

STUDY OF CHINESE HOUSEHOLD COOKING PRACTICES: ENERGY AND COOKING FUMES

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Abstract

In the past few years during this research, many buildings and families were visited in order to collect research data. The purpose of these visits was not only to understand family cooking practices in China, but also to gain an understanding of whole building energy performance. Some of the visits were to understand indoor cooking pollution and some were used to define the research direction. During the course of the research, some of the findings were published and shared with the industry, particularly those papers in the earlier days of the research. These papers constitute part of this research. However, not all of them are directly related to the discussions and final findings in this paper; rather, they helped to adjust the research direction.

The first two papers listed below were published by the author in the early research years, and pointed out the failure of natural ventilation design in a residential building in Beijing, as well as explored the generation and dissemination of Chinese kitchen cooking fumes in order to find a new way of treating cooking pollution efficiently. The first paper explores the myth that an energy-efficient building consumes more energy in real operations than the design baseline because of a lack of occupant education and awareness of energy-saving devices/features. Some of the findings in this paper are quoted in Chapter 2: Literature Review. The second paper summarizes the staged study results on cooking pollution in Chinese cooking conditions. Cooking fume, particularly ultrafine particle (UFP), generation and dissimilation patterns were monitored and simulated. Types of natural ventilation, mechanical ventilation and filters were investigated and recommended for removing cooking fume UFPs. At the end, the author proposes the necessity for treating small and large cooking particles separately in Chinese kitchens. This led to further study on finding innovative ways to remove cooking $PM_{2.5}$

(fine particulate matter).

Another important learning output in this research is the deeper understanding of overall residential building energy consumption. This is not limited to cooking, but also heating, cooling and renewables. The direct contribution of the author in research on total building energy is participating in solar wall research and solar house design.

The University of Nottingham, Ningbo Campus conducted research in 2016 of an innovative solar wall (Solar Thermal Façade). In this research, a solar wall was designed and made of stainless steel sheet, a water fluid channel, insulation board and waterproof membrane. Site testing and performance measuring were conducted in the same year. The author took part in the product development and co-authored and reviewed the research papers.

In 2016, with newly acquired knowledge from the PhD study, the author took part in the Solar Decathlon Competition 2017, hosted by the Chinese city of Dezhou. The Solar Decathlon Competition was initiated by the US Department of Energy in 2002. Competition collegiate teams are expected to spend almost two years designing and building energy-efficient houses powered by the sun. In the final competition, the teams and their houses go head to head in 10 contests to determine an overall winner. The University of Nottingham, Ningbo Campus will take part in the 2017 competition. During this period, the author is working as a design advisor helping university students with passive design, energy analysis and renewable energy selection. At the time of submitting this thesis, the conceptual and schematic design were finished.

List of Publications

- Hong Wang, Han Lin, Vicky C.Y. Ng, et al., 2013. Failure of Natural

Ventilation Strategy in a Sustainable House in China. International Journal of Low-Carbon Technologies. 23 May 2013.

- Hong Wang, Xin Ye Liu, Chen Jin, 2015. Chinese Cooking Style, Fume Generation and Removal in a Typical Chinese Home Kitchen. 14th International Conference on Sustainable Energy Technologies. 25-27 August 2015.

- Jinshu Wu, Xingxing Zhang, Jingchun Shen, Yupeng Wu, Karen Connelly, Tong Yang, Llewellyn Tang, Manxuan Xiao, Yixuan Wei, Ke Jiang, Chao Chen, Peng Xu, Hong Wang, 2016. A review of thermal absorbers and their integration methods of the combined solar photovoltaic/thermal (PV/T) modules. Renewable and Sustainable Energy Reviews (2016) http//dx.doi.org/10.1016/j.rser. 2016.11.063

- Jingchun Shen, Xingxing Zhang, Tong Yang, Llewellyn Tang, Hiroyuki Shinohara, Yupeng Wu, Hong Wang, Song Pan, Jinshun Wu, Peng Xu, 2016. Optimizing the Configuration of a Compact Thermal Façade Module for Solar Renovation Concept in Buildings. CUE 2016 – Applied Energy Symposium and Forum 2016: Low Carbon Cities and Urban Energy Systems, Energy Procedia. 104 (2016) 9-14.

- Jingchun Shen, Xingxing Zhang, Tong Yang, Llewellyn Tang, Hiroyuki Shinohara, Yupeng Wu, Hong Wang, Song Pann, Jinshun Wu, Peng Xu, 2016. Experimental Study of a Compact Unglazed Solar Thermal Façade (STF) for Energy-efficient Buildings. CUE 2016 – Applied Energy Symposium and Forum 2016: Low Carbon Cities and Urban Energy Systems, Energy Procedia. 104 (2016) 3-8.

- Hong Wang, Jingchun Shen, Xingxing Zhang, Robin Wilson, Llewellyn Tang, Ruoyu Jin, Ali Cheshmehzangi, Yupeng Wu, 2016. Due Pension House Schematic Design Summary, UNNC ALPHA, Solar Decathlon China 2017.

- Hong Wang, Jingchun Shen, Xingxing Zhang, Robin Wilson, Llewellyn Tang, Ruoyu Jin, Ali Cheshmehzangi, Yupeng Wu, 2016. Due Pension House Technical Volume, UNNC ALPHA, Solar Decathlon China 2017.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACH – air change rate per hour
ASTM – American Society for Testing and Material
BAM – beta attenuation monitor
CFA – construction floor area
CFD – computational fluid dynamics
CNEMC – China National Environmental Monitoring Centre
COF – cooking oil fume
CookEUI - cooking energy use intensity
C & C – capture and contain
EACD – embracing air curtain device
ECI – energy consumption indicator
ECM - energy control measures
EUI – energy use intensity
FLC – family life cycle
HCAs - heterocyclic amines
HEMS – home energy management system
HVAC – heating, ventilation and air-conditioning
IPMVP – International Performance Measurement and Verification Protocol
LED – light emitting diode
LiFi – light fidelity
MUA – makeup air
PM 2.5 – particle matter 2.5
PAH – polycyclic aromatic hydrocarbon
RFID – radio frequency identification
POC - photocatalytic oxidation
TEOM – tapered element oscillating microbalance
THUBERC – Tsinghua University's Building Energy Research Centre
UFD – ultrafine particle
VLC – visual light communication
w/ - with
w/o - without
μm – micro meters
μg – micro grams

Chapter 1: INTRODUCTION

1.1 Background

China has been on a fast economic growth track for many years and living conditions for most Chinese people have been improved to a great extent. Every year, 1,600,000,000-2,000,000,000 m^2 construction floor area (CFA) of new buildings are erected in the country. This number is close to the sum of all new buildings built in all the developed countries around the world. These buildings, old and new, consume about 30% national energy, while residential buildings take 60% of total building energy consumption. Energy saving in residential buildings is becoming increasingly important, as space heating, lighting, hot water and cooking energy take the largest proportion of the energy consumption in these buildings.

With the fast move towards urbanization and industrialization, air pollution, especially particulate contamination, has become increasingly common and severe in many Chinese cities. A large amount of particulates exist in the air and cause many health problems, particularly those fine particles with a diameter no larger than 2.5 micrometres (μm) ($PM_{2.5}$). $PM_{2.5}$ not only contains a great deal of poisonous and harmful matter, but is also able to stay in the air for a long time and travel a great distance. $PM_{2.5}$ is, therefore, claimed to be very harmful to human health. As people tend to stay indoors for a longer period of time, particularly children, patients and the elderly, indoor air quality is critical to human health (Klepeis, et al., 2001). The following sections explain the details of the challenges from these two aspects i.e., energy consumption and particulate matter, in the current Chinese situation.

Chinese Residential Building Energy Consumption

Energy consumption in Chinese residential buildings can be split into space heating/cooling and others, based on the climate location and amount of energy consumed. Buildings of the north of the Long River are required to have a space-heating system based on one of China's building codes. In recent years, buildings of the south of the Long River also started to have space-heating systems for cold winters. Lighting, air conditioning, hot water are key energy end users, while cooking and home appliances often listed as 'others' in most codes and research papers.

Research papers published in recent years disclose many end-user energy consumption details. In 2009, Xu, Tian and Jiang (2011) carried out an energy use survey of three Beijing residential buildings. The split in the energy consumption in the three buildings is shown in Figure 1-1. Winter space heating uses the most energy in northern China's residential buildings. Factors impacting space heating efficiency include a centralized/decentralized heating plant, boiler efficiency, building envelope thermal performance and the extent to which windows and doors are airtight.

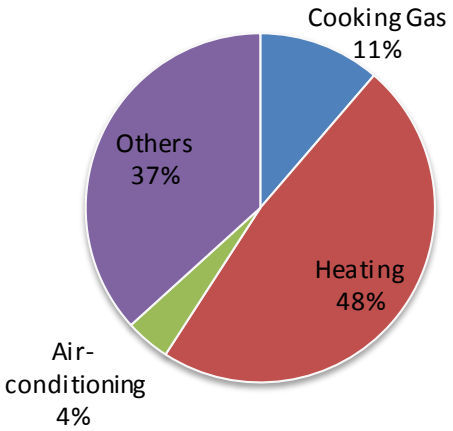


Figure 1-1: Percentage of annual energy consumption in three Beijing residential buildings (Source: Xu, Tian and Jiang, 2011)

Non-heating energy consumption amount is affected by many other social and engineering factors, such as family structure, family income, equipment energy efficiency and the occupants' behaviour. In 2007, Ou Yang, Gao, Luo, Ge and Kazunori (2007) carried out a study on the relation between household lifestyle and household energy consumption. Surveys with 100 Hangzhou families in four different weeks over four seasons were carried out in 2006/2007. They found that energy consumption was closely related to household lifestyle; thus, whether energy-saving measures can be successfully implemented depends on the occupants' receptivity. The results of the surveys show that energy-saving consciousness was improved by corresponding education. Energy consumption can be reduced by providing detailed energy-saving measures in household lifestyles for the occupants. With the penetration of various electric home appliances into more households, along with the improved quality of life, electricity consumption is steadily increasing with the years and the link between electricity consumption and household lifestyle may grow even stronger.

Sun and Li (2009) conducted a comparison study in Shanghai of two residential quarters which were built in different years: one was built in the 1980s, the other in 2003. The research concludes that energy consumption in the newer residential quarter was higher than in the older one because of better living conditions, such as more air conditioners installed. Other research (Yu & Liu, 2006) on occupants' behaviour and energy consumption in Shanghai gives the number of electric home appliances per family (Table 1-1) based on a survey study with 314 families. Liu and Peng's (2010) research in Shenzhen confirmed and expanded Hang's conclusion that home energy consumption is not only related to living conditions and behaviour, but also to family structure.

Table 1-1: Electric home appliances per family in Shanghai (Source: Liu and Peng's,2010)

Home appliance	Number per family	Home appliance	Number per family
TV	1.7	DVD player	0.9
Freezer	1	Computer	1
Washing machine	0.9	Dish washer	0.1
Game player	0.2	Fume exhaust	0.8
Water drinker	0.6	Vacuum cleaner	0.2
Electric cooker	0.8	Water heater	0.8
Video player	0.1	Microwave oven	0.8
Hair dresser	0.4	Electric kettle	0.3

Yang and Jiang (2007) classified home energy consumption into several categories and undertook a comparison study between China, Japan and US in 2007. It was found that China had the lowest energy consumption among the three countries: 27 kWh/m^2.year. However, China also had the highest energy use for cooking. Changing this into a percentage of household energy use (excluding space heating), the number is as high as 35.1%. Cooking energy is the highest energy end user for a Chinese family, apart from winter space heating (Table 1-2).

Table 1-2: Comparison of home energy consumption between countries excl. space heating (kWh/m2.year) (Source: Yang and Jiang, 2007)

Country	Total	Cooking	Hot water	Lighting	Others	Air conditioning
China	27	9.5	3~5	6.7	5~15	1~5
Japan	99	7.3	30.2	57.3		3.8
US	97	7.2	24.5	14.8	36.7	13.8

Although current knowledge indicates that cooking energy takes a great proportion of household energy consumption, there is very little research on the details in this area. For example, although Yang and Jiang (2007) pointed out that household cooking energy takes a large portion of energy consumption and that there is a big difference between Western and Chinese families, there is almost no further research to probe the reason for this and discover details. Thus, there is a need to carry out research in order to gain first-hand data. In Chapter 2, the author discusses the difficulties of obtaining household cooking energy data in China.

The next section summarizes the prevailing methodologies used in China in household energy research and explains the methodology applied in the current research.

Prevailing Research Methods for Household Energy Use

When examining the prevailing research methods, surveys/questionnaires, energy modelling and energy measurement are the tools most often used in the study of household energy use.

Survey and questionnaire: this method is ranked as the most often-used research method in the field of household energy use. It is an inexpensive way to gather data from a potentially large number of respondents. Researchers send a survey questionnaire at random or to a group of knowledgeable people to ascertain their opinions and/or acquire information. Questionnaires originated from demographic studies, such as those requiring the number of family members, family income, occupation, etc. In the household energy use study field, quantitative and qualitative data, such as the number and type of home appliances and gas and electricity usage per year, are collected. In some cases, occupant behaviour, such as

appliance use habits, is also checked. SPSS (Statistical Package for the Social Sciences) is the software most often selected to carry out analysis and establish the relation between household energy use and the factors that affect it. Additional site investigation may be applied in many cases for further exploration. Focus group study, in-house observation and interviews are also often used in site investigations.

Energy modelling, as a way to forecast building energy performance before construction, was introduced to China in around 2001. American EnergyPlus, Canadian Hot2000, UK IES and Chinese DeST are the most often used pieces of modelling software on the market. The advantage of using energy modelling is that it can quickly adjust affecting factors, such as building shape, envelope thermal performance, and orientation, in order to understand the impact of these factors on energy consumption. Unfortunately, almost none of these modelling tools include hot water energy and cooking energy details in their database, even though this portion of energy accounts for a large proportion of all that is consumed by the home.

Measurable energy data are available by checking home energy meters and gas meters in China. Home energy meters are installed in most Chinese houses as space heating calorie meters (in northern China), electric power meters and hot water meters. By reading energy and gas meters, the monthly, weekly and even daily energy consumption of a home can be understood. However, the amounts of end user energy, such as that consumed for hot water, home appliances, air conditioning and cooking energy, cannot be acquired. In some studies, researchers have used surveys to find out the number of appliances in a home and, by checking the equipment nameplate, derived the end user energy consumption. This method is not, however, accurate, since most of the time, home appliances, such as air conditioners and freezers, are not operated at full load. In recent

years, home energy management systems (HEMS) have been installed in some high-end residential house. However, this segment represents a very niche market, e.g., villas and serviced apartments. Lacking energy consumption data for individual home appliances is a problem when directing household energy saving efforts.

Chinese Residential Building Air Quality

In recent years, air pollution, particularly haze and fog in China's cities, has raised attention around the world. According to Wang, Chen, Cheng, Zhang and Wang (2014), haze events occurred on a total of 156 days in Shanghai in 2009 and a third of these events were severe or moderate (Figure 1-2). The extensive burning of agricultural residuals in and around Shanghai in June and October is one key reason leading to reduced visibility and severe haze events during this period. The greatest increase of particle number concentration was in the size ranges of 0.5 – 1 μm and 1 – 10 μm during haze events, as based on the same study (Wang et al., 2014).

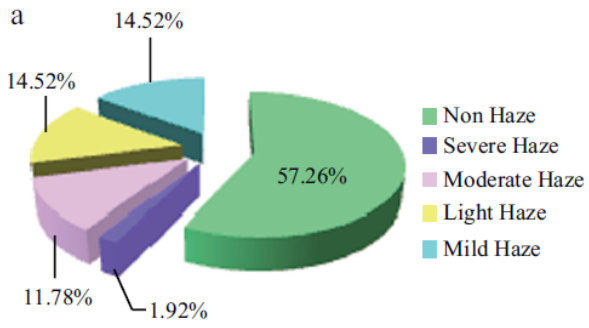


Figure 1-2: Frequency of haze events in 2009 in Shanghai (Source: Wang et al., 2014)

The China National Environmental Monitoring Centre (CNEMC) published a report that indicates that, in the first half of 2013, in the 74 cities monitored, only three cities achieved an air quality grade 2 level: $PM_{2.5}$ 35 μg/m^3.

The percentage was only 4.1% (CNEMC, 2013).

$PM_{2.5}$ indicates fine airborne particles with a diameter of 2.5 μm or less; these particles are small enough to invade even the smallest airways and are able to travel deep into the respiratory tract, reaching the lungs. Exposure to $PM_{2.5}$ fine particles can cause short-term health effects, such as eye, nose, throat and lung irritation, coughing, sneezing, runny nose and shortness of breath. Scientific studies have linked increases in daily $PM_{2.5}$ exposure with increased respiratory and cardiovascular hospital admissions, emergency department visits and deaths. Studies also suggest that long-term exposure to fine particulate matter may be associated with increased rates of chronic bronchitis, reduced lung function and increased mortality from lung cancer and heart disease. People with breathing and heart problems, children and the elderly may be particularly sensitive to $PM_{2.5}$ (US Department of Health, 2011).

