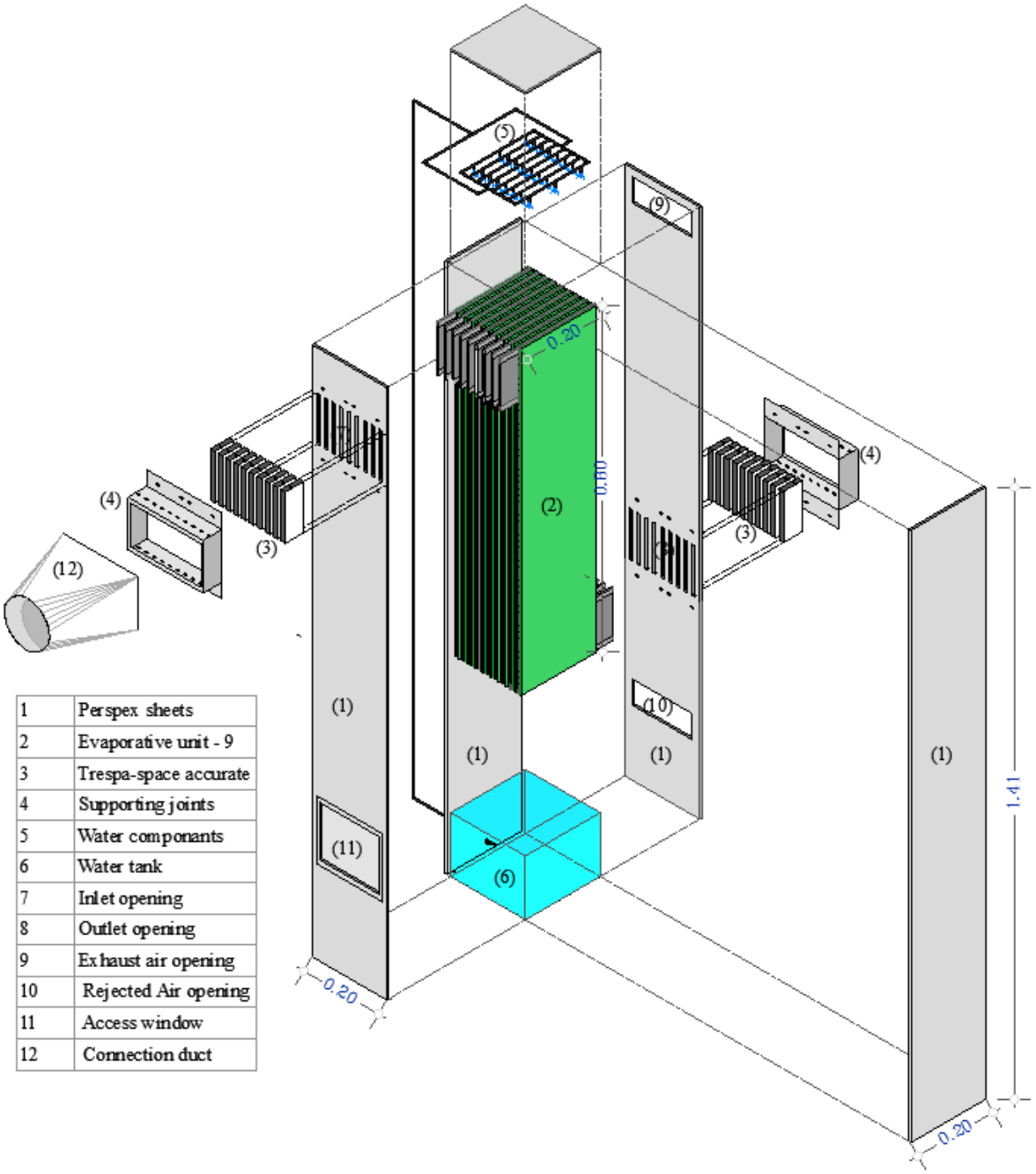
5.3. Prototype design and component assembly

5.3.1. The tower (minaret)

The outer casing of the tower was made of transparent Perspex sheets, to assist with visualising the airflow and water droplet in the channels. The square tower was constructed to a scale of 1:10, with a side dimension of 200mm, and a height of 1350mm. The core of the evaporative cooler was made of actual size of synthetic grass sheets that were 600mm thick, and 200mm wide. Details of the airflow openings into and out of the tower, together with the other components, are presented in Figure 5.4.

The Perspex casing of the tower was laser cut from 6mm thick cast acrylic sheets. The sides were then fastened together using screws for ease of modification. The airflow openings in the side sheets were also cut using a laser machine. Equal spacing between the air channels was achieved using a wood-based fibre and thermosetting resin (TRESPA) material. The airflow transition pieces between the tower inlet and the outlet and air ducts were welded from aluminium sheets.

The tower's individual fabricated components and assembly are shown in Figure 5.5.



1	Perspex sheets
2	Evaporative unit - 9
3	Trespa-space accurate
4	Supporting joints
5	Water componants
6	Water tank
7	Inlet opening
8	Outlet opening
9	Exhaust air opening
10	Rejected Air opening
11	Access window
12	Connection duct

Figure 5.4 *Sketch of the tower prototype.*

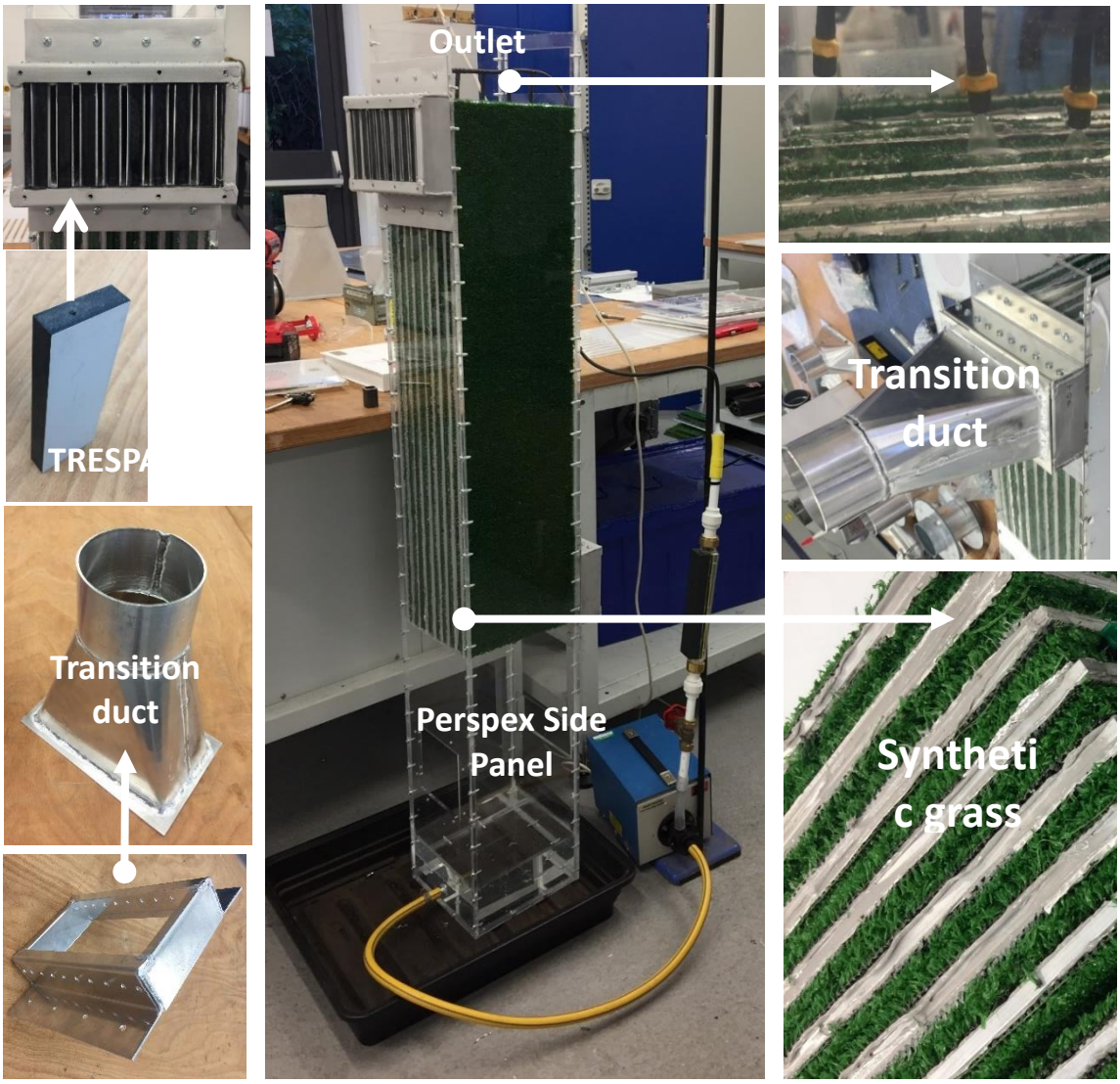


Figure 5.5 *Individual fabricated tower components*

The main specification of each component of the tower is summarized in Table 5.1.

Table 5.1 *Main dimensions of the tower.*

Element	Dimension
Tower side panels material	Clear acrylic
Tower side panels thickness	6mm
Tower cross section	200 x 200mm
Tower height	1350mm
Synthetic grass sheets	800 x 200mm

5.3.2. Manufacturing of the core synthetic grass panels

The core synthetic grass panels were constructed using aluminium tube frames of 0.6mm thick that were cut to size (800mm and 200mm). Two aluminium flat sheet frames of 1.2mm thickness were sandwiched together to form the inlet and outlet air openings of the dry channel, at the top and bottom end of the frame. The synthetic grass mats were similarly fastened to either side of the frame to form wet channels. Figure 5.6 shows the process of manufacturing the individual parts of the core of the evaporative cooling module.

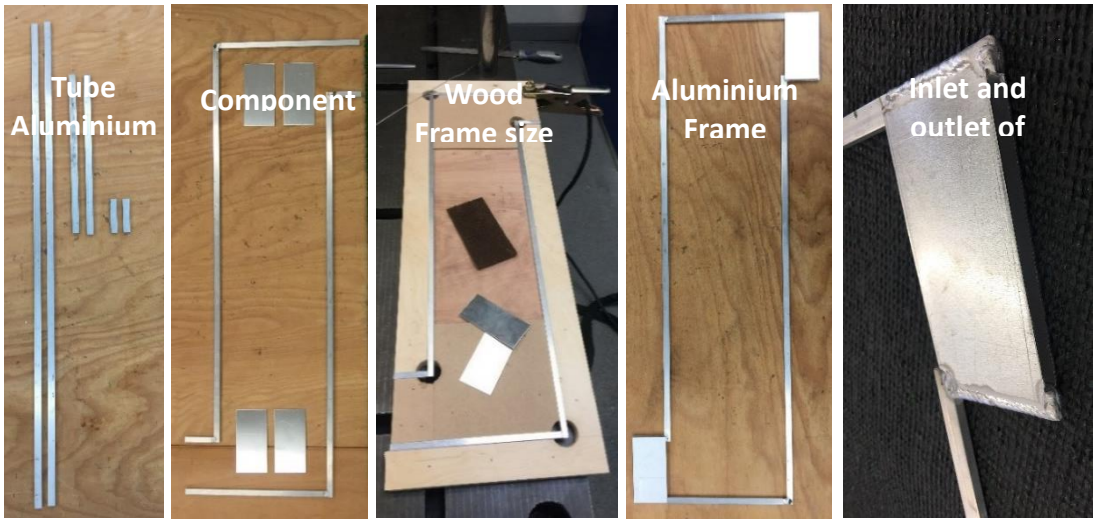


Figure 5.6 *Manufacturing process of the aluminium frames*

The synthetic grass mat was cut to size (800 x 200mm), and the side forming the dry channel was sealed with a thin, waterproof aluminium tape with a high thermal conductivity. A step-by-step manufacturing process is presented in Figure 5.7, in which a) shows the synthetic

grass mat side of the wet channel, b) shows the aluminium tape sealing the rear of the synthetic panel of the dry channel, c) shows the aluminium frame sealed with the synthetic panel, and d) shows the core synthetic grass panels.

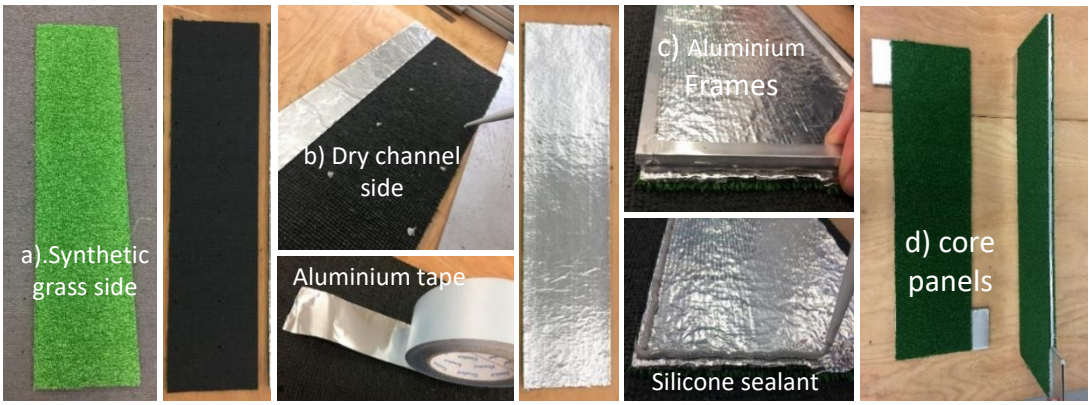


Figure 5.7 Manufacturing process of the synthetic grass mat

The individual modules were then stack together to form the core of the evaporative cooling system. The modules were sealed using a silicon sealant to form alternating dry and wet airtight channels through which the supply and rejected humid air were circulated, respectively. A summary of the design parameters of the core module is provided in Table 5.2.

Table 5.2 *Design parameters of the core module panels*

Design parameter	Dimension
Dry channel inlet/outlet	100 x 5mm
Number of dry channels	9
Dry channel airflow gap	5mm
Wet channel airflow gap	3mm
Wet surface area of synthetic grass unit	0.16m^2

5.3.3. Water spraying system

A water spraying system was used to wet the synthetic grass mats in the wet channel of the tower. It consisted of water distribution pipes and nozzles (specification in Appendix F), a pump, and a water collection tank. The water was continuously circulated by the pump between a water collection tank at the bottom of the tower, and overhead manifold distribution pipes. Any excess water dripping from the tower fell into the tank and was recirculated. The water in the tank was cooled by evaporation to the wet bulb temperature of the air inlet of the wet channel. The water nozzles sprayed water in fine particles to ensure the maximum wettability of the synthetic grass mat's surface area. Figure 5.8 shows the main components of the water spraying system.

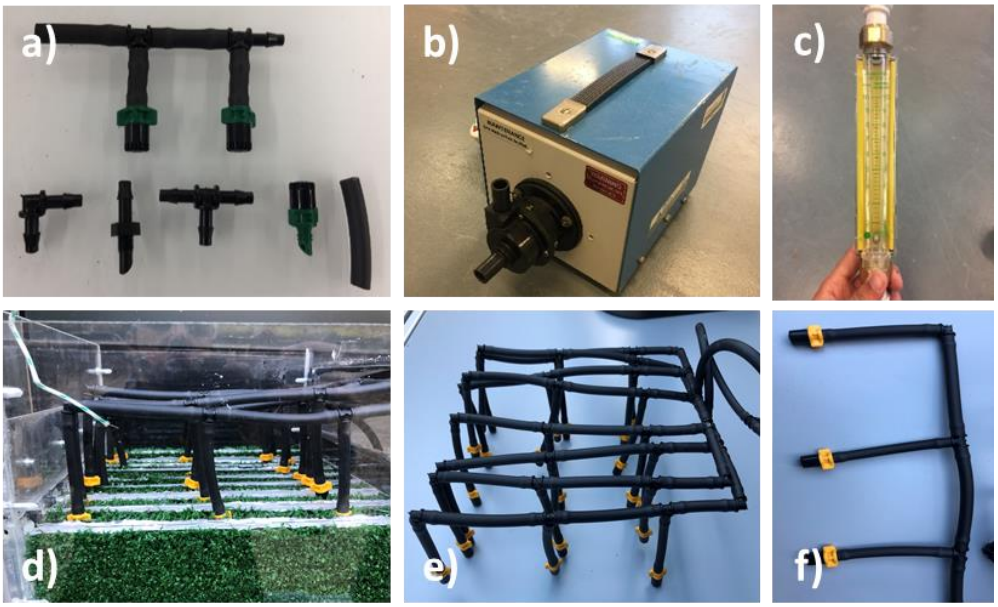


Figure 5.8 Components of the water spraying system. a) Water nozzles, b) water pump and speed controller, c) flow meter d) water nozzles, e) water spraying assembly system, f) three nozzles for one channel.)

5.3.4. Fan for air circulation control

The experimental prototype of the cool minaret was operated in three modes of evaporative cooling: direct, indirect, and dew point. Each of these three modes required a different air circulation, controlled by fans. The direct mode employed one fan to reject the air to the outside by placing the fan at top of the room's opening. Likewise, the indirect mode employed one fan to reject the air from the wet channels to the outside at the top of the tower. Meanwhile, in the dew point mode, two fans were employed, one of which was placed at the inlet dry channel, to direct the air, while the second was located at the outlet of the wet channels to extract the air, and also to control the air flow, and direct 50% of it back to the wet channel, while the other 50% was directed as supply air to the room (box). Figures 5.10, 5.11, and 5.12 illustrate the airflow arrangement in each mode. The mean air velocity was measured using an air duct cross-section area, and to achieve a uniform flow, by five point velocity measurements at the end of the circular duct. The diameter of the circular duct was 10cm, and the mean air velocity test in each mode was the maximum speed of the fan. The measurement of the direct mode was 2.85m/s, the indirect mode was 1.65m/s, and the sub wet bulb was 1.85m/s. The air mass flow rate through the air duct was calculated using the following expression:

$$\dot{m} = V\,A \qquad (5.1)$$

where, $\dot{m}$: mass flow rate Kg/s, V: mean of air velocity measured through cross section of duct m/s, A: Duct cross section area m^2**.**

5.3.5. Parametric of cooling performance

In addition to the measured data record, the cooling performance of the tower was further evaluated using the cooling effectiveness and cooling capacity.

- Effectiveness: The effectiveness of the cooling system was measured according to the ratio of the different ambient air temperature and the supply air temperature, to the difference between the ambient air temperature and its wet-bulb temperature. The calculation was defined by the following expression:

$$\varepsilon = \frac{T_{in} - T_s}{T_{in} - T_{wb}} \quad (5.2)$$

Where, $\varepsilon, effectiveness\ of\ the\ cooling$:, $T_{in}: Inlet\ temperature$, $T_s: supply\ temperature$, $T_{wb}: Inlet\ wet-bulb\ temperature.$

- Cooling capacity: The cooling capacity was defined as the difference between the ambient air temperature and the supply air temperature, multiplied by the volumetric mass flow rate of the air, calculated as follows:

$$Q_C = m \cdot c_p (T_{in} - T_s) \quad (5.3)$$

Where, $Q_C: cooling\ capacity$, m, $mass\ flow\ rate$, $c_p, specific\ heat\ of\ air$, $T_{in}: Inlet\ temperature$, $T_s: supply\ temperature$.

5.4. The prototype tower operation modes

The arrangement of the airflow inlet and outlet allowed the tower to channel the supply air in three modes of operation: 1) DEC; 2) IEC; and 3) the sub-wet bulb temperature. Each cooler mode required a different configuration of air flow circulation, and different locations for the instruments of measurement.

5.4.1. Direct Evaporative Cooling (DEC)

In the DEC mode, the air came from the top opening of the tower, over the wet channels, which in this case was the synthetic grass mat, and supplied the cooled air to the room space at the bottom of the tower, while the stale air was rejected to the outside by a fan placed at the top opening of the box.

The mean air velocity was measured at the inlet duct, within a cross section of 10cm with an air velocity of 2.85m/s. Figure 5.9 shows the air flow arrangement of the DEC mode, together with the position of the instruments of measurement.

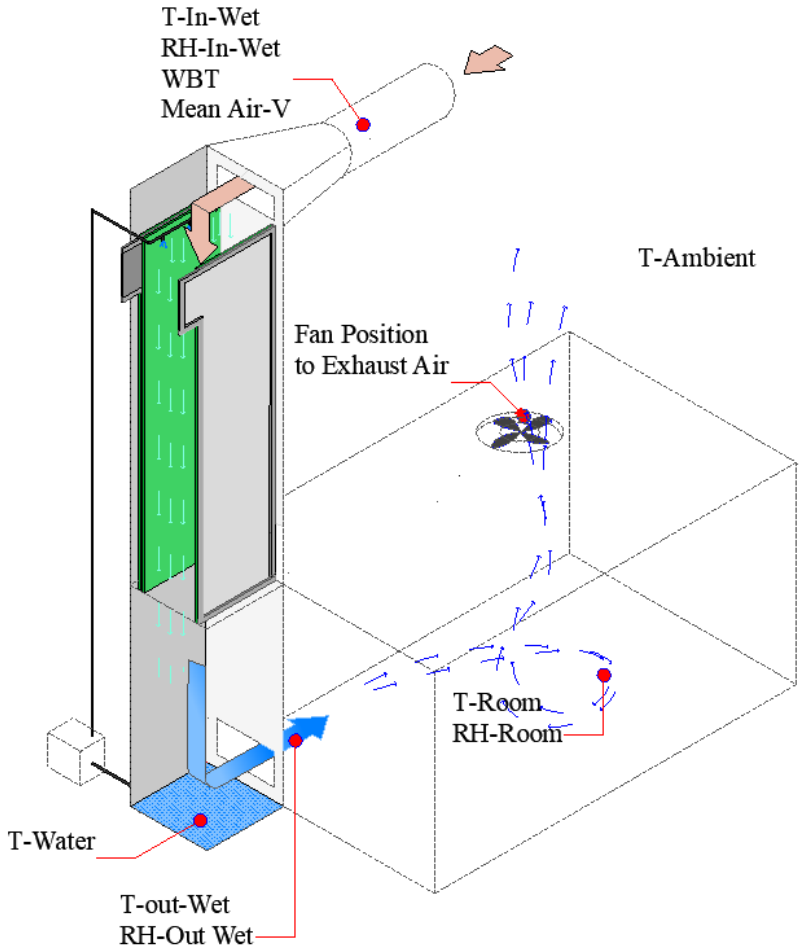


Figure 59. Air flow and location of the measurement sensors in the DEC mode.

5.4.2. Indirect Evaporative Cooling (IEC)

For the IEC mode, the hot air from the environmental chamber directed the airflow from the inlet at the top of the minaret tower through the dry channel, and into the occupied space, allowing the indirect cooling of the supply air, while the stale air was ejected through the wet channels formed by the synthetic grass mats, where water evaporation occurred. This had the advantage of supplying cooled air, without increasing its humidity. In this mode, the fan was

placed at the outlet of the wet channels, in order to drive the airflow outside the cooler, with an air velocity of 1.65m/s. The mean air velocity was measured at the inlet duct within a cross section of 10cm. Figure 5.10 shows the air flow arrangement of the IEC mode, together with the position of the instruments of measurement.

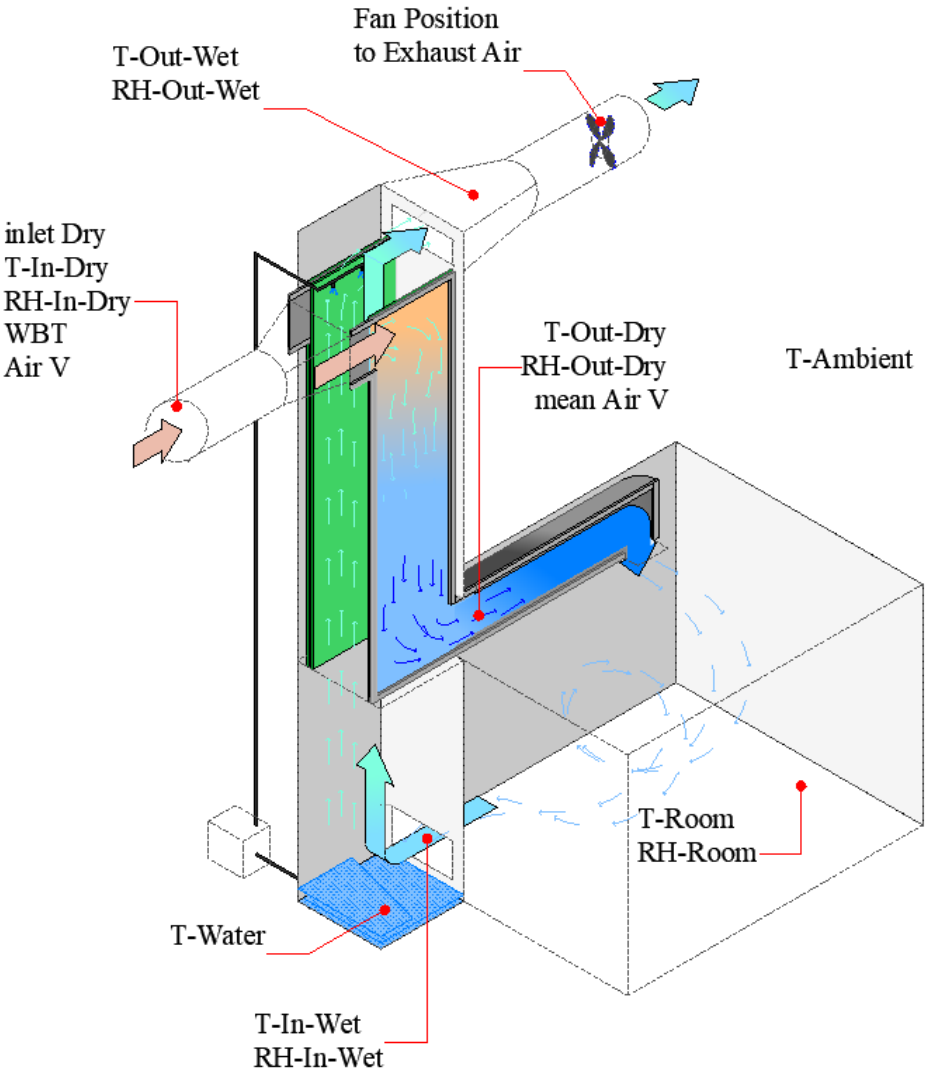


Figure 5*10.* Schematic arrangement of the cooling tower in IEC mode.

5.4.3. Dew point evaporative cooling (DPEC)

The arrangement of airflow in the DPEC mode was similar to that of the IEC mode, as it employed the dry-wet channel configuration, however, in the DPEC mode, approximately 50% of the supply air from the dry channel was rejected to the wet channels through the synthetic grass mats, to complete the evaporation process, with the remaining 50% of the supply air from the dry channel passing to the occupied space, without increasing its humidity.

In this mode, the airflow was driven by two fans to control the flow ratios (50:50%) in each channel, with an air velocity of 1.85m/s, with one fan located at the inlet, or dry channel, and the other at the outlet, or wet channel, to drive the airflow outside the cooler. The mean air velocity was measured at the inlet duct with a cross section of 10cm. Figure 5.11 shows the air flow arrangement of the DPEC mode, together with the position of the instruments of measurement.

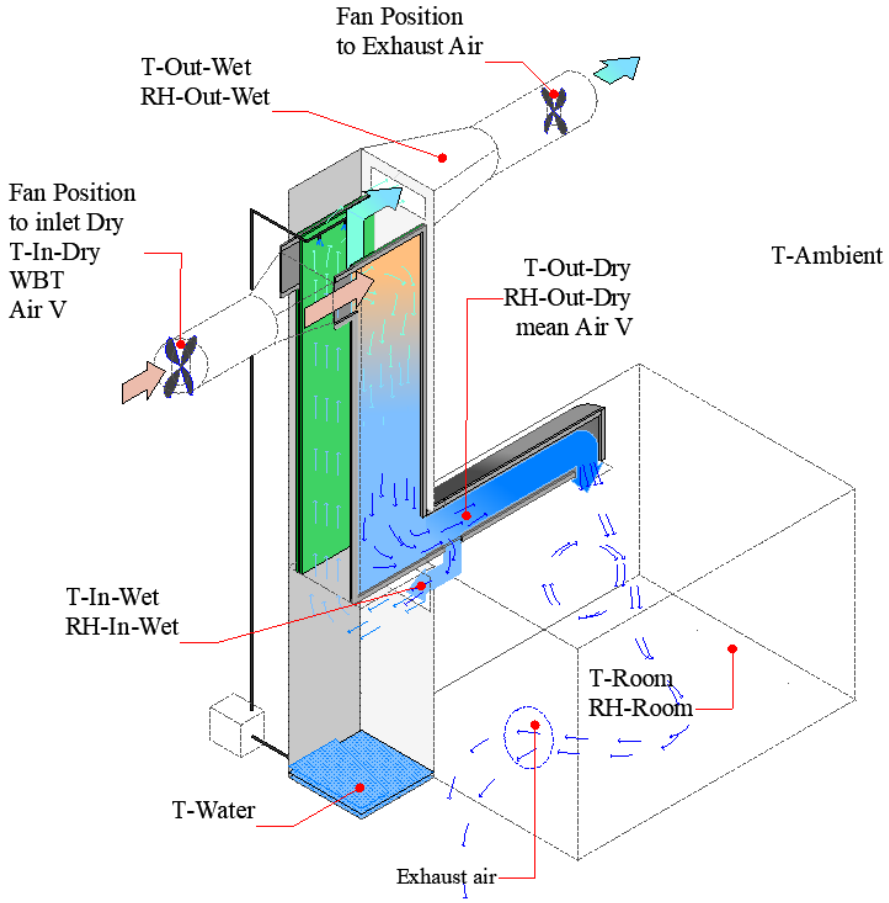


Figure 5*11.* Schematic arrangement of the cooling tower in DPEC mode.

5.5. Experimental set-up

The thermal performance of the minaret prototype was evaluated under controlled temperature and relative humidity conditions in the laboratory. Figure 5.12 shows all of the instruments' components that were connected to the prototype. All of the test experiments were located inside the environmental chamber, in order to set and control the inlet temperature and humidity using the control panel. Different arrangement modes were employed using a flexible duct and fan to supply hot air from the environmental chamber.

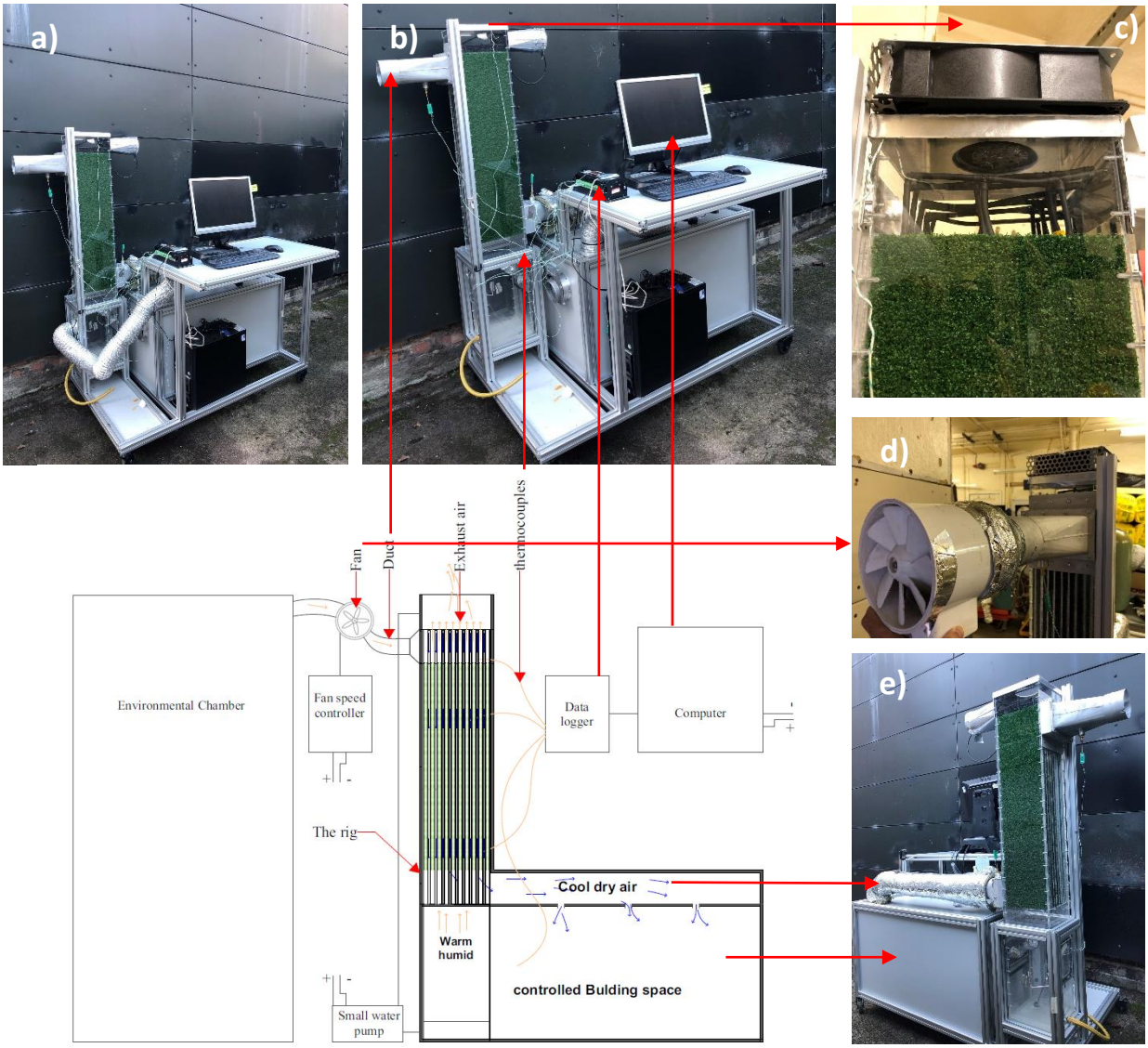


Figure 5.12 Experimental set-up: a) DPEC mode using a flexible duct, b) prototype front view, c) fan outlet, d) fan inlet, e) prototype rear view.