People typically now spend about 80-90% of their time in an indoor environment, and the rate is even higher for the elderly, children and patients. The $PM_{2.5}$ suspended in indoor air tends to be more detrimental to human health than that in outdoor air (Klepeis, et al., 2001). Therefore, occupants of buildings are usually concerned about how to maintain a healthy indoor environment with a relatively low $PM_{2.5}$ level. The main factors that may influence the indoor $PM_{2.5}$ level include outdoor $PM_{2.5}$ level, indoor contamination sources and $PM_{2.5}$ sedimentation pattern. Many studies have been conducted to investigate the relationship between indoor and outdoor PM levels. It has been found that the ratio of indoor PM concentration to outdoor PM concentration varies from 0.5 to 2 (Monn, Fuchs, Kogelschatz, & Wanner, 1995), and tobacco smoke can significantly raise the indoor $PM_{2.5}$ level (Sheldon, Hartwell, & Jones, 1989; Wallace et al., 2003). The sedimentation of indoor PM is one of the most effective mechanisms for bringing down the $PM_{2.5}$ level, as it can reduce the extent

to which occupants are exposed to PM, thus alleviating the negative effects on occupants' health (Riley, McKone, Lai, & Nazaroff, 2002).

Through a wide literature review by the author, it was found that a number of previous research projects have investigated the relationship between indoor and outdoor $PM_{2.5}$ concentrations. However, most of them focused on apartments in Western countries, which have relatively good outdoor air quality, and the real-time relationship was established by assuming that each event, such as an open window, tobacco smoke and cooking, was taking place simultaneously. The sedimentation of indoor PM was investigated mainly via the simulation of PM_{10}, while $PM_{2.5}$ was rarely taken into account. Moreover, there are only a few projects that have investigated the indoor $PM_{2.5}$ level associated with cooking activities, which is considered a key indoor source of air contamination.

Current Research Method for Investigating Indoor Air Quality

With the deterioration of China's air quality, there is rising interest in investigating indoor air quality, its relation with outdoor air quality and indoor sources of particle contamination. Currently, the most widely used research methods in China for indoor air quality study include computational fluid dynamics (CFD) and particulate concentration measurement.

CFD software is one of the most-used methods in airflow research, as it can simulate and evaluate indoor environment quality. CFD began in the early 1930s as computer simulation technology, which composited physical science, numerical methods and computer graphics as a whole. At present, CFD is widely applied in almost all fields needing to study air movement. Compared with traditional theoretical analysis methods and experimental measurements, CFD has the advantage of wide adaptation and application. CFD is often used in the following situations to build an air quality study:

- General room airflow: predicting thermal comfort and contaminant distribution in both mechanically and naturally ventilated spaces, as well as ventilation and temperature efficiency in a ventilated room with different ventilation systems and rates.
- Varying inlet/outlet arrangements: studying the performance of ventilation systems with different diffusers and various inlet and outlet arrangements.
- Displacement ventilation: studying a thermal environment and/or ventilation effectiveness.
- Large enclosures: simulating airflow within a large enclosure.
- Natural ventilation: studying wind pressure, appropriately placed openings and thermal buoyancy to provide clean fresh air to buildings and, therefore, reducing the energy requirements of mechanical ventilation systems (Wang, Lin, Ng, Yang, & Guan, 2013).
- Contaminant transport: studying airflow and pollutant concentrations, distribution and transport.

It is undoubtedly in field measurement is one of the most reliable method of providing an accurate description of indoor air quality, although it is sometimes expensive, time-consuming, the air might be toxic and it is difficult to carry out extensive parametric studies. There are different measuring instruments on the market for this purpose. Those widely used include direct reading instruments, which provide continuous measurements of particle concentrations, and filter-based gravimetric samplers that collect the particulate material onto a filter, which must then be weighed in a laboratory. The advantages and disadvantages of different instruments are provided in Table 1-3.

Table 1-3: Summary of advantages and disadvantages of the principal PM sampling methods

Technique	Advantages	Disadvantages	Estimated precision
Filter-based gravimetric samplers	The reference method for PM_{10} specified in the European Union (EU) First Daughter Directive	High operating costs. Time resolution of the measurement is limited to 24 h. Reporting requirements of the EU First Daughter Directive cannot be met and results can only be provided some days after the sample has been collected.	±2 µg/m^3
TEOM (tapered element oscillating microbalance) analysers	Provide real-time data with short time resolution (< 1 h) that can be used for public information. Improved precision compared to the reference method.	Preheated air stream causes a greater loss of semi-volatiles compared with the reference method. High capital cost.	± 0.5 µg/m^3
ß-attenuation analysers	Provide real-time data with short time resolution (< 1 h) that can be used for public information.	If a heated inlet is used, some semi-volatile material may be lost. Unheated samplers may suffer from interference due to the presence of water. The analyser contains a radioactive source.	±3 µg/m^3 but depends on analyser type
Optical analysers	Portable and often battery operated. Can measure several size fractions simultaneously.	Depends on assumptions about particle characteristics, which may vary from place to place and over time.	Depends on analyser type

Black smoke	Simple, robust, inexpensive and easy to maintain. Long time series of existing data.	Measures an index rather than a gravimetric concentration. Calibration factor not appropriate to the current mix of pollution sources. Time resolution of the measurement is limited to 24 h.	±2 μg/m^3 May be higher at current typical concentrations.
Personal samplers	Portable samplers that can easily be deployed in the field and used to determine personal exposure to particulate concentrations.	As above, depending on measurement method used. All personal exposure analysis is very labour intensive.	According to technique employed, as above

In many cases, different measuring instruments are used at the same time in the research. For example, in order to gain data for outdoor PM concentrations, filter-based gravimetric samplers are used in order to maintain the desired accuracy. Sampling time can be 48 hours or 72 hours. Particles are collected on filters and weighed after a procedure of conditioning before and after exposure. However, in order to obtain short-term fluctuations and particle size fractions for indoor environments, particle concentrations are measured with an optical light scattering instrument.

1.2 Research Aims and Objectives

The energy consumption of other major building sectors, such as commercial and industrial fields, are better understood than the residential sector due to their more centralized ownership, self-interest and expertise in reducing energy consumption, as well as high levels of regulation and documentation. The residential sector is largely an undefined energy sink. Study of end-user energy consumption is even less, regardless of the

observation that cooking energy is thought to take as much as 35.1% of total non-heating household energy, excluding space heating. This is partially due to the following reasons:

- The residential sector encompasses a wide variety of structure sizes, geometries and thermal envelope materials.
- Occupant behaviour varies widely and can impact energy consumption by as much as 100% for a given dwelling (Seryak & Kissock, 2003).
- Privacy issues limit the successful collection or distribution of energy data related to individual households.
- Detailed sub-metering of household end uses has a prohibitive cost.

Cooking fumes affect people's health a great deal. However, research into cooking fume concentration and ways to remove cooking particles is very weak in China, although some studies on indoor air pollution from different cooking fuels in rural areas have been published occasionally in the environmental protection area (Kejia, Jun, & Zeqin, 2012). Based on one piece of research carried out in the US, the most important particle source in homes was smoking and the second was cooking, particularly frying/sautéing or reporting a smoky cooking event (Wallace, et al., 2003). As fewer and fewer people smoke at home, in addition to traditional Chinese food preparation being oil-fry intensive, it is becoming urgent to study cooking fume concentration in Chinese homes.

The main aims of this study are to:

- Investigate the amount of cooking energy in residential buildings. As a result of the lack of published knowledge, as mentioned above, an experiment was set up to collect data.
- Identify the factors affecting cooking energy. Driving factors for cooking energy both on the technical and occupant behaviour sides are

revealed from the experimental data.

- Propose a solution to calculate household cooking energy in a more detailed way. This solution should consider the driving factors and their influence on household cooking energy use.
- Identify $PM_{2.5}$ emission patterns in typical Chinese cooking processes.
- Investigate the efficient removal of cooking fumes.
- Propose a solution to reduce $PM_{2.5}$ concentration effectively in Chinese cooking practices.

1.3 Research Methods and Methodology

This research concerns an understanding of household cooking energy consumption and cooking-related air quality and has proposed solutions related to this.

The research methods are based on the following:

- A review of relevant data and the existing literature in terms of household cooking energy consumption and home cooking air quality.
- Site measurements of household cooking energy consumption.
- Recording occupants' behaviour relating to cooking and home activities.
- Conducting an occupants' energy use behaviour survey using a questionnaire or online survey tool.
- Site measurements of cooking fume particle concentration.
- Site measurements of home cooking fume exhaust efficiency.
- CFD simulation on cooking fume dissemination pattern in kitchen.
- Tracer gas to measure air exchange rate of kitchen.

Challenges and Features of the Research

During the literature review, it was found that there is very little existing

knowledge of household cooking energy consumption and indoor cooking air pollution. An intensive review of the literature, both Chinese and international, did not give a clear direction for carrying out the study. As a result, the author had to undertake more work involving unstructured interviewing as well as experiments to shape the research direction and collect real-world data. Nevertheless, the positive side of conducting research on the 'root of the knowledge tree' is that the results are first hand and up to date.

The most difficult part of the experiment was gaining access to the test families' data. Since the data are on household cooking energy consumption and cooking fume concentration, a measuring and recording instrument needed to be installed to record the families' behaviour. Interruptions to the test families' daily lives were hard to avoid, although the author made every effort to limit the disturbance to the minimum level. An automatic instrument and data logger were preferred in the beginning. However, after a review of suppliers' quotations, it was concluded that the price of a data logger would have been too expensive as the number of data collecting points increased. Eventually, it was decided not to set up an automatic instrument, such as a home energy management system.

The solution involved finding suitable test families who had an interest in understanding their cooking energy and cooking fume pollution and were willing and sufficiently self-motivated to record daily data manually. It was fortunate, however, that several volunteer families signed up. Many of these families were from the author's working team and colleagues showed their enthusiasm after the research briefing. Many of them volunteered their families to record daily cooking energy consumption, as well as cooking fume $PM_{2.5}$ concentrations.

Automatic testing instruments were, however, unavoidable for measuring and recording the required data. One occasion for their use was to record

occupants' behaviour in the test families. It was found that retired couples are in the segment of those who do home cooking the most often because of the time they have available to cook and expense constrains their ability to eat out. Data collection in the segment of elderly people was essential. However, author also found that elderly people's memory tends to become short term. For example, they cannot recall morning activities clearly if the research interview is conducted in the late afternoon. For this group of participants, automatic instruments were the only solution to record the activities of occupant behaviour among the elderly. Details of the field study and experiment set-up are elaborated in Chapter 3: Field Study.

An air particle monitor was used in the research on kitchen cooking fume pollution. The monitor has a memory chip, which stores up to one week of data, using minute-by-minute particle counting, and comprising about 10,000 samples. Two air particle monitors were used for establishing indoor air quality. Outdoor air quality data came from the US Department of State Air Quality Monitoring Programme - Mission China (US Department of State Air Quality Monitoring Programme, 2015).

Unstructured interviews were another challenge in this research. The lack of published knowledge on cooking energy required the author to conduct a large number of interviews to gather first-hand opinions. The aim of these interviews was to access the point of view of the respondents using the respondents' frame of reference, rather than the researcher's pre-structured frame (Harvey, 2012-2014). The form of these interviews ranged from casual conversations to chats. These conversations were sometimes fairly free-flowing and the probe questions were built upon what the respondents stated, even if at times they seemed to be straying off the topic.

WeChat as a Research Tool

The content of the literature review is not only limited to work from published

articles and manufacturer product catalogues, but also from conversations with knowledgeable people. Even unstructured chats are considered a valuable source of information for understanding research topics. Specifically, in order to reach a broader group of people in a short amount of time, WeChat was selected as a research tool to conduct unstructured interviews.

WeChat is a mobile text and voice messaging communication service developed by Tencent, Inc. in China (Wikipedia, 2014a). WeChat provides text messaging, hold-to-talk voice messaging, broadcast (one-to-many) messaging, the sharing of photographs and videos, and location sharing. As of 2014, WeChat had more than 300 million users in and outside China. The WeChat APP is available on Android, iPhone, BlackBerry, Windows Phone and Symbian phones, and there are also Web-based and OS X.

As a communication tool, WeChat has many obvious advantages for research use.

- WeChat has many individuals (known or unknown), companies and groups. Many of them have an angle If a certain kind of information is wanted that can be called upon any time, it is possible to ask them for opinions or anything else. For example, once “Energy Saving” is input as a keyword (see Figure 1-3), a list of relevant companies’ WeChat-sites or interest groups is immediately available. Many of them have in-depth knowledge in their respective fields.



Figure 1-3: WeChat search list in the 'Finding Friends' function: 'Energy Saving' as a keyword

- WeChat gives an opportunity for researchers to conduct 'chats' with experts who might be almost impossible to locate in daily life. Many university professors open their own WeChat account to interact with students, sometimes advising those off-campus regarding questions in their dedicated field. Although the word length of a WeChat message is limited to 140 characters, the feedback content is enough to gain a hint or input to quote in a research paper.
- WeChat has a function to form a Discussion Group. Once in a Group, WeChat automatically informs the user of the latest discussion. This enables researchers to follow the latest topics of interest easily.



Figure 1-4: WeChat Low Carbon City Discussion Group and message updating

- WeChat has a function, called MessageHelp, to initiate a poll, but one that is restricted to friends in a contact list or group list. Sometimes this creates difficulties for researchers in acquiring enough results to provide a representative sample. However, it depends on what kind of questions researchers are intent on asking. If these questions are highly technical-specific, WeChat is a good, probably recommended, tool. The specifically developed APP has an effective function for carrying out online surveys. In this research, the author used So Jump to initiate a cooking behaviour online survey.

With the above-listed functions, WeChat is a useful tool to initiate unstructured interviews or poll for a specific technical group. In this research, WeChat drew useful feedback and data for the research paper.

The drawback of WeChat is the ability to save feedback and data. The most often-used practice is to cut and paste a message and send it through email. In this way, researchers can store message content. However, a sender's name cannot be verified. Further, the message can only be stored in the form of email. By the time the researcher needs to quote the source of a piece of knowledge, this becomes impossible.

With the above limitation, the author only used WeChat in this research to conduct unstructured interviews and a simple poll. The quick response time, access to knowledgeable people and the broad coverage of WeChat met the needs of the research successfully.

Radio Frequency IDentification (RFID) for Elderly Group Behaviour Study

Learning about occupant behaviour has been a long-standing issue in building research. Most of the previous studies used observations, interviews, and questionnaire surveys to record occupants' activities in the

home. However, data obtained through interviews or questionnaire surveys are based on the respondents' memory of previous activities. Therefore, these data are less detailed and not always accurate. Radio frequency IDentification (RFID) has made it easier to collect movement data with more accuracy and for a longer period of time.

In the research, the author installed an RFID real-time personal location system for two families: one was an elderly couple and the other was a couple with a child. Each system was composed of a signal receiver (reader), personal locator (tag trigger), wristband (tag), software and a computer workstation. Personal locators were installed in all functional rooms. When someone entered a room, the locator triggered the wristband tag of that person, emitting a radio signal. This signal is picked up by the reader and sent to the workstation. The software, therefore, automatically recorded the room (each locator has its ID), the person (each wristband tag has its own ID) and the time the person entered/left the room.

Each family's time spent preparing and eating food was then recorded. Data analysis was carried out later to understand the occupants' behaviour in relation to the cooking and taking of food.

One obvious advantage of applying RFID in the research was to record the elderly couple's activities in their home. Elderly people often have problems recalling short-term memory. In this case, the elderly couple could barely recall morning activities when the researcher conducted the interview in the late afternoon, so it would have been difficult to rely on the accuracy of their accounts. RFID could accurately record the activities of the elderly couple 24 hours a day, seven days a week. This was very useful in the later stage of data analysis.



Figure 1-5: RFID equipment: computer program, tag trigger, tag, receiver (clockwise from top left)

Ultrafine Particles Monitor

There are a variety of measuring methods available for the measurement of mass concentrations of particulate matter in the air. The advantages and disadvantages of each method are widely discussed in many research papers and textbooks. In this research, an optical analyser, which is often used for workplace and indoor particle monitoring programmes, was selected. This kind of portable, lightweight and battery-operated instrument is easier to deploy for the short-term measuring of a number of locations in order to build up knowledge of particle distribution in both space and time. The Dylos DC 1700 laser particle counter used in the research utilizes the interaction between airborne particles and visible laser light to both count and size-classify PM. The advantage is that a single analyser can monitor particles of a range of sizes, including PM_{10} and $PM_{2.5}$, simultaneously. However, the particle counts need to be converted to mass by calculation, using a range of assumptions whose validity may vary due to the nature of the particles sampled. The Dylos DC 1700 (see Figure 1-6) has an internal battery which provides up to 6 hours of continuous use from a single charge. It can also be operated using the wall socket power adapter included. The internal memory can store up to one week's worth of time-stamped data recorded every minute (about 10,000 samples). This means that the DC

1700 can be left in a location for sampling and then brought to a PC, onto which the data can then be downloaded and loaded into Excel or other spreadsheet programs for analysis. This was particularly useful in order to reduce the disruption of the testing to the families' daily lives.



Figure 1-6: Dylos DC 1700 $PM_{2.5}$ portable monitor

1.4 Novelty of the Research

Extensive research has been done on the aspects of building energy saving, yet there are still several gaps, some of which the content of this research has attempted to fill. By no means, however, are the solutions and suggestions proposed in this research exhaustive and perfect. This research can clearly be considered in terms of two parameters: household cooking energy and kitchen cooking UFP.

Firstly, a personal locating system, RFID, was adopted to record occupant behaviour. This was particularly useful in recording senior people's behaviour due to their difficulty in recalling short-term memory. Previous research methods such as interviews were not applicable because of the loss of memory of the more elderly interviewees. Through the use of RFID, data could be recorded accurately, as well as adequately, during the course of the research.

Secondly, in terms of household energy, this research focuses on cooking energy, which takes a large proportion of Chinese household energy consumption. In the literature review, it was found that the difference in

cooking energy consumption between Western and Chinese practice is as much as three times higher in Chinese homes. Surprisingly, there was little research, both in the academic and practical fields, found in the literature review. A clear understanding of Chinese household cooking energy will definitely benefit the general knowledge in the energy-saving field.

Thirdly, the introduction of a Chinese cooking energy consumption database is a novel way of solving the inaccuracy in most building energy simulation software. Cooking energy is normally viewed as process energy in most building energy simulation software, such as IES and eQuest. The definition of process energy is that it includes, but is not limited to, general miscellaneous equipment, such as computers, lifts and escalators, kitchen cooking and refrigeration, laundry washing and drying and lighting. In most software, process energy is considered as a percentage of the total building energy because of a lack of available data.

Fourthly, the proposed home replacement ventilation system to remove cooking fumes is a new approach to reducing home cooking pollution. Before this study, the only equipment available to fight cooking pollution was the cooking fume extractor However, it was found that most of the cooking fume extractors on the market were not as efficient at removing cooking fumes as listed on the nameplate when they were installed on site. The replacement ventilation system offers a solution to improve indoor air quality.

The ethos of this work is based on the author's visit to the New York American Museum of Natural History at the beginning of the research. At that time, China had just started its national mission towards a low carbon society. Conferences, forums and talks on low carbon, energy efficiency and green building had pervaded the industry. However, looking at these broadcast messages from the science point of view, few of them were based on in-depth research. Most of the statements were simply personal opinions. In that visit to the American Museum of Natural History, three words were

etched at the top of the west entrance: TRUTH, KNOWLEDGE, VISION. These three words intrigued the author and strengthened his determination to build his view by a deeper understanding of what the researcher was undertaking. The goal was to probe the truth, build knowledge, influence the industry in the right direction and provide useful solutions.

1.5 Thesis Structure and Overview

This thesis includes one introductory chapter, one literature review chapter, one field study, three research chapters, and a concluding chapter.

Chapter 1 presents the structure of the entire thesis, along with the aims and objectives as well as the methodology applied to achieve the set goals. This chapter also states the novelty of the research undertaken, as well as its benefit to industry knowledge. There is also a brief description of the WeChat, RFID and UFP monitor methods considered in the literature review and applied in the field work.

Chapter 2 presents the results of the literature search into the existing studies of residential building energy use and indoor air pollution. The existing residential building energy studies examine space heating, water heating, lighting, home appliances, gas (cooking) use and others. The existing residential indoor air quality studies include sources of indoor chemical contamination, smoking, cooking fumes, etc. Work that is similar to the research carried out in this thesis report were also examined and a link between the previous works and that undertaken in this report is established in this chapter. However, very little of the existing knowledge covers cooking energy use and cooking air pollution details. WeChat is presented as a useful method of reaching out and drawing opinions from a broad range of knowledgeable people.

Chapter 3 sees the work move from the literature review to the field study.

The testing carried out included investigating cooking energy by taking measurements, recording occupants' cooking behaviour using RFID, understanding cooking culture by interviewing and observation, as well as monitoring kitchen cooking pollution. A questionnaire was used to reach a broader audience in order to gain the necessary information beyond the data from the test families. Tracer gas method was used to find out kitchen air exchange rate in order to find out cooking fume extractor efficiency.

Chapters 4 and 5 are core sections of the thesis. In these chapters, detailed data, analyses and findings are reported. The analysis covers cooking-related topics, such as occupants' behaviour, cooking energy, cooking fumes, food types and fume exhaust systems. Many of these discoveries are novel and presented here for the first time in the industry. In-depth theories were reviewed to ascertain the underlying principles that affect cooking energy and indoor air quality. Tracer gas experiments and CFD simulation were used to understand and verify cooking fume distribution patterns in kitchen cooking conditions. At the end of each of these analysis chapters, a short conclusion section summarizes the main discoveries and findings. These discoveries and findings are used in Chapter 6 for proposing novel ways of removing cooking fumes and to build a database forecasting household cooking energy in building energy modelling software.

Chapter 6 is divided into two parts. Part 1 summarizes the findings regarding cooking energy and highlights those areas that most affect home cooking energy. These areas include a cooking culture lock-in effect, pressurized cooking and related utensils. The most valuable contribution of this thesis is the discovery of cooking energy use intensity (EUI). Cooking EUI is related to family life cycle. An EUI database is, thereafter, built into IES energy modelling software to forecast building energy in a more accurate way. Part 2 recaps the findings in Chapter 5 on cooking air

pollution. It points out that the current research directions and trends in the cooking fume fan industry are not proceeding in the right direction. Cooking fume fans should not go to the direction with the larger airflow and higher fan pressure as this is associated with higher energy consumption. Instead, large cooking fume and small cooking particles should be treated differently. Further, replacement ventilation systems should be applied in family kitchens. In this way, ventilation efficiency can be enhanced more than three times. The resulting energy saving will be significant, when considering that about 20 million new cooking fume extractors are sold on the Chinese market.

Chapter 7 summarizes all the work done and covers a general analysis and conclusions. It also identifies the weak areas and aspects of this research that need to be further studied by researchers along a similar line of thought.

1.6 Summary

This chapter began by introducing the background to the study of Chinese building energy consumption, which indicates that residential buildings take 60% of total building energy use. Many researchers previously focused on building energy systems, the physical structure of buildings, and their impact on building energy use. They discovered the myth behind building energy and occupants' behaviour and awareness of energy use. However, it was rare for cooking energy, which composes a large portion of home energy use, to be studied.

This chapter also pointed out the severe air pollution situation in China and the harm caused to citizens by $PM_{2.5}$. This situation is a growing challenge. Indoor air quality, especially cooking fumes, is the key source of indoor contamination but very few researchers have examined Chinese cooking fume generation, distribution patterns and removal methods.

This chapter, therefore, presented the research aims, which are to investigate home cooking energy use and home cooking fume distribution patterns. As a result of the lack of previous knowledge in these areas, experiment and field data collection were the first step in this research. Thereafter, data analysis was carried out to generate findings to be considered. A questionnaire survey and CFD modelling were applied to generalize the experiment conclusion.

This chapter also summarized the research challenges and solutions to be overcome during the research period. WeChat was applied to conduct unstructured interviews and RFID was installed to record senior people's home behaviour. Tracer gas was used to measure kitchen air exchange rates while avoiding the destruction or disruption of any occupants' home decoration or mechanical systems.

In summary, this paper is composed of one introduction chapter, one literature review chapter, one field study chapter, three research chapters, and a concluding chapter.

Chapter 2: LITERATURE REVIEW

2.1 Building, Household and Cooking Energy

It is known that China is experiencing a fast growth in its urban population (Figure 2-1) (National Bureau of Statistics of China, 2013a) and is in the process of improving the quality of life of its people. This has led to a scale of building development in China that is unprecedented. The construction industry has been a significant mainstay in China's rapid economic development for a number of years, accounting for some 6.6% of gross domestic product in 2009. By 2012, China was adding approximately 3.58 billion m^2 of new floor space on an annual basis (including both urban and rural areas) (National Bureau of Statistics of China, 2013b). In 2010, the total area of existing buildings in China was approximately 48.6 billion m^2. How to improve the building energy efficiency of the soaring number of new buildings and accelerate the retrofit of the huge stock of existing buildings are two daunting challenges currently facing China.

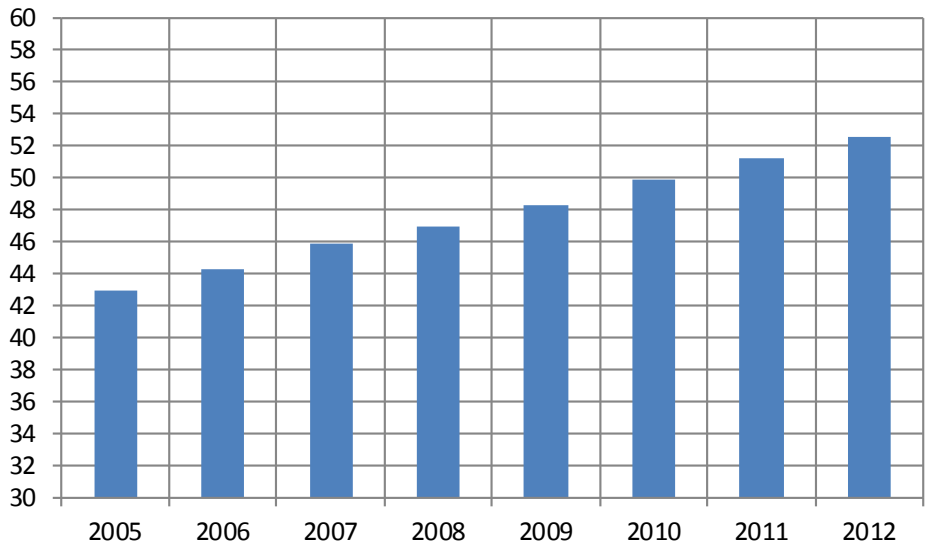


Figure 2-1: Proportion of urban population at year-end (%) (Source: National Bureau of Statistics of China, 2013a)

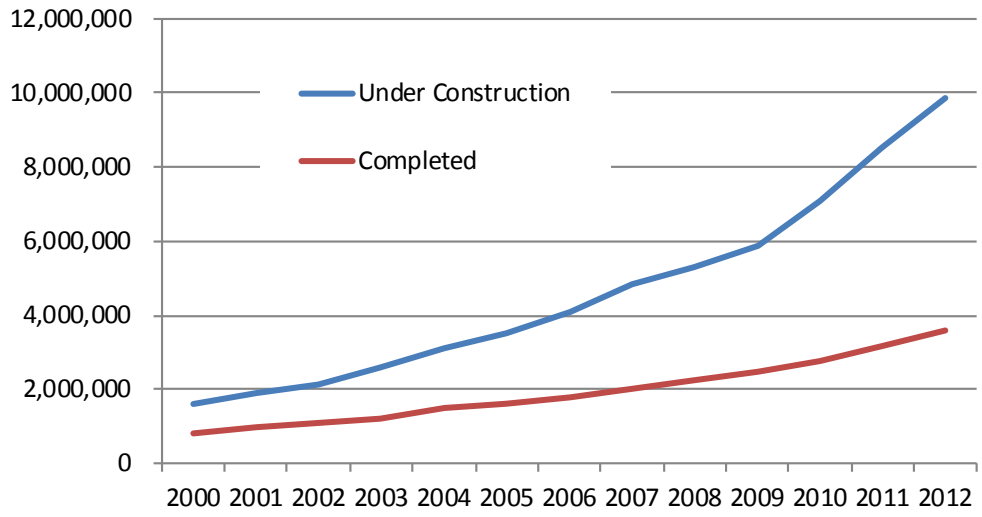
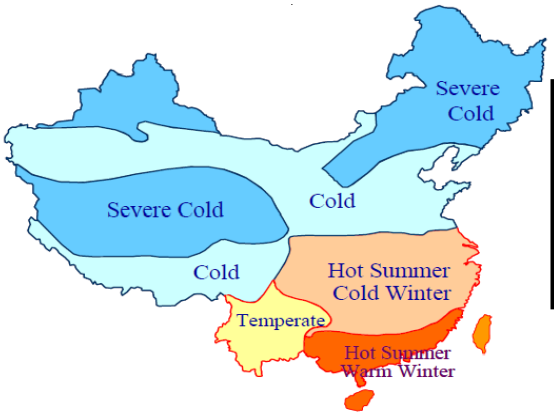


Figure 2-2: Floor area of buildings constructed by construction enterprise (1,000m2) (Source: National Bureau of Statistics of China, 2013b)

Building Energy

Climate conditions are among the most important factors influencing building energy consumption. The climate determines the amount of solar radiation and outside temperature to which a building is exposed; it also influences the amount of energy that is used for the heating and cooling of a building and the amount of energy used for lighting (Haase, Amato, & Heiselberg, 2014). China has five climate zones: Severe Cold, Cold, Hot Summer Cold Winter (HSCW), Hot Summer Warm Winter (HSWW) and Temperate (Figure 2-3) (Ministry of Construction, 2005a). The zoning is based on the monthly average temperatures of the coldest and hottest months of the year (January and July, respectively), and the number of days with a daily average temperature below 5 °C and above 25 °C.



Climate Zones	Mean Monthly Temperature	
	Coldest	Hottest
Severe Cold	≤ -10 °C	≤ 25 °C
Cold	-10 - 0 °C	18-28 °C
HSCW	0- 10 °C	25 - 30 °C
HSWW	>10 °C	25 - 29 °C
Temperate	0 - 13 °F	18 - 25 °C

Figure 2-3: China's climate zones (Source: Ministry of Construction, 2005a)

In a review of building energy consumption, building type classification is critical. The classification of building type affects the classification of building energy consumption.

According to China's building codes, buildings in China can be categorized into having civil or industrial use. Civil buildings include both residential and public buildings. Major types of public buildings include government offices, commercial buildings, buildings used in the service industries, buildings used for educational purposes, and hospitals (Figure 2-4). According to the number of floors above ground, residential buildings can be grouped into low-rise buildings (1-3 floors), multi-floor buildings (4-6), middle-high buildings (7-9) and high-rise buildings (more than 10) (Ministry of Construction, 2005b).

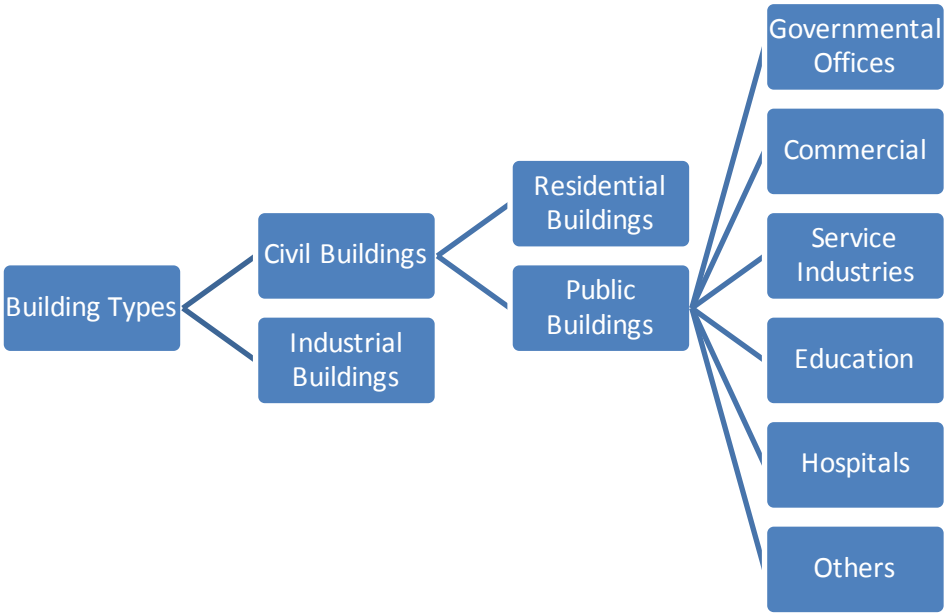


Figure 2-4: China's building types

Building energy as defined in this thesis refers to civil building operational energy consumption, including the energy consumed for space heating, air conditioning, water heating, lighting and cooking. When considering the differences in climate (southern and northern China), building types and lifestyles, the building energy consumption in many building energy studies is based on this type of classification, since it is in line with China's building codes, such as the Code for the Design of Civil Buildings.