5.6. Test methodology and conditions

The evaluation of the performance of the minaret cooling tower was conducted using different parameter settings, in order to ensure that the system operated at its optimum performance under the following conditions:

Temperature and humidity: The tests were conducted at three different temperatures (30^{o}C, 35^{o}C, and 40^{o}C), and three relative humidities (25,35, and 45%).

Air velocity: The minaret tower system inlet was installed on top, using a flexible duct, through the dry channel (indirect), or the wet channel (direct), in order that the system was able to run with a different air velocity for each mode. The experiments were run inside the environmental chamber. The fan controlling the air pressure drop channelled the air through the tower to the test room, and ejected it through the bottom of the tower to an outside cooler. Using different fan positions for each mode assisted the airflow arrangement to provide a maximum air velocity for direct, indirect, and dew point evaporative cooling, at 2.85, 1.65, and 1.85 m/s, respectively.

Water flow rate: Water was used to wet the synthetic grass mats in the wet channel of the tower, and it was continually circulated by a pump. The test was conducted under a water air flow of 0.5/m, with the water nozzles spraying water in the form of fine particles, to promote the maximum wettability of the synthetic grass mat's surface area.

5.7. Measuring instruments

The system employed the following auxiliary electrical devices to assist in its functioning, to measure the variables, and to save the data recorded during the testing.

Thermocouples: K-type thermocouples were located at several points at the centre of the air flow passages to measure the temperature simultaneously, (Rang from -50 to +250°C Accuracy of reading (±0.5°C), as illustrated in Figure 5.13 (a)

Data logger: A data-taker, model DT500, Series 2, was used. All the thermocouples were connected to this data acquisition device to store readings, and save them temporarily. The data taker was connected to a computer running DE Logger 4, which read all of the data sent from the data taker, and displayed it on a monitor. This data was then saved on a computer for later analysis. See Figure 5.13 (d).

Humidity and temperature meters: RS-232 humidity and temperature meters were employed at the exit of the wet air channel to measure the humidity and temperature of the working air, while an RS-1365 thermometer (Figure 5.13 (c)) was located at the inlet of the dry air channel to measure the humidity and temperature of the inlet air. (Rang -20 to 60 ℃, Accuracy of reading ± 0.5 ℃), (Rang from 10%-95% RH, Accuracy of reading ± 1% RH).

Hotwire anemometer: A portable hotwire anemometer (Testo 405-V1) was employed to measure the flow velocity at the inlet and exit of the dry channel, and that of the wet channel. (Rang from 0 to 10 m/s, Accuracy of reading ±5 %)



Figure 5.13 Photographs of the measurement instruments: (a) Type K thermocouple, (b) hotwire anemometer, (c) RS-232 humidity and temperature meter, (d) RS-1365 thermometer.

5.8. Safe operating procedure

The following safe operating procedure was followed during the prototype experiments.

1. Check all electrical connections and sockets of the computer, data logger, fan, and fan controller;
2. Check the duct is connected by a fan from the environmental chamber and the prototype;
3. Check that all of the thermocouples are connected to the point measurements, in the right order;
4. Check the environmental chamber settings;
5. Check that water has been added in the bottom tower tank, and that it is connected to the pump;
6. Commence the experiment by:

- Switch on the environmental chamber, and setting it to the required temperature and humidity;
- Switch on the computer and data logger to check that the thermocouples are providing readings;
- Switch on the fan when the temperature and humidity inside the chamber reach the desired values;

- Ensure that air comes from the environmental chamber throughout the prototype's testing, and that the warm, dry air from the environmental chamber enters at the top of the tower;

7. Open a new file on the computer, and commence monitoring the temperature and humidity readings;
8. Use the fan controller to change the fan's speed to the required speed;
9. After recording for the required period, switch off all of the equipment:
    - Switch off the environmental chamber;
    - Switch off the fan and pump;
    - Save all data files, and then switch off the data logger, and then the computer;
10. Double check that all of the devices' switches are closed;
11. The experiment is complete.

5.9. Summary

The thermal performance of the proof-of-concept minaret prototype was evaluated in the laboratory under controlled climatic conditions. The cooling minaret tower was operated in three modes of evaporative cooling: direct, indirect, and dew point. The three modes allowed for the adaptation of the cooling performance, according to the prevailing weather conditions. In each mode, nine tests were conducted, in which the temperature of the inlet air of the minaret were set at 30, 35, and 40^{o}C, and the relative humidity at 25, 35, and 45%, reflecting the climatic conditions that prevail in large areas of the Middle East.

Chapter 6. Laboratory prototype experimental results analysis

6.1. Experimental set up and test conditions

The thermal performance of the proof-of-concept minaret prototype was evaluated under controlled climatic conditions in a laboratory. Using an environmental chamber, the temperature and humidity of air entering the minaret was set at desirable values of 30, 35 and 40^{o}C and corresponding RH of 25, 35, and 45%. Thus, representing climatic conditions that prevail in large parts of Middle East. As stated in chapter 5, the cooling minaret tower was operated according to three modes of evaporative cooling: direct, indirect, and sub wet bulb. The three modes supported the adaption of cooling performance, according to prevailing weather conditions.

6.2. Direct evaporative cooling (DEC) mode

In a direct evaporative cooling mode, the supply of air into occupied space is channelled through a wet channel and cooled to approximate its wet bulb temperature under conditions of maximum moisture content. This mode of operation may be necessary when it is very dry and the addition of moisture into the occupied space is required. The thermal performance of the laboratory synthetic fibre grass mats in direct cooler mode was evaluated at temperatures of 30, 35 and 40°C and at corresponding RH of 25, 35 and 45% with inlet air velocity of 2.85 m/s. The supply of air is admitted at the top of tower, and through the wet channels, to circulate air to the bottom of the tower

where the test room is located, while a fan is used to removed stale air from the room via the dry channels. Figure 6.1 shows the DEC mode air flow arrangement, measurements sensor location, and controlling fan position.

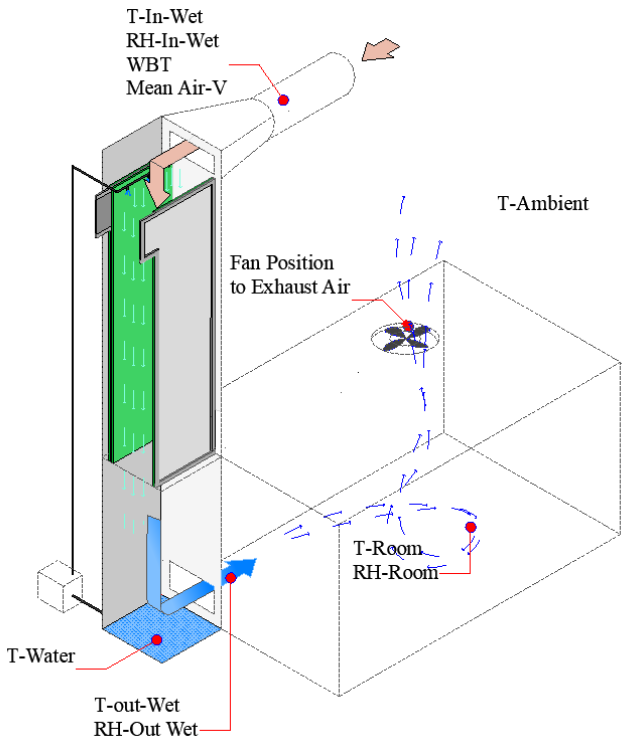


Figure 6.1 Air flow diagram and measurements sensors location of DEC mode

6.2.1. Cooling performance

In the Direct Evaporative cooling (DEC) mode, the air supply directed towards the test chamber is cool and saturated. At steady states, the air temperature supply is cooled by as much as 12.9°C. Figure 6.2 shows an ambient inlet air temperature of 40°C, and humidity of 30.9%, the air temperature of the supplied fell to about 27°C.

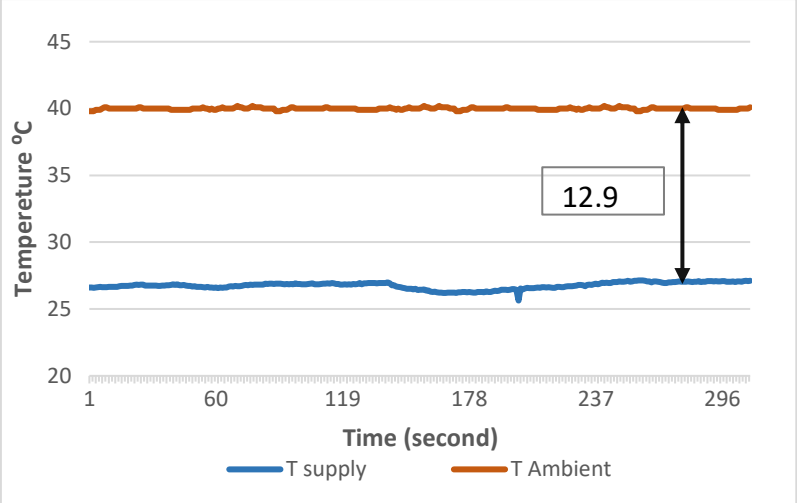


Figure 6.2 Steady state DEC mode: RH 30.9%

The overall steady state cooling performance of the cooling tower is summarised in Table 6.1. It is shown that the air temperature supply fell to within 2°C of the wet bulb temperature (i.e., 27.1°C compared to 25.3°C), with a RH approaching full saturation (90.6%). In addition, the cooling performance of the tower was further evaluated according to cooling effectiveness and cooling capacity. The cooling effectiveness is calculated with the following expression:

$$\varepsilon = \frac{T_{in} - T_s}{T_{in} - T_{wb}} \qquad (6.1)$$

Similarly, cooling capacity was calculated as follows:

$$Q_C = m \cdot c_p (T_{in} - T_s) \qquad (6.2)$$

Table 6.1 reveals the effectiveness of the tower is high, at 0.877, while the cooling capacity is equal to 339.57w.

Table 6.1 DEC mode operating parameters

Inlet Air velocity	Mass flow rate	RH-in-W	T-in-W	T-O-W	T-Wet	T-dew	RH-o-W	Tower effectiveness	Cooling capacity
m/s	kg/s	%	˚C	˚C	˚C	˚C	%	%	W
2.85	0.027	30.9	40	27.1	25.3	19.61	90.6	0.877	339.57

6.2.2. Effect of inlet air temperature and RH on drop in air temperature supply

The effect of ambient air temperature and RH on the supply air temperature was measured at different ambient temperatures, and RH (30, 35, 40°C and 25, 35 and 45%). This is clarified in Figure 6.3, which shows that at 40℃ and 25% RH ambient air conditions, a temperature drop of 12.9℃ was achieved; whereas at the same temperature and RH of 45%, the inlet air temperature reduction was only 10℃. The lowest value temperature drop (of 5.7°C) effected the inlet air condition of 30°C. Therefore, the temperature drop of the inlet air through the cooler improved as the ambient air conditions become hotter and greater air cooling was achieved at low RH and higher temperature levels. This is expected in direct evaporative cooling systems, as the high temperature and low RH (i.e., dry ambient conditions) of air has a greater moisture absorption potential. This is obviously one of the advantages of evaporative coolers over other vapour-compressed cooling systems, as their performance decreases when the ambient temperature rises.

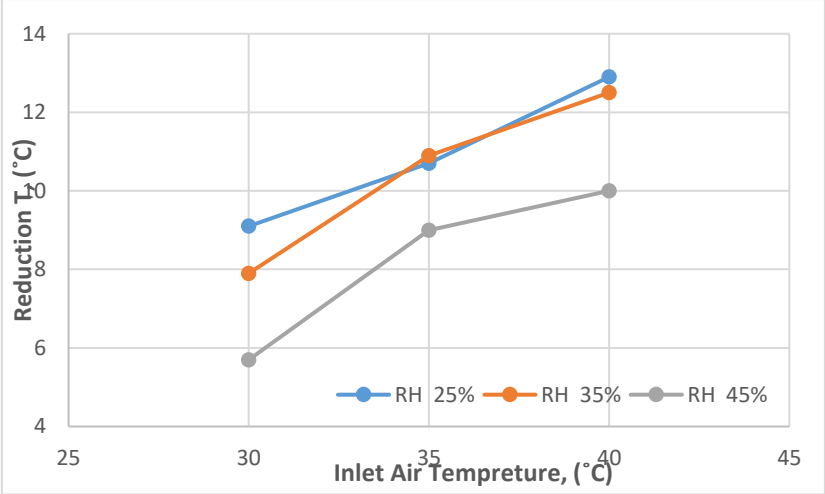


Figure 6.3 Supply air temperature drop (air velocity =2.85 m/s)

6.2.3. The effect of inlet air temperature and RH on effectiveness

Cooling effectiveness is calculated by the expression (6.1). The effect of ambient air temperature on the effectiveness of the cooling tower was further measured, as shown in Figure 6.4, at different temperatures and RH. It can be seen that the effectiveness of the DEC cooling system increased slightly as the inlet ambient air temperature rose. The greater effectiveness was achieved at high inlet air temperature, and effectiveness peaked at 0.97, at inlet temperatures of 40 ℃ and 45% RH. In theory, the wet-bulb effectiveness cannot be greater than 1 in DEC.

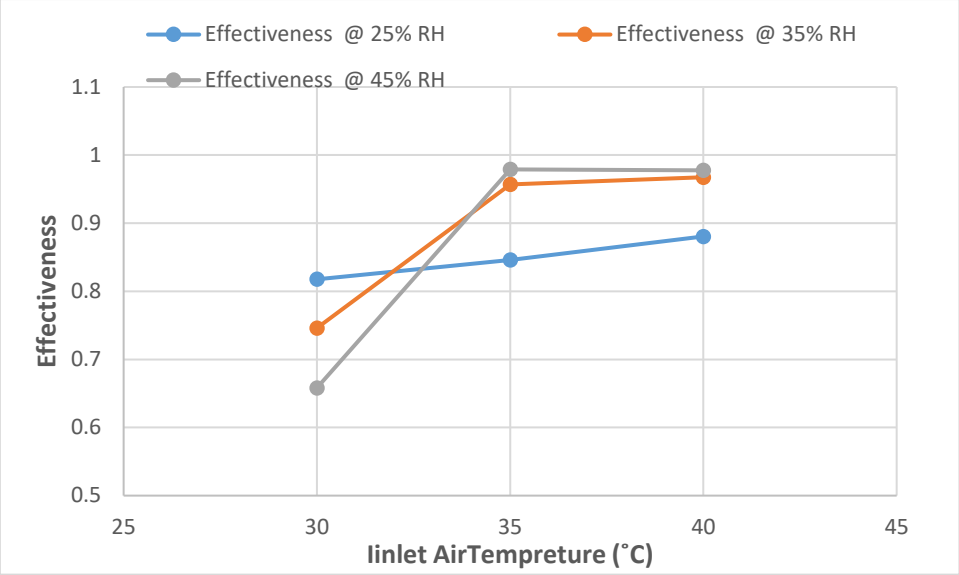


Figure 6.4 Effectiveness of cooling tower (air velocity =2.85 m/s)

Another important parameter influencing the DEC system's effectiveness is the RH of inlet air, i.e. air moisture content. Figure 6.4 shows the calculated results for cooling effectiveness as informed by different inlet air RH at 2.85 m/s inlet air velocity. From the results, it is apparent that increasing ambient RH gives greater cooling effectiveness. Where, the effectiveness falls at 40°C, and (25, 35, and 45%) RH is varied between 0.88, 0.96, and 1.05 respectively.