However, another view of building type classification is used in the research at the Tsinghua University's Building Energy Research Centre (THUBERC). In this method, building energy consumption is divided into two categories: residential and public. At present, taking the urban-rural differences into account, along with differences in regional climate, characteristics of energy use and other factors specific to the national context, building energy consumption is generally classified at THUBERC into four categories: (1) space heating in northern urban buildings; (2) the non-heating energy consumption of urban residential buildings; (3) the non-heating energy consumption in public buildings; and (4) the energy consumption of rural residential buildings (Tsinghua University's Building Energy Research

Centre, 2008).

- Space heating in northern urban buildings: this refers to all urban building space heating in winter in the region of the north of the Long River. Space heating is a compulsory building service system under the building code. Essentially, 70% of buildings (by floor area) use a centralized heating system and 30% use various decentralized heating measures.
- Non-heating energy consumption of urban residential buildings: this refers to cooking, lighting, home appliances, air conditioning and other energy consumption equipment relevant to the daily life of people in urban buildings. All energy consumption equipment other than air conditioning is climate irrelevant.
- Non-heating energy consumption in public buildings: this refers to energy consumption in office buildings, hotels, shopping centres, mixed-development, transportation hubs, etc. The systems include lighting, air conditioning, office automation machines, lifts and other building service systems.
- Energy consumption of rural residential buildings: this refers to all energy consumption in rural residential buildings, including space heating in northern China, lighting, hot water, cooking and home appliances.

In 2012, overall energy consumption in the above four categories showed signs of equality, as shown in Figure 2-5. Based on THUBERC's report, other than biomass fuel used in rural areas, national energy consumption in all four categories had been increasing since 2001 (Tsinghua University's Building Energy Research Centre, 2014).

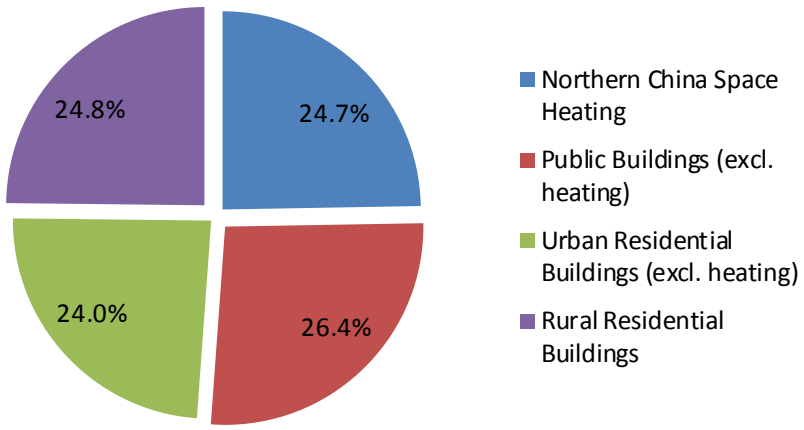


Figure 2-5: Energy consumption percentage of four building types in total building energy consumption (2012) (Source: Tsinghua University's Building Energy Research Center, 2014)

Figures 2-6 and 2-7 show the trends of these building types' energy consumption from 2001 to 2012. According to the report, space heating energy consumption per square meter in northern China reduced continuously. This was partially attributed to energy efficient policies having been successfully implemented in the previous several years. In the meantime, energy consumption in public buildings had been increasing. This was largely attributed to an energy use increase in end-user equipment, such as lighting and air conditioning.

In urban residential buildings, although energy-efficient lamp bulbs were widely used in households, total energy rose slightly because of the increased use of hot water, air conditioning and home appliances. In rural areas, space heating still relied on coal fuel. Energy-efficient home appliances and lamp bulbs were not as widely adopted in rural households. Cooking and hot water energy was high per family compared with that in urban families because of the larger number of family members. All these reasons made total energy use per household in rural regions higher than that in urban areas.

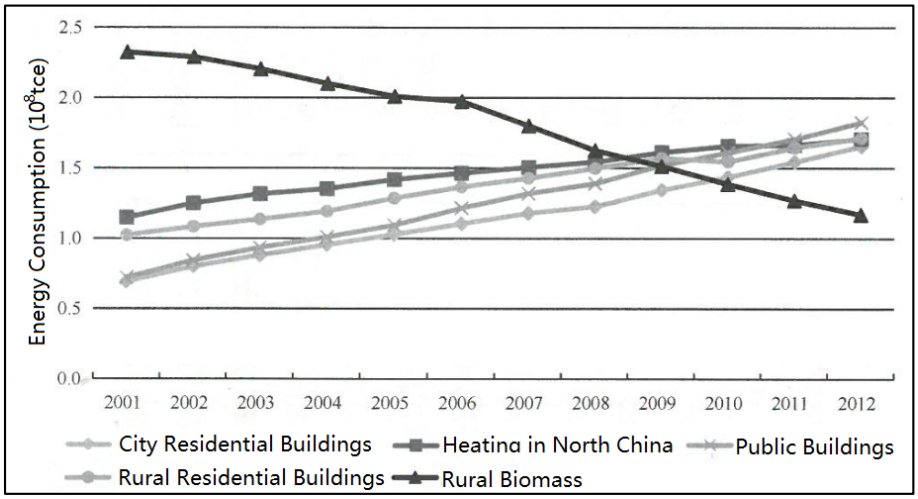


Figure 2-6: Energy consumption trend in four building types 2001~2012 (Source: Tsinghua University's Building Energy Research Center, 2014)

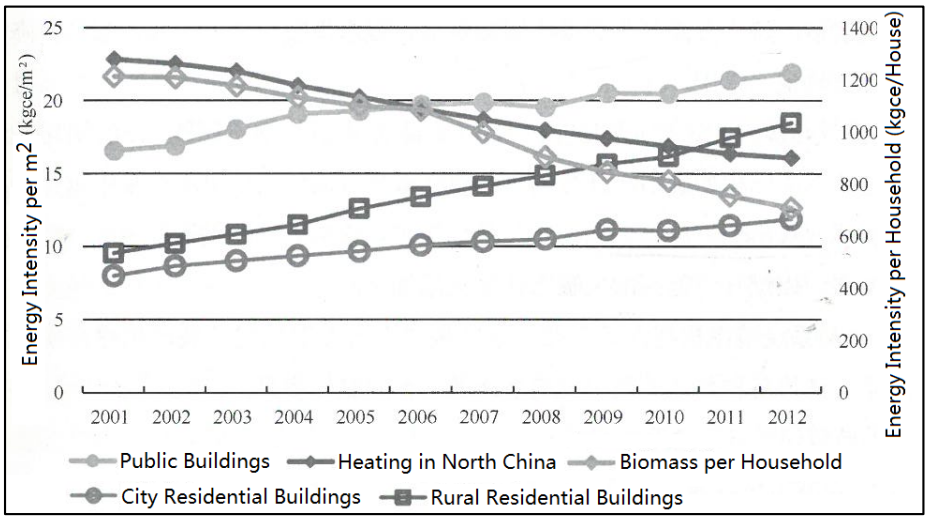


Figure 2-7: Energy consumption intensity trend in four building types 2001~2012 (Source: Tsinghua University's Building Energy Research Center, 2014)

Household and Cooking Energy

In 2012, urban residential buildings (excluding space heating) took 24% of total building energy consumption. The trend in the past several years in rural residential buildings is shown in Figures 2-8 and 2-9.

Cooking, home appliances and lighting are the three largest energy end users in urban rural residential buildings apart from space heating. Although it remains the largest household energy end user apart from space heating,

the increase in cooking energy has been slow. This is partially attributed to the wide adoption of gas cooking fuel instead of coal fuel, because gas fuel increases cooking efficiency on a large scale. Home appliances and lighting energy consumption have increased slowly. However, their overall percentage of household energy use has remained unchanged for the past several years. One contribution is the wide adoption of highly efficient light bulbs, which increase lighting efficiency 4-5 times. In 1996, hot water energy took a very small piece of household energy consumption. In 2011, it took a 10% increase in household hot water use in recent years. The most significant energy increase has been in the aspects of summer air conditioning and space heating in the HSCW region. It is predicted that the energy use in these two aspects will increase faster as the need to maintain comfortable indoor quality increases (Tsinghua University's Building Energy Research Centre, 2013).

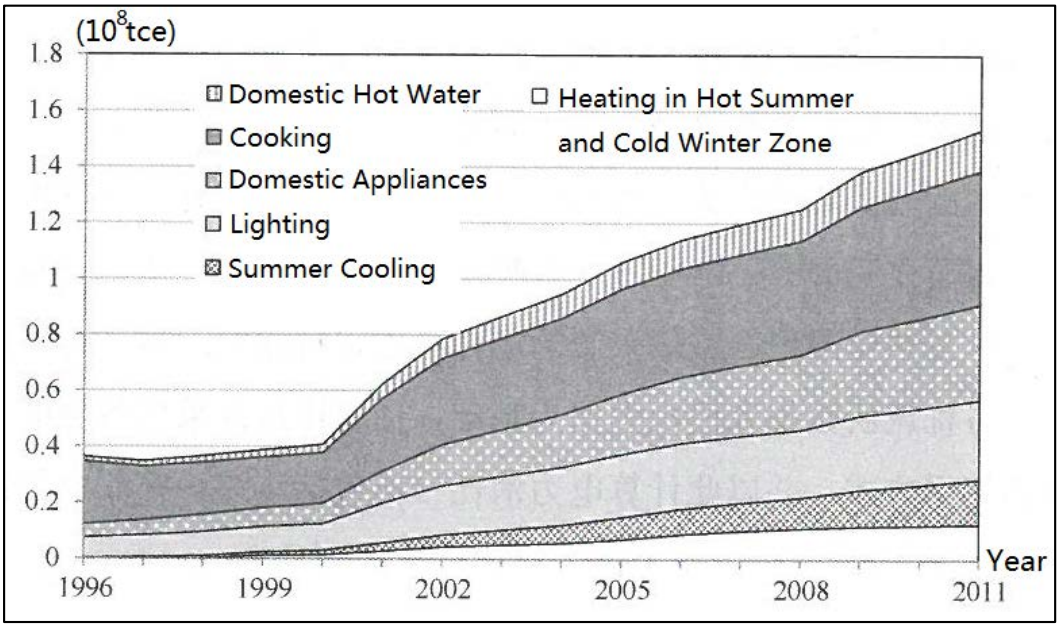


Figure 2-8: Energy end-user consumption trend in urban residential buildings 1996-2011 (Source: Tsinghua University's Building Energy Research Center, 2013)

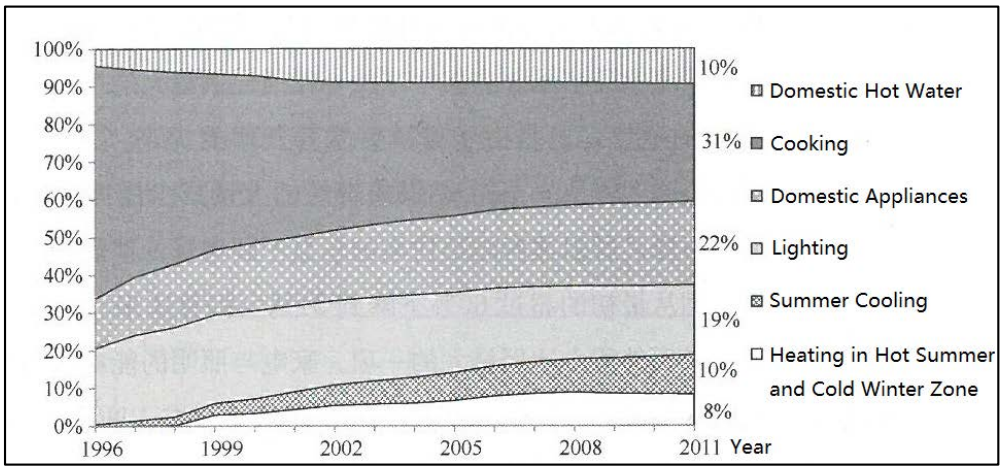


Figure 2-9: Energy end-user consumption percentage trend in urban residential buildings 1996-2001 (Source: Tsinghua University's Building Energy Research Center, 2013)

Household energy consumption reported by other researchers sometimes shows slight differences compared with THUBERC's. Yang, Chen and Wu (2005) report that in Hong Kong air-conditioning energy is the largest end user, taking 26% of overall household energy consumption. Hot water, lighting and cooking take 22%, 22% and 20%, respectively. Yang et al.'s study also depicts the energy consumption trend from 1982 to 2004 in Hong Kong, as shown in Figure 2-10. The sharp increase in air- conditioning energy consumption is due to the rise in living conditions and people requesting a more comfortable indoor environment in Hong Kong's hot climate.

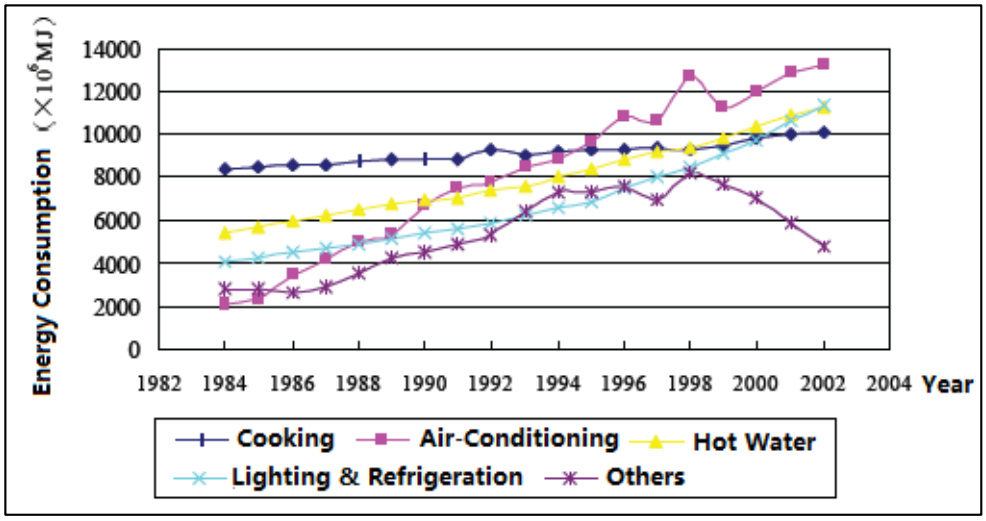


Figure 2-10: Energy end-user consumption trend in residential buildings in Hong Kong 1982-2004 (Source: Yang, Chen and Wu, 2005)

Dong (2009) carried out energy measurements for two typical residential buildings in the city of Beijing from December 2007 to February 2009. His report reinforced THUBERC's discovery that space heating and cooling took the largest energy consumption for the two families. The second-largest energy consumption involved cooking and hot water.

Mei (2007) conducted a similar energy measurement for two typical residential buildings in the city of Changsha. Household energy consumption was recorded from December 2006 to September 2007. Since Changsha is in southern China, space heating and cooling energy consumption was lower than that in Beijing in Dong's (2009) research. However, Mei's (2007) research also strengthened the conclusion that cooking was the second-largest energy end user in Chinese households.

One comparison study indicates that in Western countries residential buildings consume more of the national energy than all types of buildings. However, cooking takes a smaller percentage of household energy (Yang & Jiang, 2007), as shown in Tables 2-1 and 2-2.

Table 2-1: Household energy use comparison for China, Japan and the US 2004 (excluding heating) (Source: Yang & Jiang, 2007)

	Residential building energy consumption in all buildings (%) excl. heating energy	Residential building energy consumption (kWh/m^2) excl. heating energy	Floor area (m^2/person)	Residential building energy consumption (kWh/person)
China	21%	29	25	684
Japan	38.5%	99	31	1,966
US	32.4%	97	53	5,201

Table 2-2: Household energy use comparison for China, Japan and America (kWh/m2.a) (Source: Yang & Jiang, 2007)

	Total	Cooking	Hot water	Lighting	Others	Air con.
China	27	9.5	3~5	6.7	5~15	1~5
Beijing	10~30	--	--	--	--	2~4
Shanghai	20~40	--	--	--	--	5~10
Japan	99	7.3	30.2	57.3		3.8
US	97	7.2	24.5	14.8	36.7	13.8

According to the above research findings, it can be concluded that significant progress has been made in the energy consumption study of Chinese residential buildings. However, further investigations are still needed for the following reasons. (1) The extent of current research projects is limited to one particular building type in a particular city, and research has not been implemented on a nationwide scale. (2) Most of the current works merely investigate one specific energy type (e.g., electricity), while the total energy consumption of each household or unit is rarely taken into account. (3) The current database of building energy consumption is insufficient and lacks classification. Only electricity and gas consumption might be available, while the other energy end-use data (i.e., the energy consumption of heating, ventilation, air conditioning, lighting, electrical appliances, transportation, cooking, water supply and drainage, domestic hot water

supply, etc.) can only derived from estimation or computer simulation. The main reason is that the meters installed in most Chinese buildings are incapable of carrying out sub-metering for each energy end user. In most cases, the electricity consumption of home appliances and lighting is not separated, and the gas consumption of cooking and domestic hot water supply is also mixed. (4) Currently, no feasible measurement method and standard have been prescribed and widely implemented across the whole country. Only a few cities have established their regional building energy conservation standards but lack consistency. (5) Further validation is needed for whether the data and standards used in previous research projects are sufficiently accurate to represent the building energy consumption level of a target city. (6) Since there are a number of factors that may affect a building's energy consumption, and the effects are dynamic and random, the method for analysing the factors requires further investigation. Nevertheless, it is difficult to implement such work accurately.