6.2.4. The effect of inlet temperature and RH on cooling capacity

The effect of the RH of ambient air on cooling capacity can be seen in Figure 6.5. It shows the values for cooling capacity gradually decreased as the ambient air moisture content increased. This decline in system performance can be interpreted by linking cooling capacity with the temperature drop in inlet air 'cooling capacity calculation' (6.1), which is inversely relational to inlet air humidity. Therefore, cooling output is adversely influenced by increases in inlet RH, as

apparent from the figure below. Higher values for cooling capacities were obtained when inlet air RH was lower. For example, cooling capacity declined by about 20%, as the RH of the inlet air rose from 25 to 45%. There is clearly an inverse in terms of proportionality between inlet air RH, and cooling capacity and air supply temperature.

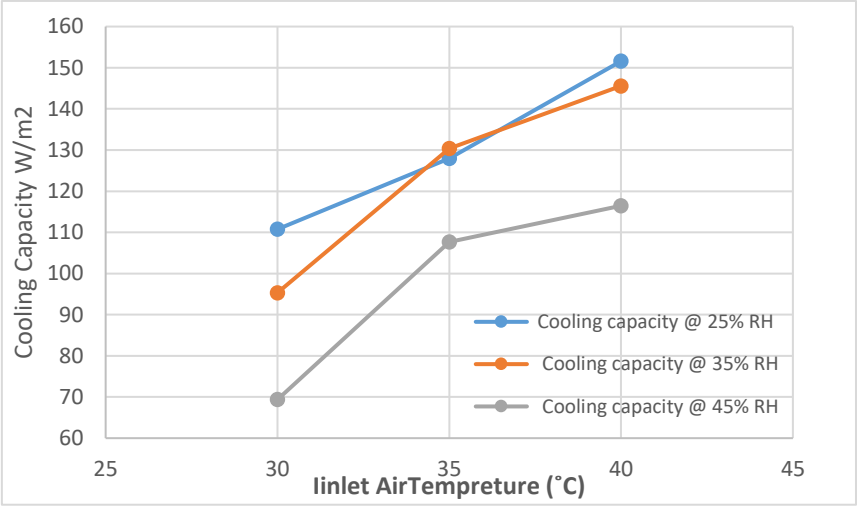


Figure 6.5 Cooling Capacity DEC (air velocity =2.85 m/s)

The effect of ambient air temperature on cooling capacity is presented in Figure 6.5. Under the same test conditions, the results reveal an increase in the air inlet temperature would positively influence the cooling capacity of the cooler. For example, cooling capacity improved by about 27%, from 110.76 to 151.59 (W/m^2), and ambient air temperature rose from 30°C to 40°C at 25% RH. According to the cooling capacity calculation (6.1), there seems to be a direct link between cooling capacity and variation in temperature reduction. This is because the inlet air temperature drop is directly linked to inlet air temperature. Thus, cooling capacity is directly related to inlet ambient air temperature.

6.3. IEC mode

The arrangement of airflow channels within the minaret tower allows cooling of the air supply indirectly; as illustrated in Figure 6.6. In this arrangement, hot dry inlet air is forced through the dry channels into the occupied space, from which it is then distributed through air nozzles at ceiling height; whereas, stale air is rejected through wet channels, formed by synthetic grass mats in which water evaporation takes place. This has the advantage of cooling without increasing humidity.

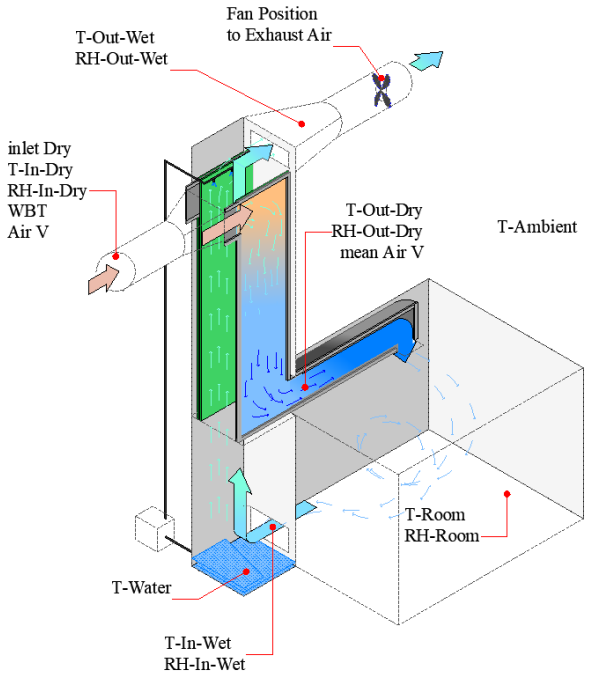
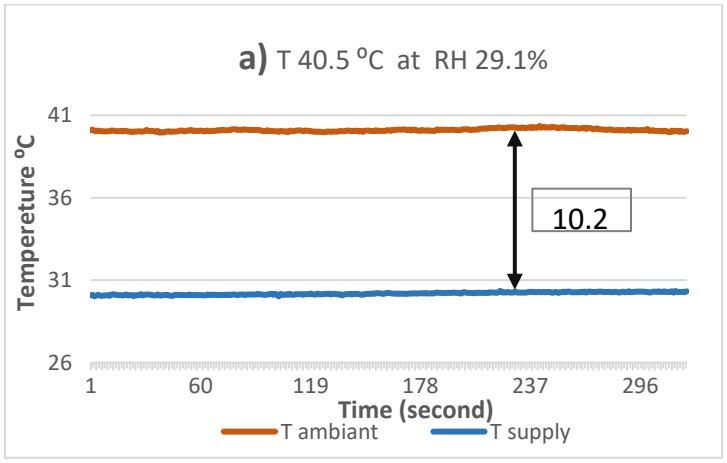


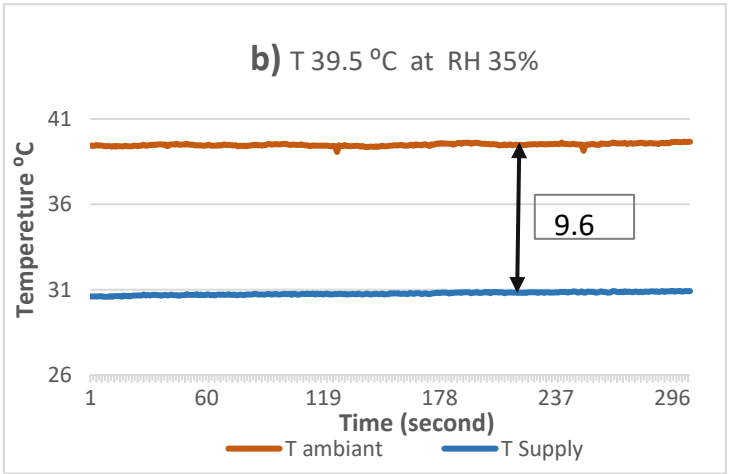
Figure 6.6 Schematic arrangement of the cooling tower in IEC mode

Similar to the case of DEC, the thermal performance of the cooling tower was evaluated at temperatures of 30, 35 and 40°C, with corresponding RH of 25, 35 and 45% and air velocity of 1.65 m/s, as explained in chapter 5.

6.3.1. Steady state cooling performance

The steady state cooling performance of the cooling tower in IEC mode was measured under inlet conditions of 40°C and RH of 29, 35, and 45%, while air flow velocity was held constant at 1.65 m/s. Figures 6.7 a), b), c) show the measured steady state temperature of the dry channel inlet (ambient) air, and outlet (supply) air through the dry channel. This demonstrates the cooling effect generated by the cooling tower, which experiences a maximum temperature drop in inlet air of 10.2°C for inlet temperatures of 40.5°C and a RH of 30%.





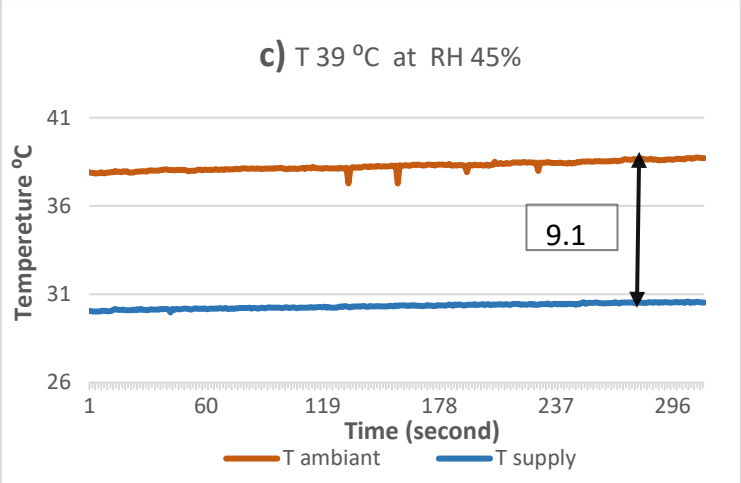


Figure 6.7 Steady state IEC (1.65 m/s inlet flow)

A summary of measured steady state performance data for the cooling tower in IEC mode is given in Table 6.2. The table shows the measured operating temperature and RH, and the calculated cooling tower indices for effectiveness and cooling capacity. Effectiveness is less than 1 here, while the highest cooling capacity is 155.4w.

Table 6.2 Measured steady state performance parameters in the indirect evaporative cooling mode

Inlet Air velocity	RH-in-D	T-in-D	T-O-D	T-Wet	T-dew	T-in-W	T-o-W	RH-o-W	Calculated effectiveness	Calculated Cooling capacity
m/s	**%**	**˚C**	**˚C**	**˚C**	**˚C**	**˚C**	**˚C**	**%**	**-**	**W**
1.65	29.1	40.5	30.3	25.4	19.09	36	32.1	87.7	0.67	155.4
1.65	34.9	40.4	30.8	26.8	21.9	34.9	32.7	87.6	0.70	144.9
1.65	45	39.6	30.5	28.7	25.4	33.6	31.9	86.7	0.83	137.4

6.3.2. Influence of inlet air temperature and RH on supply air temperature drop and tower effectiveness

The effect of ambient air temperature and RH on the supply air temperature was measured at different ambient temperatures, RH, and inlet air velocity at 1.65 m/s. This is presented in Figure 6.8, which shows that at an ambient air temperature of 40°C and 25% RH, the temperature fell by 10.2°C. Meanwhile at the same ambient temperature, a 45% drop in RH prompted a drop in ambient temperature by 9.1°C. However, the lowest achieved drop in ambient air temperature was by 5.2°C at 30°C and 45%, which means that hotter and dryer conditions yield a greater temperature drop.

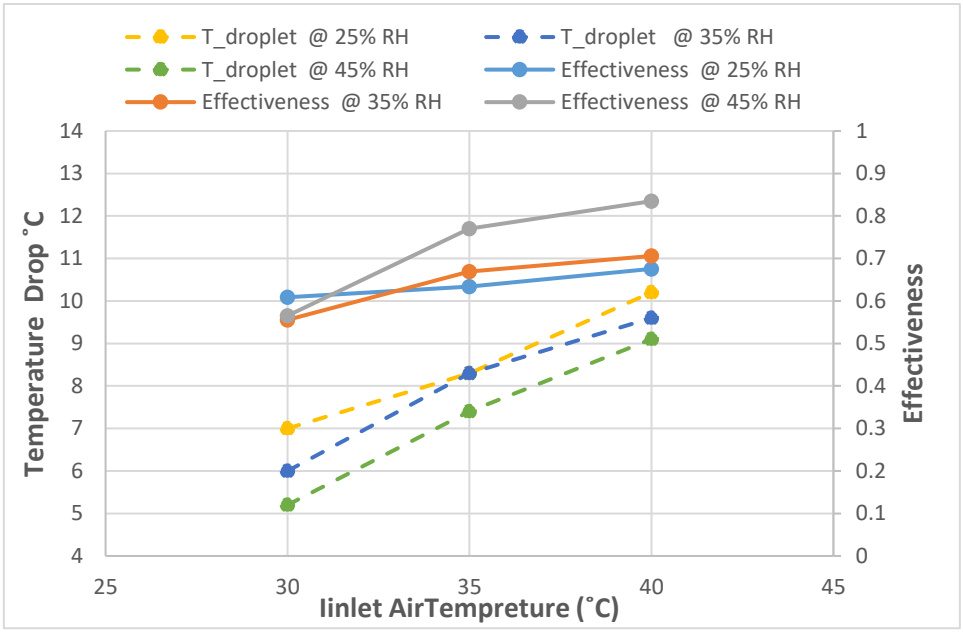


Figure 6.8 Effectiveness and inlet air temperature drop

According to the effectiveness calculation detailed in equation (6.1), Figure 6.8 shows the effect of ambient air temperature on the effectiveness of the IEC system. Similar to the test conditions, an

additional higher ambient temperature provides a greater increase with greater cooling efficiency. It was found that the high achievement of cooler effectiveness is 0.85 at an ambient air temperature of 40°C, while the lowest result was 0.56 at 30°C. In contrast, RH influenced IEC cooler effectiveness. Thus, it is clear that increasing the ambient RH, results in greater cooler efficiency. For example, effectiveness coolers at 40°C, and different RH (25, 35, and 45%), varied between 0.67, 0.70, and 0.83 respectively. Thus, a drop in ambient air temperature and cooler effectiveness is influenced by similar trends reflecting variations in ambient air temperature and RH.

6.3.3. The influence of inlet temperature and RH on cooling capacity

The influence of ambient air temperature on the cooling-capacity was further calculated, as shown in Figure 6.9, when employing the same test conditions at different temperatures and RH. It was found that increases in the inlet-air temperature positively influence the cooling capacity of the system, with an improvement of about 21%, from 57.47 to 69.39 W, at inlet-air temperatures of 35°C to 40°C. Accordingly, lower inlet air temperatures are directly related to a negative impact on cooling capacity.

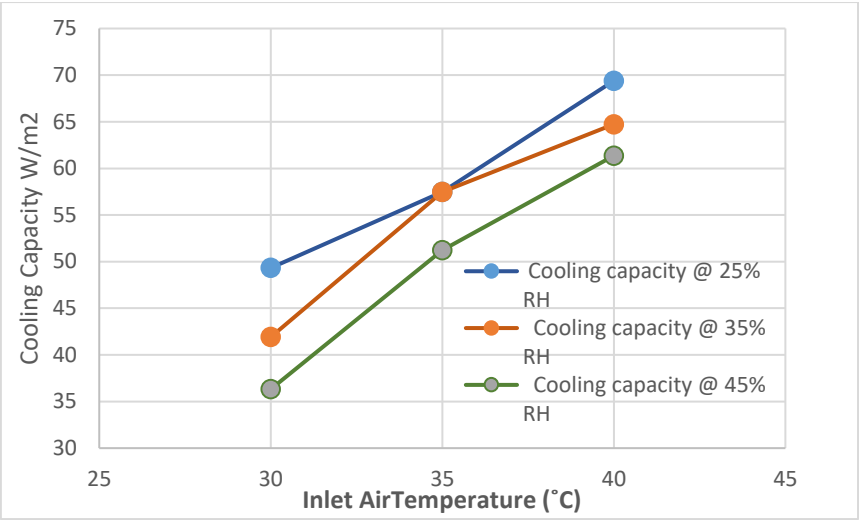


Figure 6.9 Cooling Capacity IEC cooler system

Another parameter influencing cooling capacity is the RH of the ambient air, as shown in Figure 6.9, which details how the cooling capacity gradually decreased as ambient air moisture content increased. This is inversely relative to the humidity of inlet-air. Therefore, cooling output is adversely influenced by the increase in inlet RH, as higher values were achieved for cooling capacities obtained at a lower level of inlet air RH. For example, the cooling capacity dropped by about 36%, as inlet air RH rose from 25 to 45°C. It is therefore evident that there is an inverse proportionality between the inlet air RH and the cooling capacity.

6.4. Dew point evaporative cooling operation mode

In dew point evaporative cooling mode (DPEC), part of the air supply, about 50% from the dry channel, passed through wet channels to complete the evaporation process, whereas 50% of the air supply from the dry channel entered the occupied space, without increasing its humidity. The aims in this operation mode are to cool the air

supply temperature below the ambient air wet-bulb temperature. Figure 9.10 shows the schematic arrangement of the cooling tower during the dew point evaporative cooling mode.

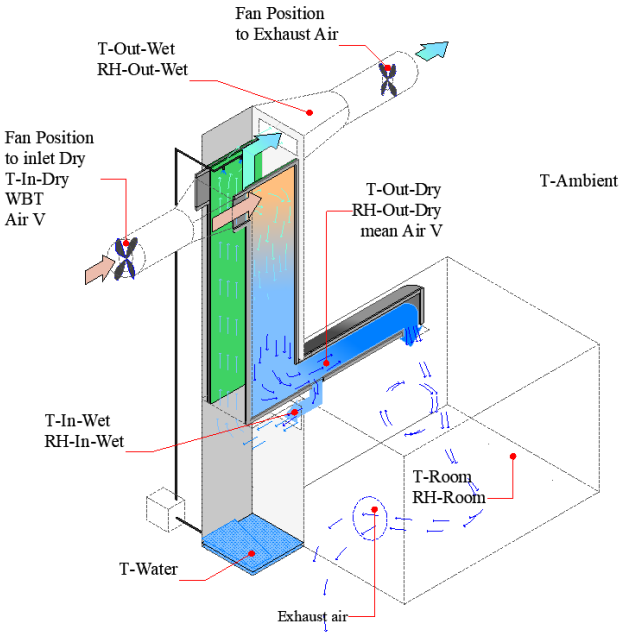


Figure 6.10 Schematic arrangement of the cooling tower in dew point evaporative cooling mode

6.4.1. Steady state cooling performance

Similar to the previous cases regarding modes (DEC) and (IEC), in (DPEC) the thermal performance steady state of the cooling tower was evaluated at temperatures of 30, 35 and 40°C and a corresponding RH of 25, 35 and 45% with an air velocity of 1.85 m/s. Figure 6.11 shows a steady state measurement for ambient air temperature (inlet dry channel) at 41.8°C, and a supply of air temperature (dry channel outlet) of 31.5°C at an ambient RH of 27.4%. This demonstrates the cooling effect generated by the cooling tower, with a maximum temperature drop of inlet air of 10.3°C.

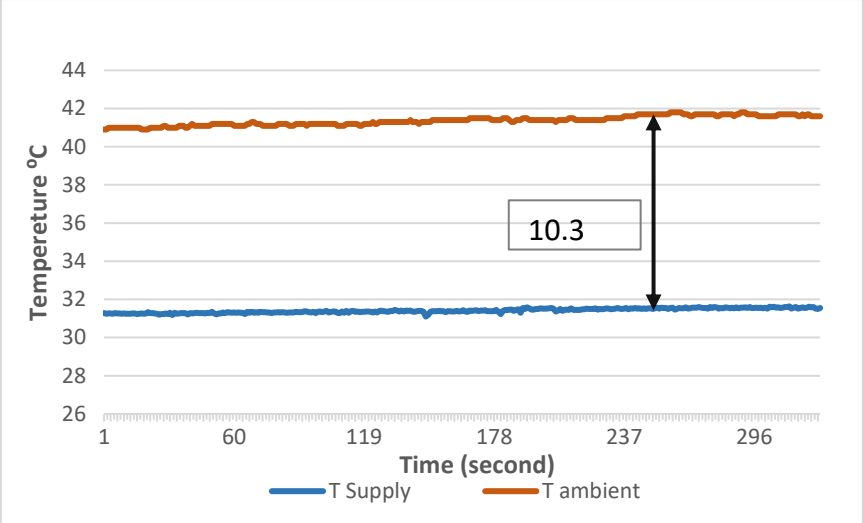


Figure 6.11 Steady state dew point evaporative cooling mode: RH 27.4.9%

Table 6.3 gives an overall summary of measured steady-state performance and the calculated cooling tower in DPEC mode. It can be seen that the outlet temperature for the dry channel (supply) is equal to the inlet temperature in wet channel (33.3°C), showing the outlet temperature of the wet channels increased by 1.8°C (i.e., 31.5°C compared to 33.3°C). Therefore, it is concluded that water temperature becomes lower than the wet-bulb temperature because the air supply is passing back through the wet channels. Therefore, effectiveness here is less than one, while the highest cooling capacity is 174.4W.

Table 6.3 Dew point evaporative cooling mode operating parameters

Inlet Air Velocity	RH-in-D	T-in-D	T-O-D	T-Wet	T-dew	T-in-W	T-o-W	RH-o-W	Calculated effectiveness	Calculated Cooling capacity
m/s	%	˚C	˚C	˚C	˚C	˚C	˚C	%	%	W
1.85	27.4	41.8	31.5	25.5	19.22	31.5	33.3	86.1	0.67	174.4

6.4.2. Effect of inlet air temperature and RH on temperature drop in air supply

The effect of ambient air temperature and RH on the temperature of the air supply was measured at different ambient temperatures and RH (30, 35, 40°C and 25, 35 and 45%). Figure 6.12 clarifies that in DPEC mode, there is a high ambient temperature drop at high ambient air temperatures and low RH. For example, inlet ambient air temperature at 40°C and RH of (25, 35 and 45%) achieved a drop in air temperature of 10.3, 9 and 7.6°C. Additionally, the difference ambient air temperatures effected air supply causing a temperature drop, wherein the reduction produced was 10.3, 9.8 and 7.9°C at 30, 35 and 40°C, with the same RH (approximately 25%). This demonstrates that the evaporative cooler experienced the greatest amount of air cooling, achieving low RH and a high-temperature.

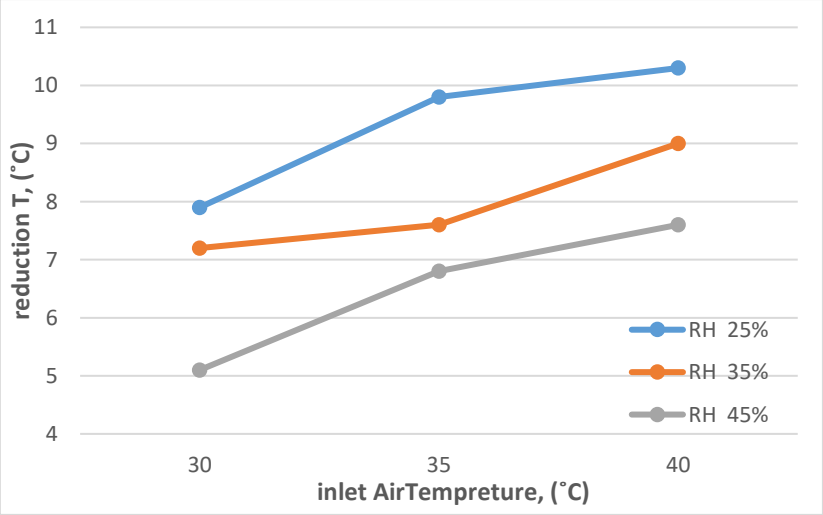


Figure 6.12 Supply air temperature drop (air velocity =1.85 m/s)

6.4.3. The effect of inlet air temperature and RH on effectiveness

The effect of inlet air temperature and RH on the effectiveness of the cooling tower in DPEC mode is shown in Figure 19. The measured data was at different temperatures and RH, and effectiveness achievement was below 1. High performance and greater cooling effectiveness was 0.67 at an ambient air temperature of 40°C, while the lowest result was 0.53 at 30°C. This means a higher inlet air temperature yields greater cooler effectiveness. A further parameter measured that effected cooling efficiency was ambient RH; the data showed varying RH at (25, 35 and 45%) with the same ambient temperature at 40°C and effectiveness decreased from 0.67 to 0.63. However, cooler efficiency decreased with an increasing inlet RH.

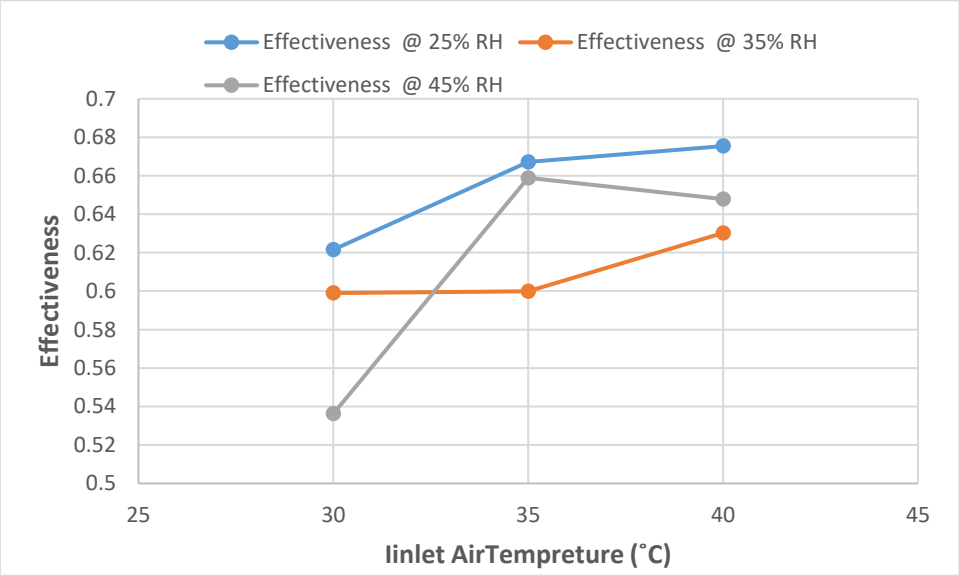


Figure 6.13 Effectiveness of cooling tower (air velocity =1.85 m/s)

6.4.4. The effect of inlet temperature and RH on cooling capacity

Within the same test conditions, Figure 6.14 shows the effect of inlet air temperature and RH on cooling capacity as measured and

calculated for DPEC mode. It is apparent that the cooling capacity of the cooling tower can be increased gradually by increasing the ambient air temperature. The maximum cooling capacity achieved at 40°C and RH 25%, was 77.8 W/m^{2,} and the minimum was 39.9w/m^{2a} at 30°C and RH 45%.

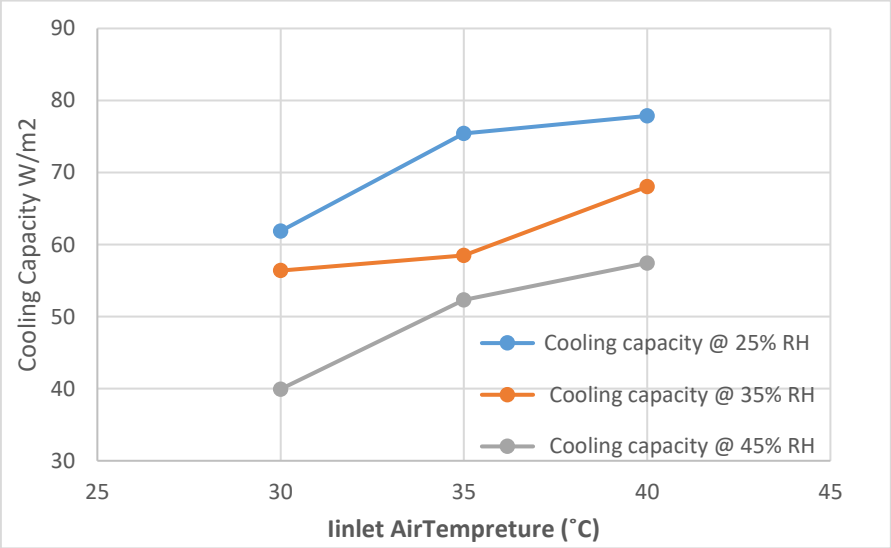


Figure 6.14 Cooling Capacity DPEC cooler system

Therefore, it is shown that the ambient RH influences cooling capacity. The values of the cooling capacity gradually dropped as the moisture content of the ambient air increased. As seen in Figure 6.14, higher cooling capacities were obtained when the inlet air had a lower RH. For example, cooling capacity declined from (77.8 to 56.4 W/m^2), according to ambient RH (25 to 45%). There is clearly, therefore, an inverse proportionality between inlet air RH and the cooling capacity and the temperature of the air supply.

6.5. Comparative performance of current three modes

Taking all this into account, it can be noted, that for the temperature and humidity of inlet air of the minaret was set at desirable values of 30, 35 and 40^{o}C, corresponding to RH of 25, 35, and 45%. For all three modes of evaporative cooling show whether more favourable cooling performance was obtained at higher inlet air temperatures and lower humidity levels. The trends observed relate to the physical principles of evaporating cooling, because higher temperatures and lower humidity ratios yield conditions further from their saturation point.

The laboratory results test of synthetic fibre grass mats shows the effect of water consumption on temperature droplets for the current three configurations of the evaporative cooler. To compare the best temperature droplet for all three systems, the same air inlet temperature was set at 40°C with 25% RH, as shown in Figure 6.15. This shows there was high water consumption for both indirect systems with a lower temperature droplet, but as direct the result there was less water consumption by about 40%, with high-temperature droplets. This could explain the use of wet and dry channels with both indirect systems, explaining and taking into account the mass transfer process, which both indirect systems involve. Nevertheless, the direct mode used just the wet channels to provide cooled air.

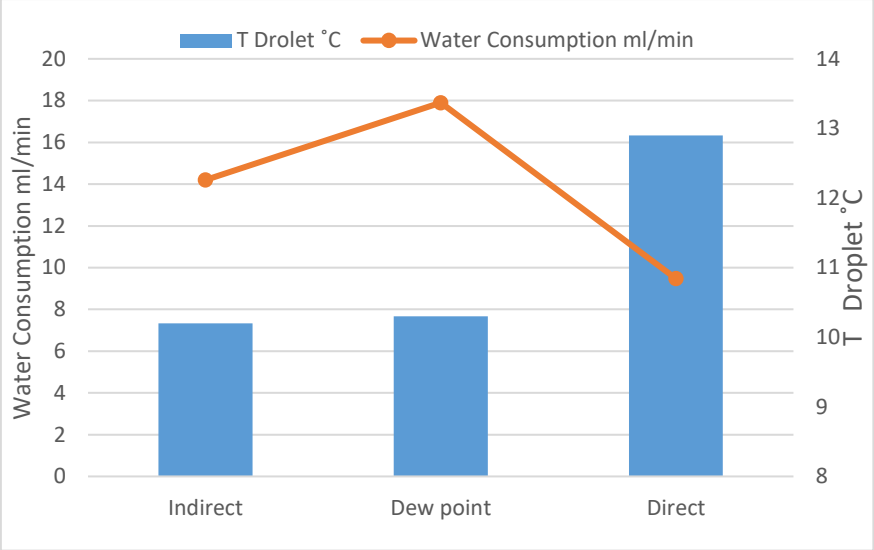


Figure 6.15 Experimental result for the water consumption and droplet temperature for current three configurations at 40°C RH 25% Comparative performance with existing studies

The temperature drop associated with the current three modes of evaporative cooler effects cooling capacity. Figure 6.16 shows the experimental results for cooling capacity for current direct, indirect, and dew point evaporative coolers, using synthetic fibre grass mats, and four other works using porous ceramics Musa (2008), Ibrahim et al. (2003), and Ford et al. (2010) as DEC systems, and sub-wet bulb temperature Boukhanouf et al. (2013). From this figure, it is clear that cooling capacity increased with the temperature drop, and the highest values for cooling capacity and temperature drop were achieved in the current mode of the DEC, at about 12.9°C, which was set at an inlet temperature of 40°C with a 25% RH.

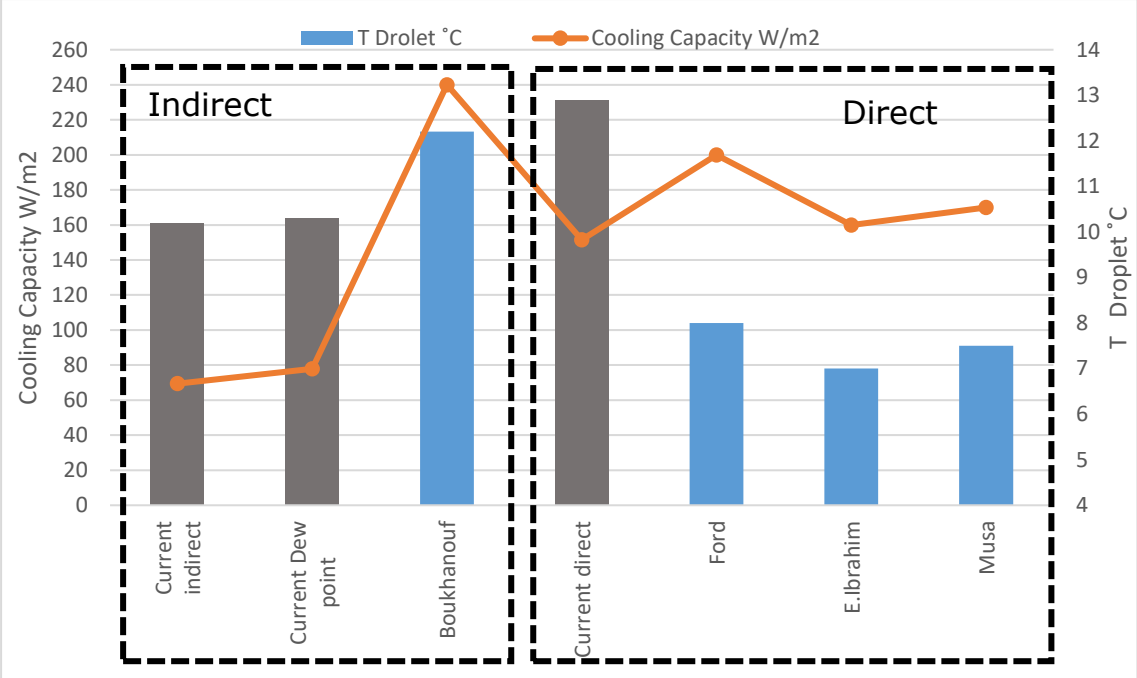


Figure 6.16 Experimental results for the cooling capacity and temperature drop for current three modes compared with previous studies at 40°C RH 25%

The current three modes and systems using synthetic fibre grass mats were compared with previous work on sub-wet bulb temperature evaporative coolers (Boukhanouf et al.), and DEC, carried out by (Musa), both of which used porous ceramic materials. Considering all cases, the air inlet temperature was set at 35 with 35% RH, and results were as shown in Figure 6.17. It can be seen that higher water consumption reduces effectiveness, as demonstrated in the results of the current work. When comparing the findings for both IEC systems in this study with Boukhanouf, Figure 6.17 details the water consumption of the current coolers using synthetic grass material, finding it is more effective than porous ceramic, as the current dew point effectiveness is lower. Furthermore, the efficiency of the current direct configuration system

is slightly less than given by Musa when discussing DEC systems, and current water consumption is more by 25%.