2.2 Cooking Behaviour and Food Culture

As described in the above section, the literature review has confirmed that, in China, cooking energy consumes the second-largest amount of household energy apart from space heating. Researchers also point out that, compared with Western household energy consumption, Chinese cooking energy is much higher. Research by Tsinghua University reported that daily cooking energy is 3.04 MJ and 3.9 MJ in the cities of Beijing and Nanning, respectively, based on a survey of more than 700 families in Beijing and Nanning in 2001. The research also reported that the daily percentage spent eating out for the families studied was 26% in Beijing and 3.5% in Nanning. If family members could eat at home every day, the figure would be 4.12 MJ and 4.19 MJ, respectively. This equals 985 Kcal per head per day. The energy consumption amount was 45% higher than the 680

Kcal reported in 1990 (Jiang, He, & Wang, 2014).

The number of pieces of research on cooking energy, particularly cooking culture and the impact of cooking behaviour on cooking energy use, is low. However, in the literature review, there were still a few discoveries to be made.

Cooking Technique, Cookware and Behaviour

A study comparing quick and patient cooks revealed that a quick cook, who does not seek to control the cooking parameters, uses 4061-4637 MJ, while a patient cook uses 1746-2326 MJ (DeMerchant, 1997). Das et al.'s (2006) detailed study on rice cooking in various cooking parameters reinforced the point that controlled energy input, cooking under pressure and soaking rice prior to cooking are three approaches that result in energy saving. Some of these behaviours lead to significant energy saving, as shown in Figure 2-11.

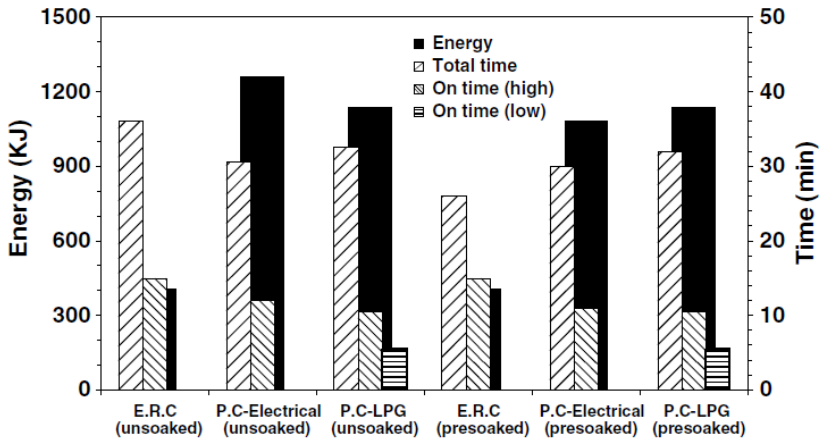


Figure 2-11: Rice cooking energy use vs. cooking parameters (Source: Das et al.'s, 2006)

Another study designed a feedback tool: a home energy consumption indicator (ECI) to display and alter household energy use behaviour (Wood & Newborough, 2003). It was reported that, overall, 14 out of 31 households achieved energy savings of greater than 10%, and six of these achieved

savings of more than 20%.

Cooking techniques, such as steaming and simmering, use different amounts of energy and boiling uses the most. Hager and Morawicki (2013) summarized energy use data from various references, as shown in Table 2-3. Passive cooking is referred to as the use of residual heat after termination of the heat source to finish cooking the food.

Table 2-3: Potential energy savings associated with various cooking techniques (Source: Hager and Morawicki, 2013)

Techniques	Reduction in energy[a] (%)
Cooking method	
Simmering (~90 °C) rather than boiling (100 °C)	69–95[b]
Steaming rather than boiling	9–56
Passive cooking[c]	17–23
Simmer with a pot lid	50–85[d]
Bake at lower temperatures	4–13

Cooking equipment, particularly cookware, was also the focus of Das et al.'s (2006) research. Pressure cooking reduces the cooking time, as the cooking is carried out at an elevated temperature corresponding to the higher pressure maintained inside the cooker. This also leads to significant energy savings, as pressure cooking is operated as a closed system minimizing the water evaporation loss. An energy saving of up to 44% can be achieved for cooking rice, compared with open cooking.

Microwave heating is gaining popularity over conventional heating due to its inherent advantages of rapidity and convenience. This is because materials containing polar molecules are rapidly heated when exposed to microwave radiation. In one study (Lakshmi, Chakkaravarthi, Subramanian, & Singh, 2007) in India, it was reported that rice cooking in a microwave oven substantially reduced energy consumption with unsoaked (14-24%) as well as pre-soaked (12-33%) rice compared with normal cooking.

Hager and Morawick (2013) also summarized the energy use difference

between various items of cooking equipment. This equipment involved stove-top cooking and oven cooking. The fuel source and cooking equipment affect energy use, as shown in Table 2-4. However, there is no obvious energy efficiency advantage of one piece of cooking equipment over another.

Table 2-4: Comparison of modern cooking appliance efficiencies for specific foods (Source: Hager and Morawicki, 2013)

Product (quantity)	Stoves			Ovens			Pressure	
	Electric[a]	NG	LPG	Electric	NG	LPG	Microwave	Cooker
Barley (4 serv.)	180 kJ/serv.	–	–	–	–	–	270 kJ/serv.	–
Beef patty (1)	343–373 kJ	569–654 kJ[b]	795–917 kJ[b]	B: 1416–1936 kJ R: 2283–2107 kJ	B: 2608–3519 kJ[b] R: 3851–5387 kJ[b]	B: 2842–3484 kJ[b] R: 4492–6631 kJ[b]	154 kJ	–
Boiling water (250 mL)	1112 kJ/kg[c]; 1145 kJ/kg[d]						760 kJ/kg	–
Boiling water (1000 mL)	551 kJ/kg[c]; 565 kJ/kg[d]						745 kJ/kg	–
Broccoli (4 serv.)	2380 kJ[4]	–	–	–	–	–	490 kJ	E: 482 kJ ES: 788 kJ
Navy beans (4 serv.)	1004.4 kJ[c]	–	–	–	–	–	1238 kJ	E: 522 kJ ES: 889 kJ
Potatoes (2000 g)	991.4 kJ[c]; 2369 kJ[d]	–	–	Steam oven: 1697 kJ[f]	–	–	–	1283 kJ[f]
Potatoes (4 serv.)	300 kJ/serv.	–	–	1300 kJ/serv.[g]	–		510 kJ/serv.[g]	–
Potatoes (4 serv.)	2088 kJ[c]	–	–	4493 kJ[g]	–	–	796 kJ[f]	ES: 1357 kJ E: 1465 kJ
Rice (300 g)	–	–	–	–	–	–	4200 kJ/kg	LS: 4000 kJ/kg
Rice (1 serv.)	340 kJ/serv.[e]	–	–	–	–	–	630 kJ/serv.	–
Rice (4 serv.)	120 kJ/serv.[e]	–	–	–	–	–	230 kJ/serv.	–
Rice (296 g)	2880 kJ	–	2098 kJ	–	–	–	–	E: 1620 kJ LS: 1180 kJ

There is an argument that Western scholars' study of food preparation and cooking rests on its long history of travellers and seafaring. Food was acquired by hunting and fishing and the main dish was mostly meat with a high fat content and a large number of calories. This food culture is suitable for high-latitude cold weather. Cold dishes are often served as side dishes at the dinner table. In Chinese food culture, however, people more often eat five types of cereal as the main dish, with vegetables as a side dish and with little meat. Food is more often cooked and served hot. Some scholars found that, in China, diet has a sense of 'beauty' (Tao, 2013). People judge the standard of food using the words 'delicious' and 'non-delicious'. This is unlike Western culture, in which the standard is often measured by the

nutrition provided. The pursuit of beauty in Chinese cuisine is sometimes undertaken with a kind of 'play' when food is prepared (Figure 2-12). As a result, special and sometimes unique cooking techniques are used to satisfy this philosophy.



Figure 2-12: Chinese home-made cuisine

The difference in food culture traditions leads to a large difference between Western and Chinese cooking techniques. Cooking techniques represent the art of preparing food for consumption with the use of heat (Wikipedia, 2014b). In Western countries, there are not many methods of cooking, most of which have been known since antiquity. These include baking, roasting, frying, grilling, barbecuing, smoking, boiling, steaming and braising. A more recent innovation is microwaving. Various methods use different levels of heat and moisture and vary in cooking time. The method chosen greatly affects the end result because some foods are more appropriate to some methods than others. Below is a list of major Chinese hot cooking techniques:

- Roasting (烤): a cooking method that uses dry heat, whether an open flame, oven, or other heat source, to prepare the food, usually a large piece of meat.

- Baking (烙): a cooking method that uses prolonged dry heat by convection, rather than thermal radiation, normally in an oven, but also

in hot ashes or on hot stones.

- Boiling (煮): a method of cooking food in boiling water, or other water-based liquids such as stock or milk.
- Frying (炸): the cooking of food in oil or fat.
- Steaming (蒸): works by boiling water continuously, causing it to vaporize into steam; the steam then carries heat to the nearby food, thus cooking the food. The food is kept separate from the boiling water but has direct contact with the steam, resulting in a moist texture to the food.
- Smoking (熏): the process of flavouring, cooking, or preserving food by exposing it to smoke from burning or smoldering material, most often wood. Meat and fish are the most common smoked foods.

Since cooking is a broad heat-treatment process, Hager and Morawicki (2013) summarized a description of each type of cooking, the mechanism of heating (conduction, convection, or radiation), and the typical uses, based on Karel and Lund's (2003) publication on the *Physical Principles of Food Preservation,* as shown in Table 2-5. Table 2-5, combined with Table 2-4, could be used to identify the daily energy use for the food on a Western family's dining table. However, to the author's knowledge, a similar study on Chinese cuisine cannot be found. To acquire details of such energy use is becoming more difficult, since Chinese cuisine applies more complex cooking techniques.

Table 2-5: General categories of cooking and heating mechanisms (Source: Karel and Lund's 2003)

Category	Description	Heat transfer mechanism	Uses
Baking	Food in oven: 100–300 °C	Convection (air); radiation (oven walls); conduction (pan)	Flour-based foods; fruits
Roasting	Food in oven: 100–300 °C	Convection (air); radiation (oven walls); conduction (pan)	Meats; nuts
Broiling	Food in oven: up to 300 °C	Primarily radiation (burner); some convection (air); Some conduction (pan)	Meats
Frying	Food submerged in hot oil (deep-frying) or cooked in a thin layer of fat (pan-frying)	Deep-frying: conduction (pan); convection (liquid) Pan-frying: conduction (pan)	Meats; vegetables
Stewing/boiling	Food cooked in boiling/simmering water	Conduction (pan); convection (liquid)	Meats; vegetables; grains; pastas

Chinese Cooking Culture Evolution

Contrary to the simple discussion on the origins of and differences in Western and Chinese food by Li Ben Tao (Tao, 2013), a more thorough and complex view of the diversity of Chinese cuisine is summarized by Wikipedia from different sources. The summary points out that Chinese cuisine includes styles originating from the diverse regions of China, as well as from Chinese people in other parts of the world. The history of Chinese cuisine in China stretches back for thousands of years and has changed from period to period and in each region according to climate, Imperial fashions, and local preferences. Over time, techniques and ingredients from the cuisines of other cultures were integrated into the cuisine of the Chinese people due to both Imperial expansion and from trade with nearby regions in pre-modern times, and from Europe and the New World in the modern period (Wikipedia, 2014c).

Looking through the history of mainland China through the different dynasties, cooking methods were applied to food according to different techniques and tools with the various cultures and local preferences.

In the Tang Dynasty (618-907), the staple foods eaten most often at the everyday dining table were rice and porridge because people had mastered knowledge of growing rice in the Long River terrace over a long history. The cooking method was mainly boiling. As for side dishes, fish, rather than meat and vegetables, was the main item on the dining table (Liu & Huang, 2009). The cooking method for side dishes was mainly boiling too, since cooking oil was only widely used in the later Ming Dynasty (1368-1644). In another study by Bin (2008), it was found that the Turkestan food tradition was introduced in the Han Dynasty (206 BCE-AD 200) (thousands of years before the Tang Dynasty) from the current Xingjiang Province to the Long River Delta and widely accepted. Thus, in northern China, the pancake was

one of the most popular Turkestan staple foods for supper. Roast mutton was also often served as a daily meal.

The Song Dynasty (960-1279), the dynasty following the Tang, was a prosperous period in China's history. It lasted for 320 years and food types and cooking methods all made great progress. In the Song Dynasty, the staple foods became more diverse. Rice, porridge, noodles, steamed buns and Chinese dumplings were among the foods most often served at the dining table. Cooking methods for these staple foods were boiling and steaming (Hui, 2008). Pork and vegetables became popular (Xi, 2004). Fish was still the food cooked most often in every family. A novel food, soup, appeared on most family tables and was quoted in historic documents, even in many Song poems (Hui, 2006).

The Yuan Dynasty (1271-1368) that followed was the first foreign dynasty to rule all of China. Non-Han race rulers expanded the definition of 'China' to include non-Han peoples, in addition to Han people, wherever they ruled China. Many non-traditional Han foods were brought in from Mongolia and cross-cultural foods and cooking methods started to appear. Human-made food, e.g., doufu (tofu), was introduced at that time. Domestic fowl, such as geese, ducks and chickens, were widely raised. Fowl was, therefore, served on the dining table (Lei, 2012). The cooking methods for rice and porridge were steaming and boiling. Pancakes involved baking and frying in thin layers. The cooking methods for meat were roasting and smoking, while the cooking methods for vegetables were frying, boiling and steaming (Shi, 2007).

By the following Ming Dynasty, all the current Chinese cooking methods were being used. According to Li's (2009) research, there were more than 100 items of cooking jargon. Cooking methods included boiling, braising, frying, salting, steaming, stewing, baking, deep frying, roasting, and many others which do not need heating. One of the largest changes in cooking

history was the wide use of rapeseed oil. A Ming Dynasty science encyclopaedia, *Construction Content*, recorded different types of vegetable oil and different techniques for making cooking oil. As a result of advances in technology and the wide growing of rapeseed, the price of cooking oil was brought down to an affordable level for ordinary people.

Over the history of Chinese food tradition, accompanied by advances in technologies, tens of different cooking methods have been developed. According to the *Baidu Encyclopaedia*, there are 10 basic types of heat cooking in the Chinese tradition. These techniques are an expansion of and different from the Western styles listed in Marcus's research (Karel & Lund, 2003), such as baking, boiling, frying, steaming, smoking and roasting. These Chinese cooking techniques are (Baidu, 2014):

- Stewing (炖): cooking by putting food in water with slow boiling. The cooking time can last as long as 3 hours.
- Decoction (熬): a cooking method for heating food in oil first, then cooking it slowly to extract nutrients into the simmering liquid.
- Braising (烩): a cooking method involving putting different foods with seasonings together and boiling them in a soup.
- Quick boiling (汆): adding ingredients and seasonings to boiling water or broth and immediately serving the dish with the cooking liquid when everything has come back to a boil.
- Simmering (焖): adding ingredients to cold water along with seasonings and allowing the contents to come slowly to a prolonged simmering boil.
- Red soya sauce braising (卤): cooking over prolonged and constant heat with the ingredients completely immersed in a strongly flavoured soy-sauce-based broth.
- Deep frying (炸): full or partial immersion cooking in hot oil or fat.
- Stir frying (炒): cooking ingredients in hot oil and stirring quickly to

completion.

- Steaming (蒸): as described earlier.
- Boiling (煮): as described earlier.

Unlike those published in Western studies on heat cooking methods, Chinese cooking research publications have few energy consumption figures. Comparison of which method is more energy demanding is very difficult. One of the key tasks in this research is to measure energy consumption for each Chinese cooking method. Using data collected in the research as described in Chapter 4, the author developed a cooking energy consumption table for cooking methods across China's history. Table 2-6 uses the supper of a four-member family as an indicator, showing cooking energy consumption in different dynasties with comments regarding important cultural and technique changes in food cooking methods.