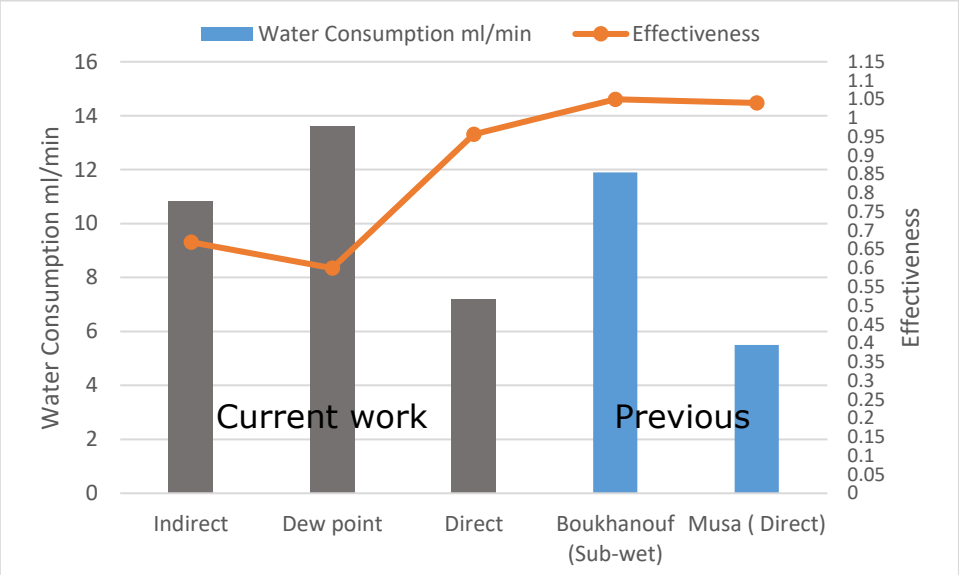


Figure 6.17 Water consumption and effectiveness for current three modes work and Boukhanouf & Musa work at 35°C and 35% RH

The overall findings for the dew point-indirect evaporative cooler can be compared with the findings of Amer experimental study. The present experimental research results provide similar values for the outlet performance indices. Nevertheless, lack of significant differences can be explained by measurement inaccuracy and changes in ambient conditions.

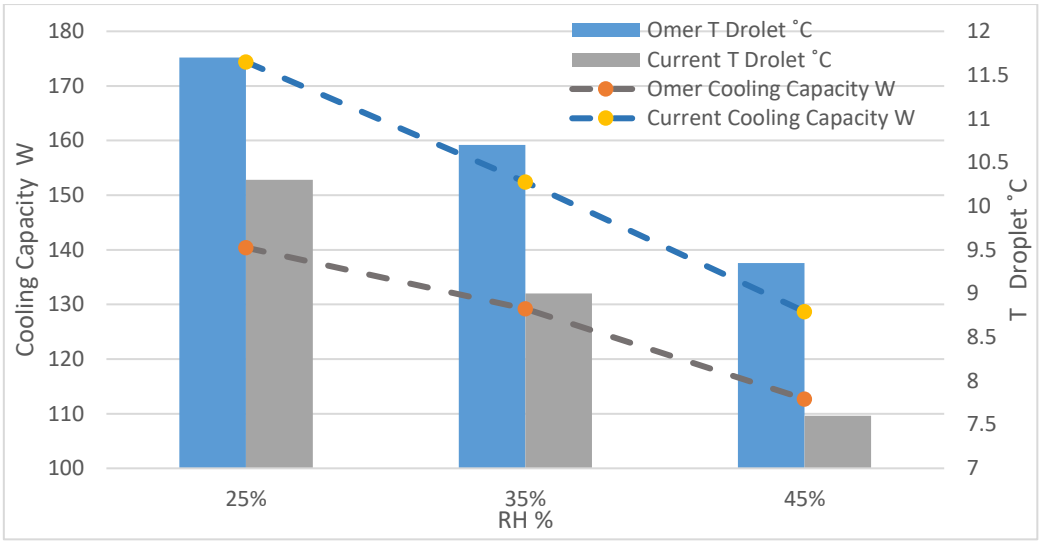


Figure 6.18 Experimental results for the cooling capacity for current dew point evaporative coolers using synthetic-grass materials, compared with Amer (Source: (Amer, 2017)).

The performance and experimental results concerning cooling capacity and temperature drop for current dew point evaporative coolers using synthetic grass were compared with Amer (2017) work on a sub-wet bulb temperature evaporative cooler using heat pipe-ceramic tube (see Figure 6.18). At an inlet temperature of 40°C, cooling capacity and temperature droplets for both coolers decreased, with increasing inlet RH. Although the inlet air velocity for both systems was set at a range of 1.8-2 m/s, by way of 50% working-to-inlet air flow ratio, the cooling capacity (W) achieved by the current cooler proved much higher than the cooling capacity result for the sub-wet bulb evaporative cooler. This is due to the use of more wet media materials to ensure a greater contact surface area than would be achievable with synthetic grass.

6.6. Possible reasons for experimental results

Using the experimental methods to evaluate the thermal performance of the minaret prototype cooler revealed variations between measured and predicted findings, as detailed in the previous sections. Several possible reasons for the discrepancies might be:

Surroundings condition effect: as the cooler unit has been testing it in the environmental chamber to get a real condition, but that gain the heat into the device due to the non-insulation the external walls of unit components.

Synthetic grass materials: The grass material was designed for playing on the ground as it has thicker plastic at the bottom; it could also deliver better performance in terms of heat transfer being as thin as possible. In addition, it might be not enough to hold the water.

Water distribution system: The cooler was designed to fit the water circulation system, permitting the mechanism to drive water through synthetic grass to wet the surface, although this might not be good enough. The spray nozzle type works as a droplet from the top, and could be used mainly as a fog nozzle type requiring a compressor pump.

The fabrication process: all construction work for the prototype was undertaken manually, due to limitations in the laboratory. This inevitably resulted in inaccuracy and imprecision, which this might have led to a leak; thus, we expect that factory machinery work will eradicate these problems.

6.7. Summary

The 'cool minaret' prototype was fabricated in the laboratory for three arrangement modes; i.e. direct, indirect and dew point. The cooling performance of the cooler was investigated experimentally to evaluate various operating conditions.The proposed evaporative cooler was mainly composed of a synthetic grass sheet-stacked panel with multiple groups of dry and wet channels inserted as vertical air guiders, allowing room for testing. The heat transfer side of the dry channels was comprised of an aluminium tab sheet, and the internal surface of the wet channels was layered with a synthetic grass mat to enhance the surface's wettability. The experimental results from the research were compared with examples from existing published work, and the reasons for disagreements analysed.

To conclude the findings of the present experimental study, the drop in temperature for the current three modes under similar various operating conditions, varied from 5.7-12.9°C, 5.2-10.2°C, and 5.1-10.3°C for direct, indirect and dew point modes respectively. Graphs for all the test results showed air temperature rises with greater inflow temperature. Moreover, with higher humidity air supply the cooling power, wet bulb effectiveness decreases. Increase in inlet dry air temperature leads to an increase in either effectiveness or air supply temperature. We conclude that the DEC mode system is the best across an indirect range of 20% for temperature drop. However, this might not be considered a significant difference if it fails to satisfy the cooling requirements of the space as effectively as the IEC does.

Chapter 7. Conclusion

The aim of this research project was to determine the most effective approach for passively cooling water vapour in mosques. In hot, dry climates, like that in the KSA, porous media such as wet materials, have been an important aspect of vernacular architecture. In recent years, there has been an increasing desire to abandon the use of mechanical cooling solutions, such as air conditioning, due to their energy consumption, and to environment issues. Previous research demonstrated the applicability of porous media as an evaporative cooling mechanism for buildings, and this project advanced the knowledge in the field regarding the design of windcatchers or towers, passive cooling techniques, and material compatibility. The specific objectives of this research project were:

- To evaluate and develop various aspects of mosque design, such as the comfort level of worshippers, the cooling load, and energy consumption, in terms of how they relate to the building's envelope;
- To design a minaret configuration that incorporates an evaporative cooling system;
- To select materials for an evaporative cooling system that are suitable for integration in this context;
- To build and test a small-scale laboratory prototype under controlled climatic conditions.

The findings of this study are summarized below.

7.1. Increasing energy consumption and cooling demands in mosques

A review of the background, and of the extant literature concerning the energy consumption in mosques in the KSA highlighted the increase in the use of air conditioning in this building sector, due to its market availability, and the low performance of these buildings' envelope, and to meet comfort standards. The KSA has the largest number of mosques in the world, and these buildings are characterized by a high consumption of energy per person, compared with other public buildings.

7.2. A review of passive cooling strategies in buildings

In appropriate architectural design, the cooling load of buildings can be reduced by curtailing the direct heat conduction and solar gain through the envelope. Summer heat, in particular, imposes the most thermal stress on the envelope of buildings in hot regions, and the climatic design of the building must address its summer performance. Hence, a reduction in the indoor temperature of these buildings should be the primary focus of the design, alongside ensuring the inclusion of successful natural ventilation, when it is prudent. As well as traditional methods for evaporative cooling, which are green and low energy, cooling solutions include DEC, IDEC, and DPEC.

7.3. Energy analysis of a typical mosque

The study presented an investigation and analysis of the thermal performance of a typical Saudi mosque design, in terms of its energy

consumption pattern. The mosque that constituted the base case is located Hail, the model of which has also been applied to mosques in areas with different climate conditions, such as in Dhahran and Abha, all of which were included in the investigation as examples of typical mosques. In order to conduct the assessment, the thermal software 'Design-builder' modelling system was employed. The results of the analysis demonstrated that the base case mosque possesses a very low performance in the summer months, when there is a peak outdoor temperature of 36.2°C, and a subsequent significant energy consumption, the highest of which was 3606 kWh, recorded in the month of July. The cooling load necessitated the highest energy consumption, with the maximum cooling load occurring in August, when the cooling load constituted 100% of the total energy demand. The main reason for this was the poor insulation of the mosque's envelope.

Using the software, several passive cooling techniques were simulated, including insulating the wall and roof, and adding double-glazed windows and envelope shading. Compared with the uninsulated and unshaded base case mosque, the combination of improvements demonstrated a potential to reduce the cooling load of the mosques in Hail, Dhahran, and Abha by approximately 37%, 30%, and 40%, respectively, thereby demonstrating reductions in the wall, roof, and glazing insulation heat gains.

An active approach that employed the introduction of an evaporative cooling system was deemed to be an appropriate method for cooling mosques, in which the RH is low for the majority of the year, and the results of the assessment showed that the mosques in Hail and Abha

qualified for this approach. The extant research conducted by Boukhanouf et al. (2013) demonstrated that the use of porous ceramic materials as a sub-wet bulb evaporative system can achieve a cooling capacity of 225 W/m^2 of the floor area of a building. The model in the present study illustrated that, in the Hail case, which had a cooling load of 23,067 W, a wet surface area of about 102 m^2 would be required to meet the cooling load demand for the prayer room, whereas in Abha, a wet surface area of around 46m^2 would be required to meet 10,465 W of the cooling load demand. It was concluded that the size of the minaret, according to the wet surface area required, would be appropriate for meeting these cooling loads.

7.4. Design and develop a porous material that can be combined into a minaret as a windcatcher to supply cooling

The next stage of the project concerned the adaptation of the minaret as a multi-functional element of the mosque, including serving as a passive air cooler, using an integrated windcatcher/evaporative cooling system. Different design proposals were considered in terms of the airflow patterns, the cooler configuration, and the cooling specification of the building, together with construction materials of both porous ceramic and synthetic grass mats. The ceramic materials were compatible with integration into the structure of the minaret, while the synthetic material offered a modular design and flexibility that facilitated its integration into the structure. Different modes of operation of the 'cool minaret' system were explored that incorporated fixable airflow patterns that provided a healthy indoor environment for the mosques' occupants.

7.5. An experimental prototype design concept and component assembly

A small-scale prototype 'cool minaret' model was designed that integrated evaporative coolers, to demonstrate the feasibility of the concept. The main laboratory rig included a Perspex tower, a wet media material in the form of synthetic grass matting for the purpose of water distribution, and air inlet and outlet ducts. Instruments were employed to measure the performance and modes of operation of the system, in terms of DEC, IEC, and DPEC. In each mode, nine tests were conducted, in which the temperature of the inlet air of the minaret was set at 30, 35, and 40^{o}C, and the relative humidity at 25, 35, and 45%, reflecting the climatic conditions that prevail in large areas of the Middle East.

7.6. Demonstrate and analyse the performance of the cool minaret prototype using synthetic grass matting

The results of the thermal performance of the proof-of-concept minaret prototype was evaluated in the laboratory under controlled climatic conditions. The aspects of the performance that were evaluated using an environmental chamber included the temperature reduction, the cooling capacity effectiveness at different ambient air temperatures, and the humidity. The results of all three modes of the evaporative cooling system revealed an overall positive trend in terms of the physical principles of evaporating cooling as a favourable cooling mechanism at a high inlet air temperature and low humidity levels, because the higher temperatures and lower humidity ratio provided conditions that were distant from the saturation point.

The thermal performance of the synthetic fibre grass mats for all three modes was evaluated at temperatures of 30, 35, and 40°C, and at a corresponding RH of 25, 35, and 45%. In the DEC mode, the supply air temperature was cooled by as much as 12.9°C, demonstrating that the supply air temperature was decreased to within 2°C of the WBT, which is to say, 27.1°C, compared with 25.3°C, and that the RH was approaching full saturation (90.6%). The effectiveness of the cooling capacity of a design that employed a surface area of 151 W/m^2 of wet synthetic grass matting was approximately 0.97, as in theory, the wet-bulb effectiveness cannot be greater than 1.0 in DEC. In the IDEC mode, in which the cooling effect was generated by a cooling tower, the maximum temperature drop of the inlet air was 10.2°C, producing an effectiveness score of less than 1.0, and the highest cooling capacity was 69.3 W/m^2. Meanwhile, in the DPEC mode, the supply air temperature was reduced by 10.3°C, hence the water temperature was lower than that of the WBT, because part of the supply air was returned through the wet channels. The effectiveness was therefore less than 1.0, while the highest cooling capacity was 77.8W/m^2 of the wet synthetic grass matting's surface area.

The experiments therefore demonstrated that the use of synthetic grass matting in evaporative cooling is a feasible option for integration into building elements. The matting has the additional benefits of firmness, low maintenance, and ease of manufacture, as well as not being detrimental to health.

7.7. Further work

This thesis demonstrated the technological principle of evaporative cooling, in terms of DEC, IEC, and DPEC, using a synthetic grass material as a wet media that can be integrated into windcatchers in minarets. Further research could extend the concept of the 'cool minaret', and the following are recommendations for future work:

- Investigate and test the performance of different sizes and types of synthetic grass, and different air gap channels, including improving the flat rear material of the matting to enhance its mass transfer surface;
- Model analyses of the synthetic grass material in different applications, using computational fluids dynamics (CFD) that can be evaluated, and perform the required cooling load;
- This project demonstrated the application of synthetic grass material in the minarets of mosques. Other materials that can be integrated into building elements, such as walls or the roof, to deliver thermal comfort for the building's occupants, might also be explored.