Table 2-6: Cooking energy used in a traditional Chinese supper in different dynasties

	Staple food	Side dish	Cooking method	Cooking energy, per supper /kWh	Comment
Tang Dynasty	Rice, porridge, pancake (occasional)	Fish	Boiling/roasting	0.46	Pancake introduced from the current Xinjiang Province
Song Dynasty	Rice, porridge, noodles, steamed buns, dumplings	Fish, pork meat, soup, vegetables	Boiling/steaming	1.81	Soup introduced
Yuan Dynasty	Rice, porridge, pancake	Fish, soup, vegetables, mutton, duck, goose	Boiling/ steaming/ roasting/smoking /baking/frying	0.99	Human-made food, doufu introduced/ domestic fowl reared widely
Ming Dynasty	All modern food	All modern food	Boiling/braising/ frying/salting/ steaming/baking /deep frying/ steaming/ roasting	1.79	Wide use of rapeseed oil
Qing Dynasty	All modern food	All modern food	All modern techniques	1.79	Refer to later chapter in the dissertation

Interesting findings are made if food cooking energy consumption is examined through history.

- Chinese civilization originated from the Central Plain, in the modern-day Henan Province, on the lower reaches of the Yellow River. In ancient times, fish was the main dish; rice and porridge were the main staple foods. Boiling, being the primary cooking method, has the lowest cooking energy consumption, because fish is easy to cook.

- In the Song Dynasty, people started to raise pigs, and pork soon became a popular side dish. Compared with fish, pork requires more energy to cook. As a result, cooking energy increased significantly in the Song Dynasty. The actual energy consumption figures for cooking fish and pork are presented in a later chapter of this dissertation.
- In the Yuan Dynasty, domestic fowl, such as geese, ducks and chickens, were reared widely. Chicken and goose were prepared by roasting and smoking. Although fowl meat is not as tough as pork, the cooking energy used is more than for boiling fish.
- In the Yuan Dynasty, domestic fowl, such as geese, ducks and chickens, were widely reared. Chicken and goose were prepared by roasting and smoking, which consumes more energy than boiling fish but less than cooking pork.
- Starting from the Ming Dynasty, cooking energy varied little, and various modern cooking techniques appeared. The miscellany of food and the variety of cooking methods make it difficult to calculate the energy consumption for each dish, so a vast amount of research is needed. In a later chapter, the researcher lists the energy consumption for most of the traditional home-made dishes.
- The study of cooking energy, particularly in ancient China, is difficult because cooking fuel, cooking utensils, and cookware at that time were very different from those used today. The list of cooking energy presented in the above table was acquired from experiments and calculated using data for modern fuels, cooking utensils and cookware.

2.3 Cooking Air Pollution

Indoor air pollutants in Chinese households mainly come from smoking, cooking, cleaning, incense burning, and consumer products such as paints

and deodorizers (Liao, Chen, Chen, & Liang, 2006; Zhang, Gangupomu, Ramirez, & Zhu, 2010). Among these pollutants, cooking is regarded as the most significant particle-generating activity, accounting for about 30% of indoor PM from 0.5 to 5 μm in radius, according to Liao et al. (2006). The inhalation of cooking oil fumes (COF) generated during cooking activities is proved to have potential adverse impacts on human health, due to the presence of some carcinogenic compounds such as polycyclic aromatic hydrocarbons (PAH), heterocyclic amines, nitro-polycyclic aromatic hydrocarbons and unsaturated aldehydes (Li, Zhao, Jiang, & Hou, 2012; Wu, et al., 2004). According to Lai (2005), Chinese housewives spend, on average, 3.4 to 4 hours in the kitchen every day on preparing and cooking meals, i.e., 1/4 of their daily activity. A comfortable and healthy cooking environment is, therefore, very important.

A comparison study summarized by See and Balasubramanian (2006) reveals that COF emissions in Western and Chinese kitchens differ greatly; however, the difference in the mass concentrations observed cannot be solely attributed to the difference in the cooking methods without doing further study. This is because many additional factors play a role in determining the mass concentrations of fine particles, such as the intensity of the cooking activities, the characteristics of the sampling sites, particle sampling heights, the nature of the instrumentation employed for collecting the fine particles, ventilation rate, indoor temperature, relative humidity, and the quality of the fuels used. Table 2-7 shows a summary of the relevant pieces of research referred to in See and Balasubramanian's (2006) study.

Table 2-7: $PM_{2.5}$ mass concentrations measured in different kitchens (Source: See and Balasubramanian's 2006)

Country	Sampling site	Sampling period	instrumentation	$PM_{2.5}$ ($\mu g\ m^{-3}$)	Number (cm^{-3})	Notes	Reference
Chinese cooking, Singapore	Commercial food stall	Sep.~Oct. 2003	Time-integrated	312.4	7.73 x 105	Mean values during operating hours	See and Balasubramanian (2006)
Hong Kong	Chinese hot pot restaurant, centre of dining area	Apr.~Jul. 2000	Real time	81.1	-	Mean values during dinner hours	Lee et al. (2001)
Hong Kong	Chinese dim sum restaurant, centre of dining area	Apr.~Jul. 2000	Real time	28.7	-	Mean values during lunch hours	Lee et al. (2001)
Shenzhen, China	Hunan restaurant, exit of exhaust duct	Jul. 2001	Time-integrated	1406.3	-	Mean values during lunch and supper	He et al. (2004a)
Shenzhen, China	Cantonese restaurant, exit of exhaust duct	Jul. 2001	Time-integrated	672	-	Mean values during lunch and supper	He et al. (2004a)
Western cooking, HK	Western canteen, centre of dining area	Apr.~Jul. 2000	Real time	21.9	-	Mean values	Lee et al. (2001)
Boston, US	Food court, centre of seating area	Jun.~Aug. 200	Real time	200	1.4 x 105	Mean values	Levy et al. (2002)
Brisbane, Australia	14 residential kitchens, 2 m from stove	Mar.~Jun. 1999	Real time	535.4	2.86 x 104	Max. concentration during cooking	Morawska et al. (2003)
Brisbane, Australia	14 residential kitchens, 2 m from stove	May.~Jul. 1999	Real time	13~745	15.6 x 103~ 1.79 x 105	Median of peak values during food preparation	He et al. (2004b)

Cooking Air Pollution in Chinese Kitchens

Cooking Methods

The emissions from various cooking methods, such as steaming, boiling, broiling, roasting, grilling and frying, are affected by the ingredients and, for example, the fat content and the quantity of food (Zhu & Wang, 2003), cooking procedures, and temperature (Zhang, Gangupomu, Ramirez, & Zhu, 2010).

Zhang et al. (2010) demonstrated that the lowest average UFP concentrations were observed during boiling, while the highest were measured during frying. Similarly, other research has shown that the $PM_{2.5}$ concentration was also low in Chinese dim sum restaurants (steaming), moderate in Chinese hot pot restaurants (boiling), and high in Korean barbecue restaurants due to the use of pan frying (Lee, Li, & Chan, 2001). Among the different frying methods, deep frying gave the largest increase (a 24-fold increase) in the amount of concentration of $PM_{2.5}$ compared with the background concentration, followed by pan frying, and stir frying (See & Balasubramanian, 2008).

A comparative study of PAH levels during boiling, broiling and frying conducted by Zhu and Wang (2003) showed that frying and broiling produced much higher levels of PAHs than boiling. Moreover, frying methods generated a higher level of PAHs than broiling for low-fat food but lower PAHs for high-fat food. Generally, cooking fatty foods would release considerably higher amounts of mutagenic particles than vegetables (Buonanno, Morawska, & Stabile, 2009).

Cooking Oils

There are dozens of different oils commonly used by Chinese households in cooking, and each produces different types of fumes. Chiang et al. (1997)

and Chiang, Wu and Ko (1999) successively tested nine commercial oils heated at 250 °C for 30 minutes, and found the amount of fume particulates generated were in the sequence of soybean > peanut oil > lard > safflower > vegetable > corn > mustard > coconut > olive, while the yields of solute in the acetone extracts of fume particulates were in the sequence of soybean > peanut oil > safflower > lard > vegetable > corn > mustard > olive > coconut. Based on their findings, soybean oil, peanut oil and lard oil seemed to be more genotoxic than the other cooking oils. Further studies compared the concentration of PAHs—B[a]P, B[a]A, and DB[a,h]A—in soybean and peanut oil fumes with those in lard fumes. The results showed that lard fumes had a relatively low concentration of PAHs but high mutagenic activity, indicating that there were unidentified PAHs or some other mutagens in lard oil fumes (Chiang, et al., 1997).

Moreover, an increasing number of researchers have claimed the mutagenicity of rapeseed oil emissions, such as Li, Pan and Wang (1994), Metayer et al. (2002), Qu et al. (1992) and Shields et al. (1995). In addition, cooking fumes from linseed oil (Metayer, et al., 2002) and soybean oil (Qu, et al., 1992) also appeared to be mutagenic and may contribute to an increased risk of getting lung cancer.

In addition to cooking oils, the amount of smoke and grease produced during the cooking process depends on the fat content of menu items and how they are cooked. Higher fat content foods tend to release more smoke and grease, regardless of the type of cooking process. For example, chicken breast, which has less fat compared with hamburger, releases fewer particulates and less grease during cooking on a charbroiler or on a griddle, compared with hamburger.

Cooking Temperature

Cooking style varies with culture, climate and geographical location, and emissions are determined by cooking processes, ingredients, both the food ingredients and the cooking oil, and temperature, according to Zhang et al. (2010). To examine emissions comprehensively, further research has been conducted on the effects of temperature on emission generation and particle distribution. Many researchers have verified a positive causal relationship between cooking temperature and particle emissions, such as Buonanno, Morawska and Stabile (2009), Tseng and Chen (2013) and Zhang et al. (2010), and particularly PAHs, such as acenaphthene (Zhu & Wang, 2003). Consequently, higher cooking temperatures would lead to a higher mutagen generation rate (Rappaport, McCartney, & Wei, 1979).

Tseng and Chen (2013) measured the variations in particle concentration and size distribution with temperature for soybean, olive, and sunflower oil, and obtained the function of temperature and particle concentration. The results showed that, in general, from 180 °C to 210 °C, every 5 °C increase in oil temperature would result in a 20-50% increase in UFP number concentration; the particle concentrations gradually increased from 10^3 to above 6×10^6 particles per cm^3 by heating oil from 180 °C to 260 °C. In addition, raising the temperature enlarged the mode diameter of oil droplets and led to a greater number of UFPs above the smoke point, which meant more free fatty acids were produced (Figure 2-13). In the figures, Dp denoted diameter of the air born droplet and W denoted concentration.

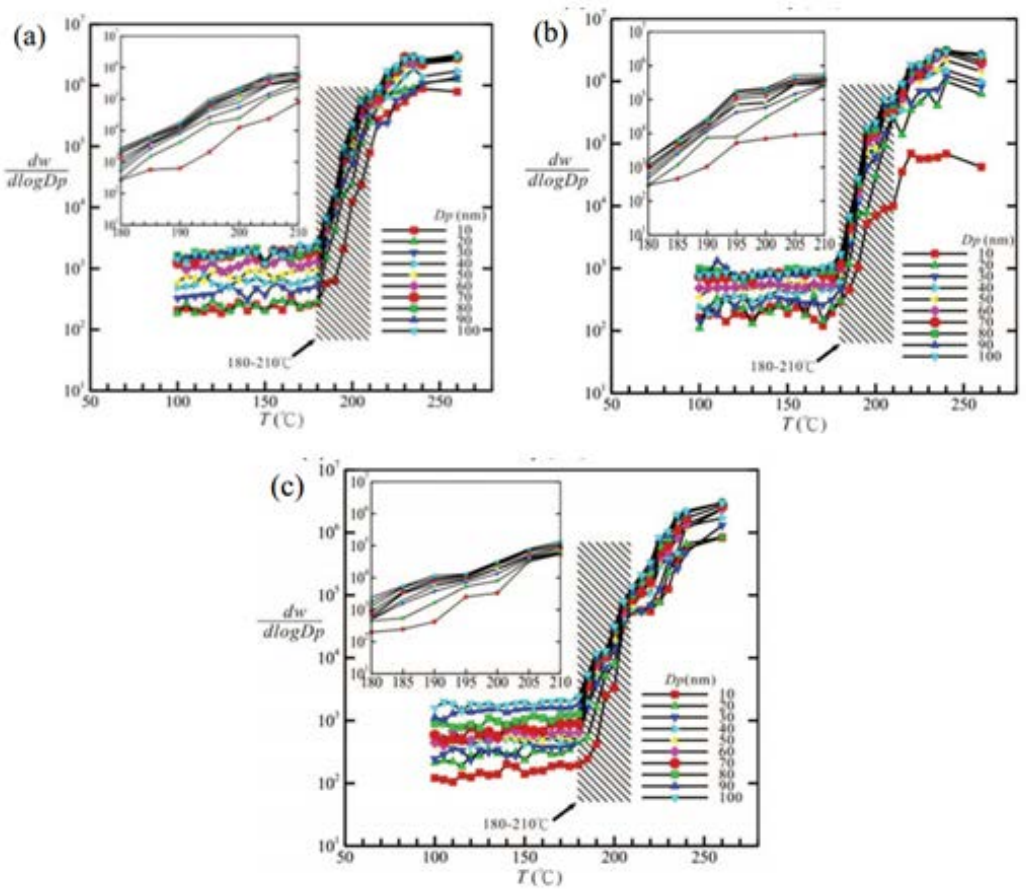


Figure 2-13: Particle concentration of heated (a) soybean oil; (b) olive oil; (c) sunflower oil measured in a test chamber (Source: Tseng & Chen, 2013)

Hood Systems

Emission factors are affected by various elements, but the dissemination of particles is only associated with natural ventilation and mechanical ventilation (i.e., smoke exhaust systems).

Wall-mounted hoods and island hoods are the two most common exhaust systems. For a wall-mounted hood, COFs are deflected toward the central region of the hood and the rear wall due to the low pressure between the flow and the wall. As a result, oil mist contaminant accumulates at the right rear corner and in the neighbouring region (Tseng & Chen, 2013). For island hoods, spiral rotation flow moves COFs up toward the hood due to negative pressure created by the suction force of the fan (Tseng & Chen, 2013). Chen,

Huang and Dai (2010) observed a wide and turbulent dispersion pattern of oil mists under island hoods. This turbulent spiral-like flow is likely to leak large amounts of PM and UFPs into the ambient air surrounding the front middle edge of the cooking pan and other vortex regions (Tseng & Chen, 2013).

Other research has investigated the detail of hood style and construction features. Wall-mounted canopy hoods, island (single or double) canopy hoods, and proximity (back-shelf, pass-over, or eyebrow) hoods all have different capture areas and are mounted at different heights and horizontal positions relative to the cooking equipment (see Figure 2-14).

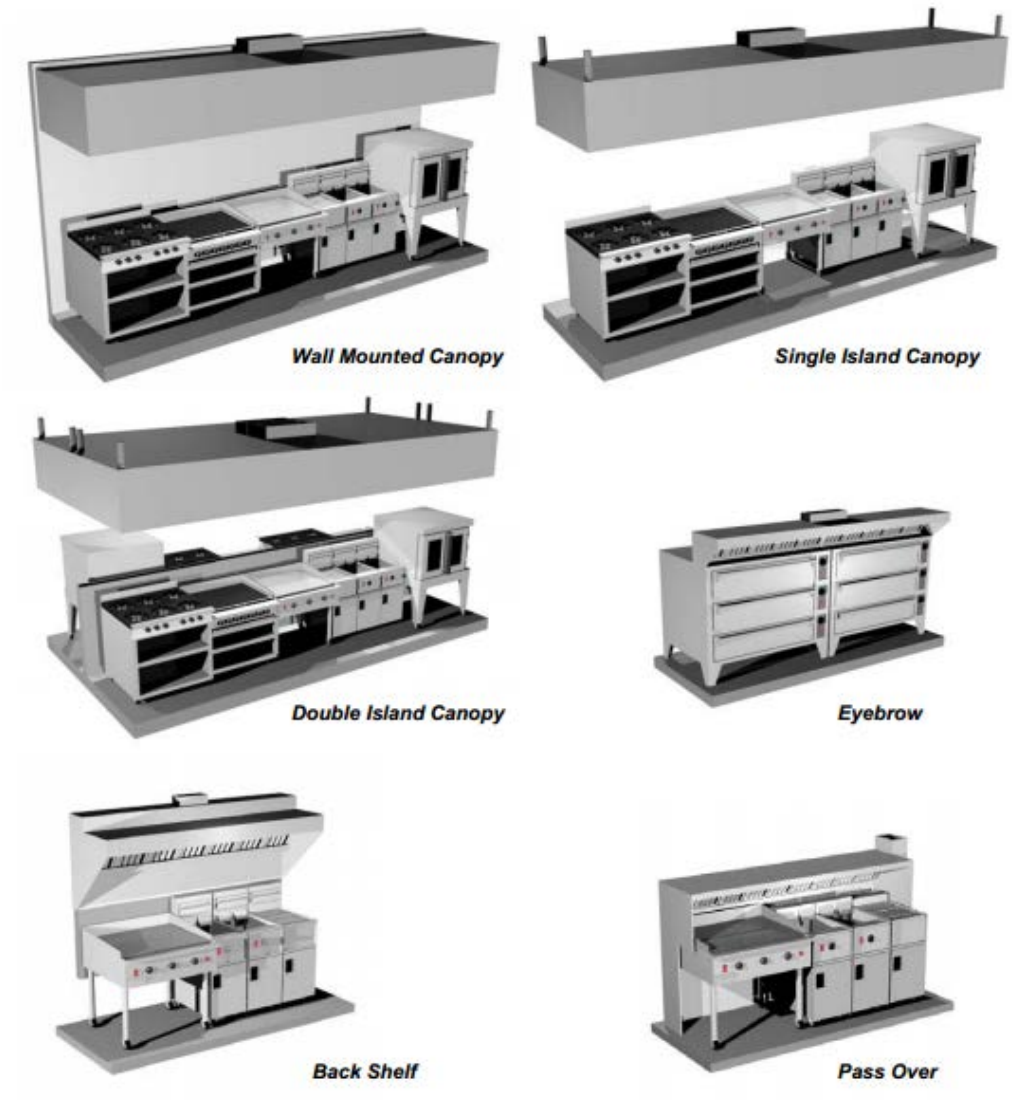


Figure 2-14: Styles of exhaust hoods (Source: Southern California Edison, 2004)

Generally, for the identical (thermal plume) challenge, a single-island canopy hood requires more exhaust than a wall-mounted canopy hood, and a wall-mounted canopy hood requires more exhaust than a proximity (back-shelf) hood. The performance of a double island canopy tends to emulate the performance of two back-to-back wall canopy hoods, although the lack of a physical barrier between the two hood sections makes the configuration more susceptible to cross drafts.