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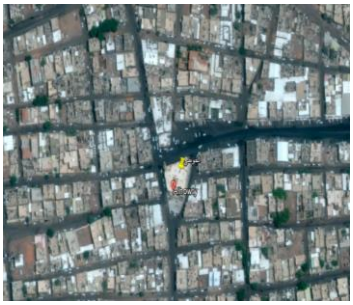
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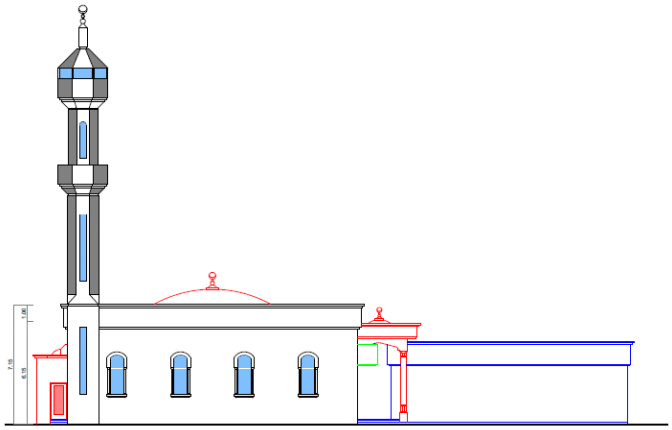
Appendix A. Actual electricity bills

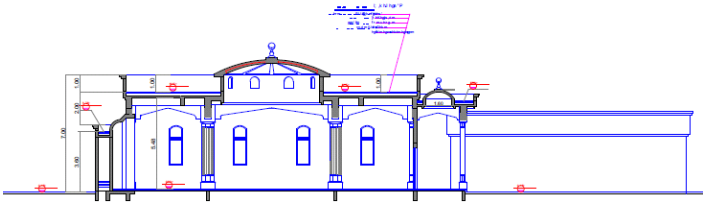
TOTAL AREA (M2)			note	Price in RS	Totasl KW	Month/2015	Mosque
500 m2	20*25		26*هلله	631	2431	1	السبهان Alsabhan
				336	1295	2	
				328	1264	3	
				277	1066	4	
				538	2072	5	
				773	2976	6	
				1394	5362	7	
				986	3769	8	
				770	2962	9	
				799	3074	10	
				354	1362	11	
				495	1906	12	
2000 m2	40*50		26*هلله	426	1641	1	البيوض Albiouz
				248	957	2	
				219	844	3	
				288	1111	4	
				729	2807	5	
				1500	5773	6	
				2056	7910	7	
				1547	5952	8	
				1528	5879	9	
				761	2927	10	
				423	1629	11	
				741	2851	12	
990 M2	30*33		26*هلله	829	3191	1	المليحان Almilihan
				307	1181	2	
				167	645	3	
				333	1283	4	
				694	2672	5	
				1371	5276	6	
				1896	7293	7	
				1470	5655	8	
				1431	5506	9	
				628	2416	10	
				172	663	11	
				694	2670	12	
495 M2	17*27		26*هلله	248	954	1	حديقة الزيتون Alziton garden
				117	450	2	
				142	547	3	
				320	1234	4	
				732	2818	5	
				1246	4794	6	
				1750	6733	7	
				1421	5469	8	
				1445	5560	9	
				353	1360	10	
				208	800	11	
				405	1560	12	

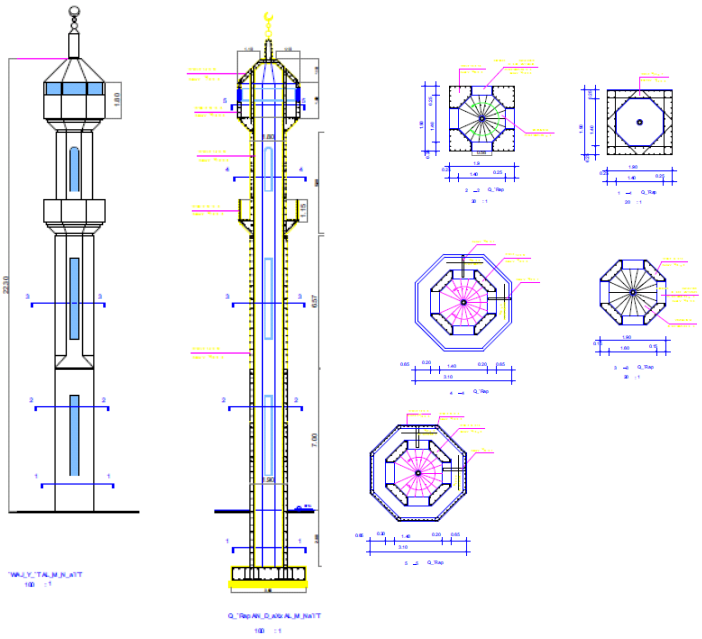
TOTAL AREA (M2)			note	Price in RS	Totasl KW	Month/2015	Mosque
1188 m2	33*36		26*هلله	1747	6720	1	الحوطى Alhoty
				1393	5360	2	
				1643	6320	3	
				1726	6640	4	
				2724	10480	5	
				4264	16400	6	
				5990	23040	7	
				4097	15760	8	
				3910	15040	9	
				2038	7840	10	
				1393	5360	11	
				2267	8720	12	
5184 M2	72*72		26*هلله	44720	172000	1	جامع الراجحي Alrajhi
				36140	139000	2	
				41340	159000	3	
				51480	198000	4	
				68640	246000	5	
				104780	403000	6	
				114920	442000	7	
				111540	429000	8	
				121160	466000	9	
				81900	315000	10	
				44460	171000	11	
				56160	216000	12	
4950 M2	90*55		26*هلله	28377	109145	1	جامع خادم الحرمين Custodian of the Two Holy Mosques
				23485	90327	2	
				24463	94091	3	
				29356	112909	4	
				44034	169363	5	
				57734	222054	6	
				62626	240872	7	
				69476	267218	8	
				60669	233345	9	
				31313	120436	10	
				24463	94091	11	
				38163	146782	12	
1800 m2	40*45		26*هلله	2652	10200	1	مسجد فاطمة الجوهر Fatemah Aljoher mosque
				2964	11400	2	
				3120	12000	3	
				4212	16200	4	
				9204	35400	5	
				13728	25800	6	
				16380	63000	7	
				11232	43200	8	
				6708	25800	9	
				4836	18600	10	
				2964	11400	11	
				3276	12600	12	

TOTAL AREA (M2)			note	Price in RS	Totasl KW	Month/2015	Mosque
540 m2	20*27		26*هلله	1102	4240	1	جامع الشهداء
				1081	4160	2	
				1310	5040	3	
				1705	6560	4	
				3744	14400	5	
				4368	16800	6	
				6240	24000	7	
				4368	16800	8	
				4056	15600	9	
				1716	6600	10	
				780	3000	11	
				156	600	12	
1024 m2	32*32		26*هلله	592	2280	1	مسجد الهقص
				124	480	2	
				156	600	3	
				655	2520	4	
				2184	8400	5	
				3307	12720	6	
				4524	17400	7	
				2464	9480	8	
				2652	10200	9	
				1029	3960	10	
				218	840	11	
				686	2640	12	
840 M2	28*30		26*هلله	2184	8400	1	مسجد حمزة
				1601	6160	2	
				1955	7520	3	
				2662	10240	4	
				422	16240	5	
				6572	25280	6	
				8923	34320	7	
				5699	21920	8	
				6094	23440	9	
				3390	13040	10	
				1643	6320	11	
				2912	11200	12	

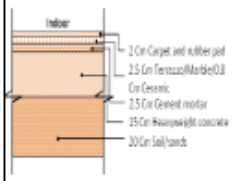
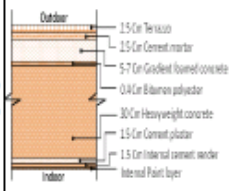
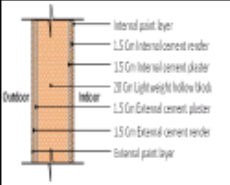
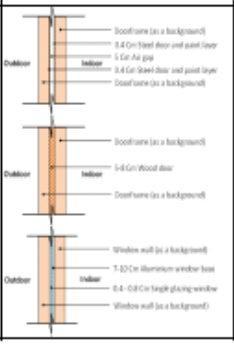
Appendix B. Case study Mosque Drawings-Minaret, elevation and section







Appendix C: Input data, assumptions and materials in the existing mosque (Shohan, 2015).

Envelope type	Material type	Based on the Ministry of Islamic Affairs (MOIA)		Based on DB rogramme						
		Description of materials	Thickness (cm)	Conductivity (W/m. °C)	Specific heat (J/kg. °C)	Density (kg/m³)	Solar reflectance		Emissivity	
							External	Internal	External	Internal
Ground floor	Opaque		Carpet and layer of rubber pad	2	0.06	1382	288	0.30	0.30	0.90	0.90
			Terrazzo tiles	2.5	1.75	850	2400	0.35	0.35	0.90	0.90
			or Ceramic	0.8	1.30	1000	2300	0.30	0.30	0.90	0.90
			or Marble	2.5	2.40	840	2600	0.55	0.55	0.95	0.95
			Cement mortar	2.5	0.94	1000	1750	0.30	03.0	0.90	0.90
			Heavyweight concrete of 0.8m³, 0.4 m³ sands, and 250kg/m³ Portland cement	15	1.95	921	2243	0.35	0.35	0.90	0.90
			Clean sands for filling the ground spaces under the concrete layer	20	0.81	837	1800	0.18	0.18	0.91	0.91
Roof	Opaque		Terrazzo tiles	2.5	1.75	850	2400	0.35	0.35	0.90	0.90
			Cement mortar	2.5	0.94	1000	1750	0.30	03.0	0.90	0.90
			Gradient foamed lightweight (L.W.) concrete of Portland cement 500kg/m	5-7	0.53	837	1281	0.35	0.35	0.90	0.90
			Cement plaster	3	0.42	837	1200	0.60	0.60	0.90	0.90
			Bitumen polyester 180/m² for waterproofing	0.4	0.50	1000	1700	0.26	0.26	0.91	0.91
			Heavyweight concrete 0.8m³, 0.4m³ sands, and 250kg/m³ Portland cement	30	1.95	921	2243	0.35	0.35	0.90	0.90
			Cement plaster	1.5	0.42	837	1200	0.60	0.60	0.90	0.90
			Internal cement render	1.5	0.50	769	1300	0.60	0.60	0.90	0.90
			Internal paint layer	0.2	999.9	0.001	0.001	0.64	0.64	0.92	0.92
External wall	Opaque		Internal paint layer	0.2	999.9	0.001	0.001	0.64	0.64	0.92	0.92
			Internal cement render	1.5	0.50	769	1300	0.60	0.60	0.90	0.90
			Cement plaster	1.5	0.42	837	1200	0.60	0.60	0.90	0.90
			L.W. hollow concrete block	20	0.50	880	465	0.35	0.35	0.90	0.90
			Cement plaster	1.5	0.42	837	1200	0.60	0.60	0.90	0.90
			External cement render	1.5	0.57	1000	1300	0.30	0.30	0.90	0.90
			External paint layer	0.2	999.9	0.001	0.001	0.64	0.64	0.92	0.92
Door & Window	Opaque		Steel and paint	0.2	43	500	7800	0.47	0.47	0.25	0.25
			or Wood	5	0.15	1633	609	0.40	0.40	0.90	0.90
			Aluminum of 1.5mm for window frame	10	204	896	2700	0.50	0.50	0.22	0.22

Appendix D: fan specification

ErP2015

EC centrifugal fans – RadiCal

backward curved, Ø 220



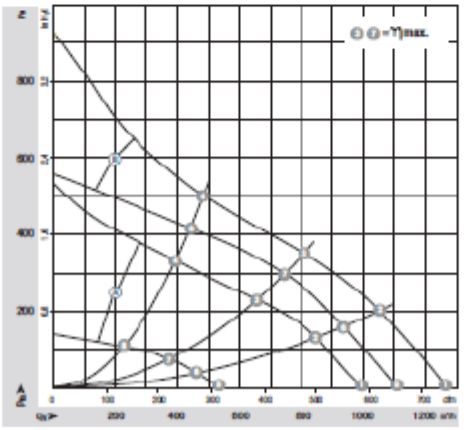
- **Material:** Housing: PA plastic 6, fibreglass-reinforced
  Impeller: PA plastic 6, fibreglass-reinforced
  Rotor: Thick layer passivated
  Electronics enclosure: Die-cast aluminium
- **Number of blades:** 7
- **Direction of rotation:** Clockwise, seen on rotor
- **Type of protection:** IP 54
- **Insulation class:** "B"
- **Mounting position:** Any
- **Condensate discharges:** None, open rotor
- **Mode of operation:** Continuous operation (S1)
- **Bearings:** Maintenance-free ball bearings

Nominal data		Curve	Nominal voltage range	Frequency	Speed/input	Max. input power	Max. current drawn	Perm. amb. temp.	Technical features and electrical connection
Type	Motor		VAC	Hz	rpm	W	A	°C	
*3G 220	M3G055-BI	Ⓐ	1~ 200-240	50/60	2580	85	0,70	-25...+60	p. 164 / H3)
*3G 220	M3G055-CF	Ⓑ	1~ 200-240	50/60	3230	168	1,40	-25...+50	p. 164 / H3)
*3G 220	M3G055-BI	Ⓒ	1~ 200-240	50/60	2580	85	0,70	-25...+60	p. 165 / H4)
*3G 220	M3G055-CF	Ⓓ	1~ 200-240	50/60	2700	115	1,10	-25...+50	p. 163 / H5)
*3G 220	M3G055-CF	Ⓔ	1~ 200-240	50/60	3230	168	1,40	-25...+50	p. 165 / H4)

subject to alterations

(1) Nominal data in operating point with maximum load and 230 VAC

Curves:
2 Speed stages



		n rpm	P_{el} W	I A	L_{WA} dB(A)
Ⓐ	①	2765	79	0,67	71
Ⓐ	②	2700	85	0,69	67
Ⓐ	③	2680	85	0,70	66
Ⓐ	④	2630	85	0,70	66
Ⓑ	①	1505	16	0,18	57
Ⓑ	②	1485	16	0,20	54
Ⓑ	③	1470	17	0,21	51
Ⓑ	④	1465	17	0,19	52
Ⓒ	①	3540	168	1,40	77
Ⓒ	②	3370	168	1,40	73
Ⓒ	③	3230	168	1,40	70
Ⓒ	④	3310	168	1,40	72
Ⓓ	①	3000	100	0,85	74
Ⓓ	②	2955	110	0,95	70
Ⓓ	③	2900	120	1,00	68
Ⓓ	④	2930	115	0,97	70

Air performance measured as per ISO 5801, installation category A, with ebm-papst inlet nozzle without protection against accidental contact. Suction-side noise levels: L_{WA} as per ISO 13347, L_{pA} measured at 1 m distance to fan axis. The acoustic values given are only valid under the measurement conditions listed and may vary depending on the installation situation. With any deviation in the standard setup, the specific values have to be checked and reviewed once installed or fitted. For detailed information see page 172 ff.

Appendix E: Pump specification

C16

DIMENSIONS



C16 Pump Weight 1.5 kg. C16C Dimensions 280 mm x 152 mm x 160 mm Weight 2.4 kg.

MATERIALS

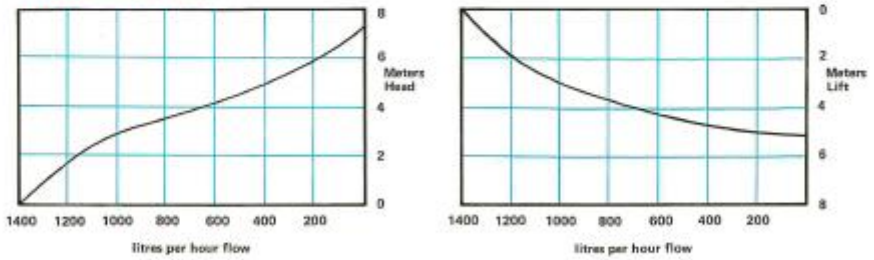
	STANDARD	OPTIONAL AT EXTRA COST
Impeller Housing	Nylon Filled Bakelite	
Impeller	Nylon Filled Bakelite	
Pump Shaft and Impeller Screw	Stainlesss Steel	Titanium
Seal	Nitrile	Viton
Gasket	Neoprene	Viton

MOTOR SPECIFICATION

VOLTAGE	STARTING CURRENT	RUNNING CURRENT	MOTOR TYPE	MAX. AMBIENT TEMP
220/240 v 50 Hz	0.33A	0.25A	Series Wound	40°c
100/120 v 50/60 Hz	0.8A/0.9A	0.4A/0.55A	Series Wound	40°c

Also available 12v and 24v DC

TYPICAL PERFORMANCE



The Company reserves the right to alter the above specifications and prices without prior notification.

Charles Austen Pumps Ltd.

100 ROYSTON ROAD · BYFLEET · WEYBRIDGE · SURREY · ENGLAND · KT14 7PB

Telephone Byfleet 43224/5 *Telex 928368* *Grams Capumps Byfleet*

2·79

Appendix F: Mist Spray Nozzles specifications

Micro Spray Jets: Winged Assembled



Two piece jets with precise watering patterns. Winged base for easy hand installation.

Features
- Nine available spray patterns.
- Colour coded bases for flow identification.
- Caps feature a snap ring which firmly engages the base.
- UV stabilised materials for long life.

Applications
Landscape areas, home gardens, nurseries and horticultural applications. Mist Jet ideal for greenhouse misting and hanging baskets. Strip Spray ideal for narrow garden beds. Use stakes and risers to elevate spray jets.



Performance Chart - all Micro Spray Jets

Pattern			360° x 18	360° x 15	360° x 12	300° x 10	270° (3 x 90°)	Strip (2 x 20°)	90°	180°	Mist
Minimum opening size			0.5 mm	0.6 mm	0.7 mm	0.7 mm	1.3 mm	1.4 mm	1.5 mm	1.5 mm	1.2 mm
Base Jet Size	Pressure (kPa)	Flow (lph)	Diameter (m)						Radius (m)		Diameter (m)
0.8 mm Black	50	15	2.6	2.2	2.6	1.2	2.4	2.4	1.1	1.2	
	100	22	4.1	3.2	3.2	3.2	3.6	4.2	1.7	1.5	
	150	27	4.6	3.6	4.0	4.8	2.8	5.4	2.1	1.7	
	200	32	5.0	4.2	4.6	6.0	2.7	6.0	2.3	1.7	
	250	36	5.3	4.8	5.0	7.0	2.7	6.4	2.6	1.8	
0.9 mm Brown	50	20	2.9	2.8	2.8	2.2	2.6	2.6	1.2	1.3	
	100	28	4.0	3.8	3.4	4.0	3.4	4.6	1.8	1.6	
	150	34	4.8	4.4	4.2	5.4	2.9	6.0	2.4	1.8	
	200	39	5.6	5.0	5.2	6.6	2.8	6.8	2.6	1.9	
	250	44	6.0	5.8	6.2	7.4	3.3	7.2	2.8	2.1	
1.0 mm Blue	50	22	3.6	2.6	2.8	2.4	3.2	2.6	1.2	1.5	
	100	33	4.9	3.8	4.4	4.8	4.2	4.8	2.0	1.8	
	150	42	5.8	4.8	5.2	7.0	3.2	5.6	2.4	2.0	
	200	49	6.2	6.2	6.8	8.6	3.2	5.8	2.8	2.1	
	250	56	6.4	7.0	8.4	9.0	3.4	5.8	2.8	2.3	
1.3 mm Green	50	36	4.7	4.2	3.2	3.0	3.5	3.8	1.4	1.5	
	100	54	6.4	5.8	5.0	5.6	3.5	5.8	2.2	2.0	
	150	68	7.0	6.2	6.0	7.2	3.7	7.2	2.6	2.3	
	200	80	7.2	7.8	7.0	8.0	3.7	8.4	2.0	2.5	
	250	91	7.6	8.8	8.4	8.4	3.8	9.6	3.1	2.7	
1.5 mm Red	50	52	4.9	4.4	4.0	4.4	3.0	4.9	1.5	1.9	
	100	75	6.8	6.0	6.2	5.4	3.8	6.5	2.4	2.4	
	150	92	8.2	7.4	8.4	8.8	4.4	8.9	2.9	3.0	
	200	107	8.2	8.8	10.0	10.4	4.8	10.8	3.1	3.2	
	250	120	7.2	10.0	11.4	11.2	5.1	11.2	3.3	3.4	
1.8 mm Orange	50	64	5.0	4.6	4.6	4.2	3.6	5.0	1.7	1.7	
	100	93	6.8	6.8	7.6	7.4	4.2	8.1	2.4	2.4	
	150	115	8.2	8.8	9.4	8.8	4.6	9.4	2.8	2.7	
	200	135	8.0	10.0	10.8	10.0	4.9	10.8	3.1	3.1	
	250	152	7.3	11.4	11.6	10.6	5.3	11.5	3.3	3.3	
2.0 mm Grey	50	80	5.3	4.8	5.0	4.6	3.4	5.4	1.7	1.7	
	100	115	7.5	7.6	8.2	7.4	4.6	9.4	2.6	2.5	
	150	140	8.1	9.6	10.2	9.2	5.1	12.0	3.1	3.1	
	200	165	7.8	11.0	12.0	10.6	5.6	13.2	3.3	3.3	
	250	185	6.7	12.4	13.0	11.8	6.2	13.8	3.5	3.6	
2.3 mm White	50	113	5.2	4.4	6.0	4.0	3.6	5.4	1.9	2.0	
	100	163	7.1	8.0	9.2	6.8	5.4	9.0	3.0	2.8	
	150	200	7.3	10.4	11.6	9.6	6.6	11.0	3.6	3.4	
	200	235	7.0	11.4	13.0	10.6	7.8	12.0	3.8	4.0	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
0.36 mm Yellow	50	13									1.0
	100	18									0.8
	150	22									0.9
	200	25									0.8
	250	28									0.8
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Ordering Information - Micro Spray Jets: Winged Assembled

Spray Pattern	Base Colour	Cap Colour	Order Code	Pack Quantity	Packs per Carton	Carton (kg)
360° x 18 hole	Blue	Red	14945	100	220	17.8
180° fan	Blue	Blue	14925	100	220	17.8
90° fan	Blue	Black	14115	100	220	17.8
Strip Spray (2 x 20°)	Blue	Black	14815	100	220	17.8
Mist	Yellow	Black	14995	100	220	17.8
360° x 18 hole	Green	Black	14435	100	220	17.8
180° fan	Green	Black	14235	100	220	17.8
90° fan	Green	Black	14135	100	220	17.8

The above Spray Jet Assemblies are standard stock items. For non-standard spray jet assemblies select BASE Colour and CAP Colour with spray pattern. Allow two weeks for assembly and despatch. Urgent orders by arrangement. Minimum order - 1000 Assemblies.

Antelco irrigation equipment metric catalogue 2019 www.antelco.com

SPRAYS

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Appendix G : Experimental results spread sheet

Direct evaporative cooling DEC														
RH% - EC set-point		25%			35%			45%						
RH% measurment inlet wet		33.70%	33.10%	30.90%	36.30%	38.20%	37.50%	46.00%	51.00%	46.60%				
Temperature - EC set-point		30	35	40	30	35	40	30	35	40				
Fan speed (m/s)		2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85				
T-in-wet	29.6	34.8	40	29.6	34.6	40.4	29.5	34.2	40.2					
T-o-wet	20.5	24.1	27.1	21.7	23.7	27.9	23.8	25.2	30.2					
WBT Wet-bulb	18.47	22.15	25.35	19.01	23.21	27.48	20.84	25.1	29.65					
Dewpoint	11.98	16.23	19.61	13.12	18.31	32.11	16.69	22.62	26.56					
T-reduction	9.1	10.7	12.9	7.9	10.9	12.5	5.7	9	10					
T-Water	19.7	22.4	26.5	21.4	22	27	23.6	23.4	29.7					
T-ambiant	28.9	33.6	38.7	30.5	33.5	38.9	29.2	32.5	39.6					
T-Room	24.4	28	31.6	26.3	27.4	32.4	27.3	28.8	34.6					
RH -in-wet	33.70%	33.10%	30.90%	36.30%	38.20%	37.50%	46.00%	51.00%	46.60%					
RH -Room	54	55	54	56	59.6	57	0	0	62					
RH-o-wet	84.5	87.1	90.6	95.7	96.9	100	96.5	99.9	100					
Effectiveness	0.817610063	0.845849802	0.880546075	0.745986778	0.956979807	0.96749226	0.658198614	0.989010989	0.947867299					
Air density (kg/m^3)	1.16	1.14	1.12	1.15	1.14	1.11	1.16	1.14	1.11					
mass flwe rate (V*A m3/s)	1480.642865	1924.995277	2427.318261	1529.040315	1849.208061	2317.094398	1314.974671	1364.169881	1771.027565					
Mass flow rate kg/s	1717.545724	2194.494616	2718.596452	1758.396363	2108.09719	2571.974782	1525.370619	1555.153665	1965.840597					
Cp	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05					
Cooling Capacity (W)	1641149.39	2465147.01	3682388.94	1458589.83	2412717.34	3375169.01	9129343.152	1469620.213	2064326.27					
cooling Capacity per W/m2	1895329.8	2190150.9	2594138.4	1631211.75	2231088.3	2491256.25	1187184.6	1842183	1993005					
COP Cofficent of performance	14123219.225	16425581.413	19158891.23	11117300.017	13041714.78	14657910.99	5018888.0238	6326638.9209	7701987.415					
moisture content out wet (kg / kg)	0.0128	0.0165	0.0206	0.012	0.0179	0.024	0.013	0.0203	0.0275					
moisture content in wet (kg / kg)	0.0087	0.0115	0.0143	0.0094	0.0132	0.0179	0.0119	0.0173	0.0221					
Water consumption m3/s	7.041937468	10.97247308	17.12715765	4.571830543	9.908056793	15.68904617	1.67790768	4.665460994	10.61553923					
Water consumption ml/h	25350974.88	39500903.08	61657767.53	16458589.95	35669004.45	56480566.2	6040467.65	16795659.58	38215941.21					
Water consumption L/h	25350.97488	39500.90308	61657.76753	16458.58995	35669.00445	56480.5662	6040.46765	16795.65958	38215.94121					
water consumption ml/min	422516.2481	658348.3847	1027629.459	274309.8326	594483.4076	941342.7701	100674.4608	279927.6596	636932.3536					

RH% - EC set-point												
			25%			35%			45%			Dew point evaporative cooling DPEC
	RH% measurment inlet dry	29.00%	27.40%	27.40%	32.20%	34.80%	34.10%	44.10%	45.10%	43.20%		
	Temperature - EC set-point	30	35	40	30	35	40	30	35	40		
	fan speed (m/s)	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85		
T-in-Dry-DBT		31.8	36.8	41.8	31.7	36.5	42.1	31.9	37.1	41.9		
T-o-Dry-DBT		23.9	27	31.5	24.5	28.9	33.1	26.8	30.3	34.3		
WBT Wet-bulb		19.09	22.11	25.59	19.68	23.83	27.82	22.39	26.78	30.17		
Dewpoint		11.62	15.01	19.22	13.12	18.5	23.03	18.19	23.23	26.8		
T-reduction		7.9	9.8	10.3	7.2	7.6	9	5.1	6.8	7.6		
T-in-Wet		24	27.2	31.5	23.2	28.8	33.4	26.5	30.2	33.8		
T-o-Wet		25.4	28.8	33.3	25.4	30.1	34.5	28.2	31.7	35.7		
T-Water		19.6	21.3	25.4	20.1	24.1	27.6	23.3	26.1	30.1		
T-ambiant		28.7	32.9	38.1	28.5	33.4	38.6	30.4	34.7	38.9		
T-Room		26.7	30.1	35.3	26.3	31.6	36.3	29.6	32.8	37.2		
RH -in-Dry		29.00%	27.40%	27.40%	32.20%	34.80%	34.10%	44.10%	45.10%	43.20%		
RH -Room		38.1	37.2	36	43.2	45.3	44.4	50.1	53.6	51.2		
RH-o-wet		90.2	87.8	86.1	89.3	87.8	88	89.9	91.7	91.4		
Effectiveness		0.621557828	0.66712049	0.635410241	0.599001664	0.599842147	0.630252101	0.536277603	0.658914729	0.647911338		
Air density (kg/m^3)		1.15	1.13	1.11	1.15	1.13	1.11	1.15	1.13	1.11		
mass flwe rate (V*A m3/s)		0.014529863	0.014529863	0.014529863	0.014529863	0.014529863	0.014529863	0.014529863	0.014529863	0.014529863		
Mass flow rate kg/s		0.016709342	0.016418745	0.016128148	0.016709342	0.016418745	0.016128148	0.016709342	0.016418745	0.016128148		
Cp		1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05		
Cooling Capacity (W)		138.6039956	168.948888	174.4259199	126.3226289	131.0215866	152.4109979	89.47852882	117.2298407	128.7026205		
cooling Capacity per W/m2		61.87678376	75.42361072	77.86871422	56.39403077	58.49177974	68.04062408	39.94577179	52.33475029	57.456527		
COP Cofficent of performance		3.223348735	3.929043907	4.056416741	2.937735556	3.047013642	3.544441813	2.080896019	2.726275364	2.993084197		
moisture content out wet (kg / kg)		0.0185	0.0221	0.0283	0.0183	0.0239	0.0317	0.0219	0.0275	0.0346		
moisture content in wet (kg / kg)		0.0063	0.0073	0.0098	0.0068	0.0101	0.014	0.0114	0.0141	0.0173		
Water consumption m3/s		0.000203854	0.000242997	0.000298371	0.0001922	0.000226579	0.000285468	0.000175448	0.000220011	0.000279017		
Water consumption ml/h		733.8743204	874.7907437	1074.134652	691.7667774	815.683261	1027.685586	631.6131446	792.040268	1004.461053		
Water consumption L/h		0.73387432	0.87479074	1.074134652	0.691766777	0.815683261	1.027685586	0.631613145	0.792040268	1.004461053		
water consumption ml/min		12.23123867	14.57984573	17.9022442	11.52944629	13.59472102	17.1280931	10.52688574	13.20067113	16.74101755		

Indirect evaporative cooling IEC												
RH% - EC set-point		25%			35%			45%				
RH% measurment inlet dry		31.60%	30.10%	29.10%	33.60%	34.60%	34.90%	44.50%	46.00%	45.00%		
Temperature - EC set-point		30	35	40	30	35	40	30	35	40		
Fan speed (m/s)		1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65		
T-in-Dry-DBT		30	34.6	40.5	30.6	35.2	40.4	30.7	34.4	39.6		
T-o-Dry-DBT		23	26.3	30.3	24.6	26.9	30.8	25.5	27	30.5		
WBT Wet-bulb		18.5	21.5	25.4	19.8	22.8	26.8	21.5	24.79	28.7		
Dewpoint		11.37	14.5	19.09	12.8	17.28	21.9	17.25	21.11	25.43		
T-reduction		7	8.3	10.2	6	8.3	9.6	5.2	7.4	9.1		
T-in-Wet		26.3	30.3	36	27.7	30.3	34.9	28.7	30	33.6		
T-o-Wet		24	27.7	32.1	25.5	28.3	32.7	26.5	28.1	31.9		
T-Water		20	22.6	26.3	21.5	23.9	27.2	23.2	24.4	27.6		
T-ambiant		29	33.7	39.2	30.2	33.7	38.6	30.5	33.1	37.7		
T-Room		26.2	30.2	35.6	27.9	30.2	34.6	28.9	29.8	33.3		
RH -in-Dry		31.60%	30.10%	29.10%	33.60%	34.60%	34.90%	44.50%	46.00%	45.00%		
RH -Room		45%	48%	50%	42%	53%	58%	59%	68%	72%		
RH-o-wet		86.5	87.7	87.7	86.1	87.2	87.6	89.5	87.8	86.7		
Effectiveness		0.608695652	0.633587786	0.675496689	0.555555556	0.669354839	0.705882353	0.565217391	0.770031217	0.834862385		
Air density (kg/m^3)		1.16	1.14	1.12	1.15	1.14	1.11	1.15	1.14	1.11		
mass flwe rate (V*A m3/s)		0.012959067	0.012959067	0.012959067	0.012959067	0.012959067	0.012959067	0.012959067	0.012959067	0.012959067		
Mass flow rate kg/s		0.015032518	0.014773336	0.014514155	0.014902927	0.014773336	0.014384564	0.014902927	0.014773336	0.014384564		
Cp		1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05		
Cooling Capacity (W)		110.4890052	128.7496266	155.4466005	93.88844042	128.7496266	144.9964088	81.36998169	114.7888237	137.4445126		
cooling Capacity per W/m2		49.32544877	57.47751185	69.39580379	41.91448233	57.47751185	64.73053967	36.32588468	51.24501057	61.35915739		
COP Coffricent of performance		2.56951175	2.994177362	3.61503722	2.183452103	2.994177362	3.372009508	1.892325156	2.669507527	3.196384013		
moisture content out wet (kg / kg)		0.0163	0.0207	0.0269	0.0178	0.0213	0.0278	0.0196	0.0212	0.0262		
moisture content in wet (kg / kg)		0.0067	0.008	0.0106	0.0078	0.0091	0.0121	0.011	0.0122	0.0142		
Water consumption m3/s		0.000144312	0.000187621	0.000236581	0.000149029	0.000180235	0.000225838	0.000128	0.000133	0.000173		
Water consumption ml/h		519.5238124	675.4369393	851.6906177	536.5053738	648.8449338	813.0155782	461.3946215	478.6560987	621.4131808		
Water consumption L/h		0.519523812	0.675436939	0.851690618	0.536505374	0.648844934	0.813015578	0.461394621	0.478656099	0.621413181		
water consumption ml/min		8.658730207	11.25728232	14.19484363	8.94175623	10.81408223	13.55025964	7.689910358	7.977601645	10.35688635		