Although a well-engineered proximity hood can be applied with success at very low exhaust rates (e.g., 150 cubic feet per minute [cfm] per linear foot

over medium-duty equipment), this same style of hood (if specified without performance data and/or in accordance with maximum height and setback permitted by code) may fail to capture and contain (C&C) the cooking effluent effectively at exhaust rates of 300 cfm/ft or more. Figure 2-15 illustrates relatively effective and ineffective applications of proximity hoods.

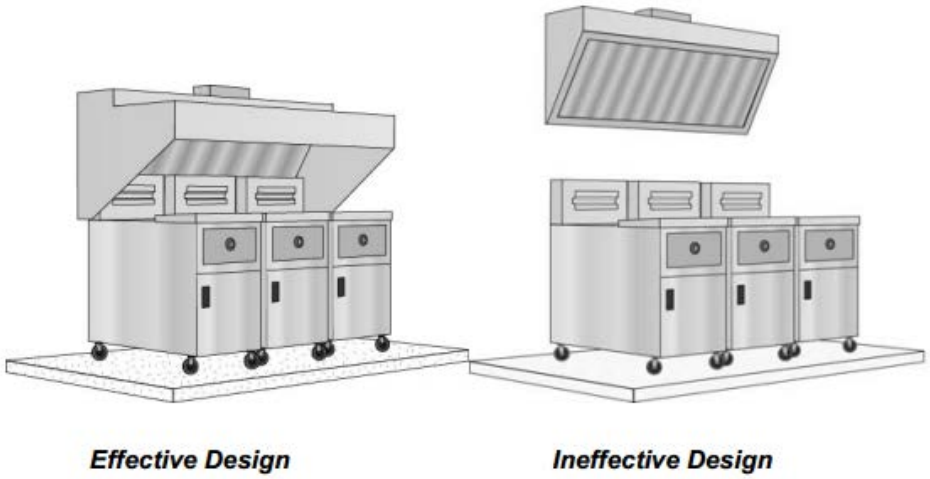


Figure 2-15: Relatively effective and ineffective applications of proximity hoods (Source: Southern California Edison, 2004)

Side (or end) panels, shown in Figure 2-16, permit a reduced exhaust rate in most cases, as all of the replacement air is drawn across the front of the equipment, which improves containment of the effluent plume generated by hot equipment. They are a relatively inexpensive way to improve C&C and reduce the total exhaust rate. Another benefit of end panels is that they mitigate the negative effect that cross drafts can have on hood performance. Partial side panels can provide almost the same benefit as full panels.

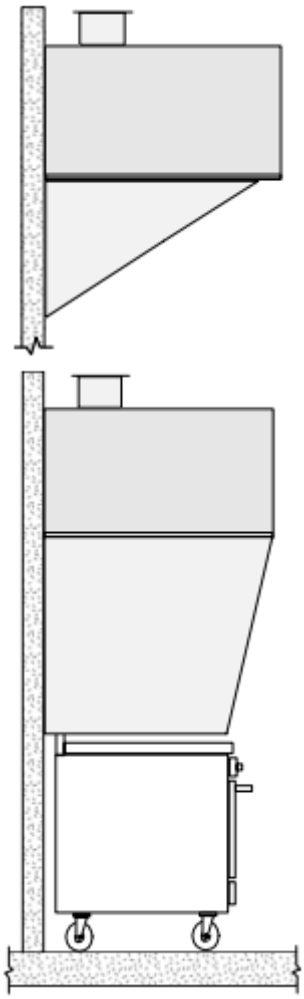


Figure 2-16: Illustration of partial and full side panels (Source: Southern California Edison, 2004)

The ability of a hood to capture and contain cooking effluent can often be enhanced by adding passive features (e.g., angles, flanges, or geometric flow deflectors) or active features (e.g., low-flow, high-velocity jets) along the edges of the hood or within the hood reservoir. Such design features can improve hood performance dramatically over a basic box-style hood with the same nominal dimensions.

As the plume rises, it should be captured by the hood and removed by the suction of the exhaust fan. Air in the proximity of the appliances and the hood moves in to replace it. This replacement air, which must ultimately

originate as outside air, is referred to as makeup air (MUA). MUA replaces an equal volume of air removed from the kitchen through one or more of the following pathways:

1. Transfer air (e.g., from the dining room)
2. Displacement diffusers (floor- or wall-mounted)
3. Ceiling diffusers with louvres (2-way, 3-way, 4-way)
4. Slot diffusers (ceiling)
5. Ceiling diffusers with perforated face
6. Integrated hood plenum including (see Figure 2-17):
    a) Short circuit (internal supply)
    b) Air curtain supply
    c) Front face supply
    d) Perforated perimeter supply
    e) Backwall supply (rear discharge)
    f) Combinations of the above

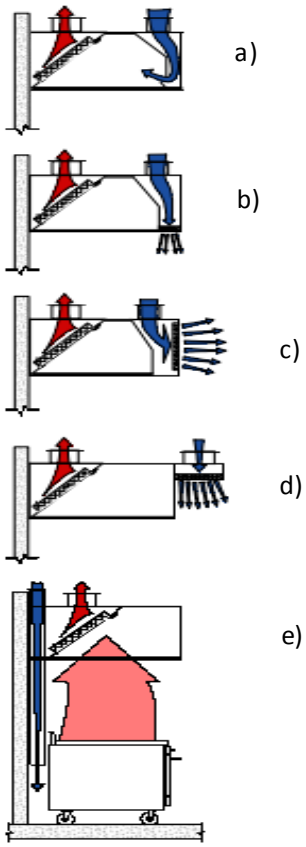


Figure 2-17: Types of MUA supply integrated with the hood

(Source: Southern California Edison, 2004)

The layout of the heating, ventilating, and air conditioning (HVAC) and MUA supply air outlets or diffusers can affect hood performance. Chiang et al. (1999) stated that the distance between a smoke exhauster and a cooking pan was a key factor determining hood efficiency. A distance of 70 cm showed limited efficiency, while that of 50 cm still presented mutagenic impacts on the human body. They suggested the use of a table-top fume extractor, since the exhaust fan was placed directly near the cooking surface. Consequently, most PAHs declined to an acceptable level, and the level of benzo[*a*]pyrene (BaP) was significantly reduced by 75%.

Installing an embracing air curtain device (EACD) on the table top was proved to be able to enhance the capture efficiency of hoods significantly, and thus reduce levels of PMs and PAHs in COF (Pan, et al., 2011) (Figure 2-18).

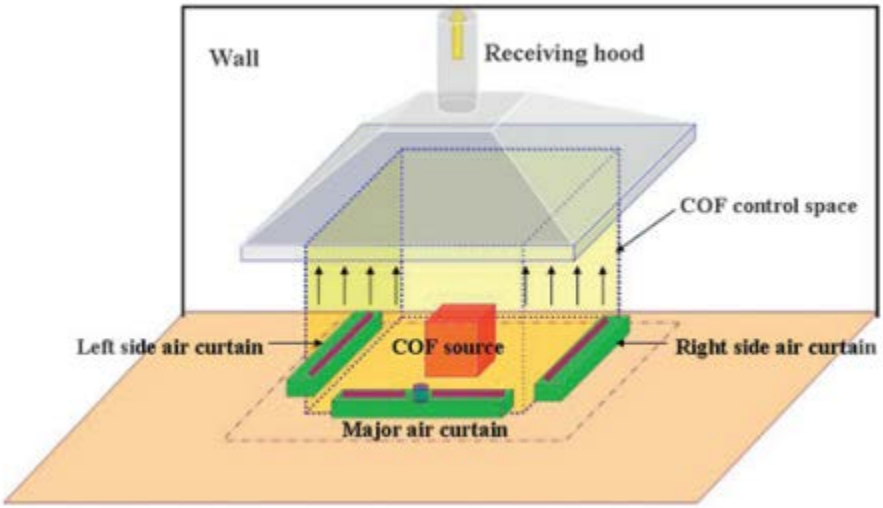


Figure 2-18: Three-piece embracing air curtain device (EACD) installed in a kitchen to reduce levels of cooking oil fumes (COF) (Source: Pan et al., 2011)

The natural ventilation condition of a kitchen space also has a certain influence on the capture efficiency of exhaust systems. Gao et al. (2013) measured the dynamic concentration of $PM_{0.1\text{-}10}$ and the inhaled particles fraction under different door and window conditions, keeping other factors constant. Table 2-8 shows the different settings for four cases.

Table 2-8: Cases under different ventilation conditions **(Source: Gao et al., 2013)**

Cases	1	2	3	4
Conditions	D: open (angle 30°), W: closed E: 518.4 m^3/h	D: open (full), W: closed E: 518.4 m^3/h	D: closed, W: open (half) E: 518.4 m^3/h	D: open (full) W: open (half) E: 518.4 m^3/h

Door size: 200 cm (height) × 97 cm (width); window size (half): 130 cm (height) × 42.5 cm (width).

The results indicated that opening a door at 30-degrees was 79.2 times more efficient than solely opening a window in reducing inhaled PM concentration, while a fully open door was 9.4 times more efficient than an open window (see Figure 2-19). However, it also suggested that the total capture efficiency of particles under different ventilation conditions was almost the same after 3 minutes.

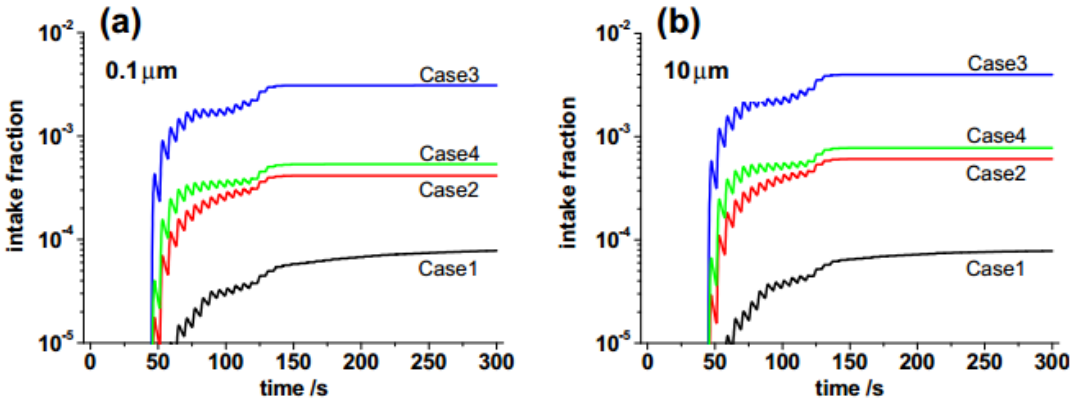


Figure 2-19: Dynamic intake fraction of fume particles by an individual along a 5-min cooking process (Source: Gao et al., 2013)

2.4 Findings and Summary

Cooking Energy

As construction had been increasing along its fast track, the literature review disclosed that China has been tightening up building, residential building and household energy saving over the past 15 years. Great progress has been made in the areas of reducing winter heating energy and lighting energy in residential buildings. Northern China space heating intensity has dropped continuously since 2001. However, cooking, home appliances and lighting continue to increase in terms of household energy consumption.

Home energy research has led to the conclusion that cooking energy is among the top home energy end users. A comparison study indicates that

cooking energy in Chinese families takes as much as 35% of the total household energy use, while in Western families, this figure is only 7% (including Japan). Very little published research is based on understanding the underlying reasons for this phenomenon. This lack of research is partially because of the decentralized energy end users, making data collection difficult, and partially due to the high cost of measuring and recording these end users' energy consumption.

The literature review showed that there is published knowledge on cooking energy in Western countries. This research has covered a wide topic area relating to cooking energy, as follows.

- Cooking behaviour: DeMerchant (1997) discovered that a patient cook can save more than half the energy of a quick cook because a quick cook does not control cooking parameters. Research by Wood and Newborough (2003) reported that a cooking energy dashboard can save up to 20% of cooking energy.

- Cooking techniques: Hager and Morawicki (2013) reported that, among different cooking techniques, boiling and baking used the largest amount of energy, while simmering (saving 65-95% of the energy used for boiling) used the least.

- Cookware: Das et al.'s (2006) research pointed out that pressure cooking reduced cooking time, as the cooking is carried out at an elevated temperature corresponding to the higher pressure maintained inside the cooker. Up to 44% energy saving can be achieved compared to open cooking. However, Hager and Morawicki's (2013) research indicated that there was no obvious energy efficiency advantage of one type of cooking equipment over another.

Hager and Morawicki's research even probed the heating mechanisms of cooking. In one of their reports (Hager & Morawicki, 2013), each cooking

technique was classified into one of the heating mechanisms: convection, radiation or conduction. In recent years, important contributions have been made by scientists and chefs. The term 'molecular gastronomy' has been used to describe the application of scientific knowledge to cooking. The term was coined in 1988 by the late Oxford physicist Nicholas Kurti and the French National Institute of Agricultural Research (INRA) chemist Hervé This (Wikipedia, 2015a). Molecular gastronomy has become a new sub-discipline of Western food science.

Unlike Western cooking, Chinese food is more often served hot. Some scholars found that in China diet is a sense of 'beauty' (Tao, 2013), while cooking is sometimes done with a kind of 'play'. According to the *Baidu Encyclopaedia,* there are 10 basic types of heat cooking techniques in the Chinese tradition. This greatly expands Marcus's classification of the Western cooking techniques of baking, frying, steaming, smoking and roasting (Karel & Lund, 2003). The richness and variety of Chinese cooking techniques is based on the long history of China's Han food cultural evolution, the merging of other invading cultures, as well as the development of cooking technologies. Staple food types, side dish types, cooking techniques, food varieties and the use of cooking oils all affect cooking energy. A review of historical food culture showed that modern cooking methods consume more energy than those used in ancient times in China. Food culture then became more consistent since the Ming Dynasty because of the wide use of rapeseed oil.

In the literature review, the most significant finding is that although Chinese cooking energy is much higher than that in Western countries, there are very few studies in this area. The review also pointed out that more cooking techniques are applied in China than in Western countries. Thus, in the following research, cooking energy, especially its relation with Chinese cooking techniques and culture, is the focus of the study.

Cooking Fumes and Ultra-Fine Particles

The literature review revealed that a number of pieces of research have been carried out in recent years in the area of cooking fumes and UFP. This is because cooking is regarded as the most significant particle-generating activity, accounting for 30% of indoor particulate matter. The inhalation of cooking oil fumes has been proved to have potential adverse impacts on human health. Since Chinese housewives spend about 1/4 of their daily activity on cooking, and cooking fume concentration is elevated by a factor of 85, from 9.1 x 10^3 cm^{-3} during non-cooking hours to 7.7 x 10^5 cm^{-3} during cooking hours, a comfortable and healthy cooking environment is very important (Lai, 2005).

Since real-time particle measurements have shown that about 80% of the particles associated with cooking are ultrafine particles in terms of particle counts (See & Balasubramanian, 2006), many studies focus on the relation between cooking oil, cooking temperature, cooking method and UFP generation. Other studies have investigated the fume removal efficiency of different hood styles, hood side panels, makeup air styles, and the distance between the smoke exhauster and the cooking pan. The literature review also revealed that natural ventilation is another key parameter for reducing cooking fume concentration. A short summary of these findings is listed below.

- In Chinese cooking methods, Zhang et al. (2010) observed that the lowest average UFP concentrations were observed during boiling, while the highest were measured during frying. Deep frying gave the largest increase in the number concentration of $PM_{2.5}$, followed by pan frying and stir frying (See & Balasubramanian, 2008).
- In the study of cooking fume generation using different cooking oils, Chiang et al. (1997) observed the amount of fume particulates

generated were in the sequence of soybean > peanut > safflower > lard > vegetable > corn > mustard > olive.

- Many researchers have verified a positive causal relationship between cooking temperature and particle emission. The results showed that, in general, from 180 °C to 210 °C, every 5 ^{o}C increase in oil temperature would result in a 20-50% increase in UFP number concentration.

- In their research on hood systems, Chen et al. (2010) observed a wide and turbulent dispersion pattern of oil mists under island hoods. This turbulent spiral-like flow was likely to leak large amounts of PM and UFP into the ambient air compared with wall-mounted hoods.

- In general, wall-mounted canopy hoods require more exhaust than a proximity (back-shelf) hood for the identical (thermal plume) challenge. Side (or end) panels, permit a reduced exhaust rate in most cases, as all the replacement air is drawn across the front of the equipment, which improves containment of the effluent plume generated by the hot equipment. The ability of a hood to capture and contain cooking effluent can also be enhanced by adding passive features (e.g., angles, flanges, or geometric flow deflectors) or active features (e.g., low-flow, high-velocity jets) along the edges of the hood or within the hood reservoir (Southern California Edison, 2004).

- Chiang et al. (1999) stated that the distance between the smoke exhauster and the cooking pan was a key factor determining hood efficiency. A distance of 70 cm showed limited efficiency, while that of 50 cm still presented mutagenic impacts on the human body. Installing an EACD on a table top was proved to be able to enhance the capture efficiency of hoods significantly (Pan, et al., 2011).

- The natural ventilation condition of the kitchen space also has a certain influence on the capture efficiency of exhaust systems. Results have

indicated that opening a door at 30 degrees was 79.2 times more efficient than solely opening a window in reducing inhaled PM concentration, while a fully open door was 9.4 times more efficient than an open window (Gao, et al., 2013).

Although the above studies reveal a causal relationship for cooking UFP generation and removal, many of these were not undertaken in real kitchen cooking conditions. In real-world kitchen cooking conditions, various elements are combined to affect UFP removal efficiency. With regard to the significance of COF impact on human health and COF emission differences reported in Table 2-7, in this research, the emission of cooking oil fumes from different Chinese cooking methods and cuisines are re-investigated. The re-investigation was carried out in real family cooking conditions. The purpose of the investigation was to understand the generation of $PM_{2.5}$ under different Chinese cooking methods and the removal of it by air filter and a mechanical ventilation system. Computer simulation, using computational flow dynamics (CFD), was also applied at a later stage to simulate cooking oil emission and dissemination patterns. Through the review of other studies and site measurements of the generation and removal of COF, this research is intended to propose an improved cooking fume removal system to enhance kitchen air quality.

Chapter 3: FIELD STUDY

Based on the literature review, this research focuses on knowledge in the fields of cooking energy and cooking fumes. The goal is not to repeat previous efforts, but to collect real field data in order to identify aspects untouched in previous research. For this reason, as the first task, test families needed to be recruited.

3.1 Selecting Test Families and Research Objects

In this research, selecting test families and survey objects was important to the success of the data collection. On the one hand, the data needed to be representative; on the other, the data should be accessible. The selection considerations with regard to the test families and survey objects are listed below.

1. Beijing families were chosen for carrying out the experiments, since, as China' capital, Beijing has been developed as a multi-cultural and multi-nationality city. People from both northern and southern China live in the same place. After many years of mixing, living behaviour and cooking patterns are representative of those nationwide.

2. Beijing city infrastructure is built to the highest national standards. Even compared with those cities in developed countries, its standards are on a high level. Weather and research data are easy to access because of sound government services. Many of these data are available online. One example of good infrastructure making for better research output is the test families' heating systems. The radiator heating system has a calorie meter because this is a compulsory requirement in Beijing building regulations. This makes energy data collection very convenient.

3. Beijing is a city representative of China and of the world. The research results can be used for guiding national practice and for international reference. The research papers will be more easily accepted and published in recognized journals and the data can, therefore, receive more exposure and be quoted in academic circles.

4. As a result of the limited resources and tight time frame of the research, it was critical to set up the experiment in an economical, fast and simple way. A lot of time was given to planning the experiment, collecting field data, adjusting the testing strategy and conducting data analysis. Time spent on travel and coordination was kept to a minimum. As Beijing is the home town of the researcher, a great amount of time was saved by choosing Beijing to set up the experiment.

5. The main drawback of selecting a single city to carry out research is the climate consideration. This consideration is in the aspects of both outdoor air temperature and outdoor air quality, since these two factors affected the research output the most. In the experiment, indoor air quality, particularly $PM_{2.5}$ in the kitchen, needed to be investigated. Although cooking energy is less affected by weather than other forms of household energy, such as air conditioning and space heating in the experiment, weather was still considered as one affecting factor and was checked in the data analysis. By realizing the influence of climate condition and outdoor air quality on the research, these factors were recorded carefully in the experiment.

In addition to city selection, test family selection was another critical consideration in the research. Several experiments needed to be carried out with these families, including a kitchen fume $PM_{2.5}$ test, energy measurement, and a study of occupants' behaviour. Considerations for selecting test families to carry out these experiments are listed below.

1. A test family needed to be representative of its group i.e., the income and family life cycle, and other factors of the test family needed to be representative. In the energy experiment, a retired couple and a young couple with child were selected. In the cooking fume study, a young couple with one child was selected.
2. A test family needed to cook at home often. Regardless of whether for energy study or cooking fume $PM_{2.5}$ recording, the selected family needed to provide related data over a long span of time. In this aspect, a single person or newly married couple was not suitable for the cooking study because these people often eat out (Horizon Research Group, 2014).
3. A test family needed to be cooperative. Since the data collecting and behaviour recording were going to be carried out for one whole year, interference with family daily life was unavoidable. Family members needed to be cooperative during the entire test period.

Selecting a Family for Measuring Cooking Energy

As mentioned in the above section, the key consideration for cooking energy measurement was to select a family which was representative and accessible. In this part of the research, an understanding of the proportion of cooking energy used in the overall household energy was important. The year-round energy use, including air conditioning and space heating, needed to be measured and recorded. Thus, the unit floor layout, not only the occupants' characteristics, which should be representative of most of Beijing residents' housing conditions, needed to be found. According to *Metro Daily*, a Beijing newspaper, 31.5% people in Beijing prefer two-bedroomed units with a floor area of about 80-95 m^2. Normally, this kind of two-bedroomed unit includes a 20 m^2 guest room, a 15 m^2 master bedroom,

a 10 m^2 guest bedroom, an 8 m^2 dining area and a 6 m^2 kitchen. Two balconies, one connected to the guest room and the other connected to the kitchen, are preferred (Metro Daily, 2010).

Another key consideration was the selection of the occupants. It was obvious that the selected occupants needed to cook often in the home, otherwise, the energy data collected would not be enough to conclude meaningful results. Based on research (Horizon Research Group, 2014), more than 30% of young people often eat out because of work pressure. Families with children and elderly people were targeted in this research as a study group of those who often eat at home.

In order to meet the requirements described above, the selection criteria for targeting families with which to undertake cooking energy measurement were as follows:

1. Selected units were preferred to be two-bedroomed units with a floor area of 80-95 m^2 in order to be representative when recording year-round energy consumption.
2. Selected families were preferred to be a young couple with a child and/or a retired couple who often cook at home.
3. Other criteria included accessibility and cooperation, as one year of data and daily cooking energy data needed to be recorded.

Selecting the Indoor Air Quality Experiment: Cooking Fume $PM_{2.5}$ Test Family

The key consideration for the indoor cooking air quality experiment was to select families who often cook at home. A $PM_{2.5}$ monitor needed to be installed in the kitchen, and the data were required to be recorded daily in different cooking circumstances e.g., cooking with the fume exhaust fan set to low, medium or high speed. This also meant that the cooperation of the

family was important. Another consideration was the outdoor air quality at the time of the data recording. It was preferred that the window was closed; thus, a minimum impact of outdoor air quality on indoor air quality was maintained. Since the experiment was mainly on mechanical ventilation efficiency and the home $PM_{2.5}$ filter/cleaner's effect on indoor air quality improvement, there was no need to consider the scenario of having the window open. In consideration of these factor, winter was chosen as the season for testing in Beijing. In winter, windows are often closed all the time because of the cold outdoor temperature.

As widely reported in the news, Beijing outdoor air quality is in a serious condition, so the test kitchen being airtight was an important consideration. The pollution of outdoor air quality should not affect indoor air quality, particularly during the data recording time.

In order to meet the requirements described above, the selection criteria for the cooking air quality study and the target families were as follows:

1. A good, airtight building envelope to reduce the impact of outdoor air quality.
2. A cold season was chosen for carrying out the data collection so that the kitchen window would be closed during the cooking fume experiment.
3. Accessibility and cooperation of the test family was very important, since many of the test instruments and cooking conditions needed to be installed and changed during the experiment.
4. It was preferred that the families tested were a young couple with a child and/or a retired couple who often cook at home.

Occupant Behaviour

The purpose of conducting this particular occupant behaviour study was to understand the relationship between cooking energy and cooking behaviour. In the literature review, it was found that a quick cook who does not control cooking parameters uses more energy than a patient cook (DeMerchant, 1997). It was also reported by Wood and Newborough (2003) that 14 out of the 31 households considered achieved energy savings of greater than 10%, and six of these achieved savings of more than 20%.

The behaviour study was carried out using interview, survey and/or real-time monitoring. At the beginning of the study, a manual record of daily behaviour was chosen. This method required a significant amount of time from the target family in order for them to record their daily activities. Key activities included the time spent cooking, resting and other family work; the time spent in different functional rooms e.g., kitchen, guest room, dining room, bedroom and others; and the start and finish times of different home activities. With these data, the relation between cooking and occupants' activities/behaviour could be understood in the later data analysis stage.

The above-mentioned recording work consumed a significant amount of time. A retired couple was selected because of the abundance of time they had. However, in the first month/30 days of recording work, it was found and heard that the time spent was too much for the retired couple. In addition, because of their age, they could not recall these activities accurately, even those activities that happened on the same day. These findings required solutions other than manual records. Based on earlier research observation and occupants' feedback, the researcher listed several criteria for alternative solutions:

1. Reasonable time was required to spend on recording work.
2. The families were comfortable and at ease regarding submitting activities data to the researcher through the alternative solution.
3. The recording method needed to be simple and automatic in order to reduce recording time and interruptions to family daily life.
4. The recording method needed to be accurate and sophisticated enough to record the required research data.

Based on these criteria, an alternative research method, RFID, was adopted in lieu of manual recording. RFID is a system that provides real-time recording of occupants' activities, including their location in the home and the start/end times of their activities. A detailed system set-up and its advantages and disadvantages are described in the following section.

Survey with Questionnaire

In order to expand the experiment findings from an individual case to a broader conclusion, a survey through questionnaire was needed. There were two methods for carrying out surveys in this research: one was to use a paper questionnaire and the other was a WeChat questionnaire.

Based on recent research by Fudan University (2016), WeChat is the most popular online social tool on the Chinese mainland: the 34.65% response indicates that they send WeChat messages more than once a week, while 11% send messages every day. Most of these messages (> 75%) are original messages, 36% of these messages receive responses and comments, and 35% are reposted by the receivers. WeChat has a function, called MessageHelp, to initiate a poll, but this is restricted to friends in the contact list or group list. Depending on what kinds of question the researcher intends to ask, if these questions are very technical-specific, WeChat is a good, probably the recommended, tool to undertake this

because most people in the contact/group list are those who share the same interests as the researcher.

Although questions are easy to raise, the channel distributing the questionnaire is a key consideration. Since the questionnaire is quite technical, the following criteria were chosen for targeting a group in order to gain valuable feedback:

1. A willingness to cooperate in the survey.
2. An understanding of household energy and a willingness to share information.
3. Possessing an electricity/gas power bill for at least 3 months.
4. Able to be accessible and convenient for receiving feedback.

Residents in a mature residential quarter in Beijing were selected. This key selection consideration was due to gas consumption bills being accessed easily. Every two months, the gas meter was checked manually and the reading recorded in a paper book which is kept at a local gas station. To maintain entries in the book meant acquiring all the gas consumption data of the residents. Gas is mainly used for cooking. Once the researcher had obtained the gas consumption data, the remaining work was in accessing the residents to gain family data. Based on the selected family cooking energy measurement findings, the residents' information required included the size of the family, the household family life cycle, and cooking behaviour. A paper questionnaire was distributed in the residential quarter. Feedback regarding the families' gas consumption data was then checked from the local gas station book.

Using this method, although a long time was spent on pre-survey audience selection, once selected, it was very efficient in acquiring the necessary data. The only affecting factor in the survey was the response ratio.

In the pre-survey research, the researcher also considered a WeChat

survey, which is very different from a paper survey because of the virtual nature of the target audience There was no way to know any information regarding the target audience before the online survey was conducted. The audience are virtual on the WeChat space. Many of them could not be visited in person. It was expected that the feedback ratio would be low and the quality of the feedback data would also be low. The advantage of being online is the large number of audience accessible in one round. However, in the pre-survey research, it was found that WeChat was not a good tool for covering families from all parts of the family life cycle required in the research. For example, most retired couples do not use smart phones and are not, therefore, accessible by WeChat. The loss of this segment would have been critical to the research, since retired couples are the segment who most often eat and cook at home.

In addition to restrictions in the use of technology, during the pre-survey research, the researcher found that people in the researcher's WeChat group were almost all green building industry practitioners. Since WeChat can only raise a pool or survey for those people in the WeChat contact list, the homogeneity of the researcher's acquaintances restricted the diversity of the online survey objects.

As a result of the above-discussed restrictions on an online survey, the researcher finally selected a paper survey for this research.

3.2 Cooking Energy Measurement

To measure the energy consumption of the different home appliances used by a test family, plug-in meters (Figure 3-1) were installed in all the power sockets in the home. The appliances were then plugged into the meter so that their use could be measured. Plug-in meters show the power used in watts (W). Over time, the energy used is recorded as kilowatt-hours (kWh).



Figure 3-1: Plug-in energy meter, gas meter monitor, space heating calorie meter (top left)

A plug-in meter is a very useful tool for measuring energy. It allows records of what type of impact each appliance has on home energy use. Small electric loads, such as a refrigerator, television or even a night light, can add up over time because they are always on. More sophisticated home energy meters/monitors can be computer programmed as a flat rate, a tiered rate or a time-of-use rate. The flat rate is simply one flat charge applied to all the kilowatt-hours. A tiered rate charges one rate for the first range of kilowatt-hours and a second rate for all kilowatt-hours used over that amount. For example, the first 1,000 kWh may be billed at $0.095 and all remaining kilowatt-hours at $0.085. Tiered rates are not affected by the time period in which the energy is used. The time-of-use electricity rate is cheap when demand is low, such as during the evenings, at weekends and on official holidays. Likewise, as daytime begins, more people and businesses turn on their lights, appliances and devices, and the electricity rate becomes more expensive.

In this research, the flat rate was the type of kWh charge used in the research house. The accumulated power consumption of each meter was recorded on a daily basis. All lighting power consumption was calculated by deducting appliances' power from the household electrical panel meter.

In the research, home appliance energy use was classified into seven categories for a later stage of the research. The home appliances in each category were measured using a plug-in meter. These categories were:

Entertainment:	Television and audio devices
Cooking:	Kitchen appliances and gas cooker
Lighting:	Indoor lighting system
Heating:	Winter radiator heating system
Hot water:	Bathroom and kitchen hot water
Cooling:	Summer air conditioning
Others:	Miscellaneous power use

In the research house, heating was supplied through a community gas boiler. The radiator system in the building is a two-pipe heating system. A heat energy meter (calorimeter) was installed on the hot water return system with a water flow sensor in each unit inlet. Temperature sensors were installed on both the hot water supply and return pipes, so that the heat usage for each unit could be calculated automatically. The energy meter was battery operated and energy usage was displayed in kilowatts (kW) on the meter body liquid-crystal display (LCD). The accumulated kW were checked manually and recorded on a daily basis.

Gas consumption was measured by gas meter and readings were also taken and recorded on a daily basis. Gas is mainly for cooking use.

3.3 Radio Frequency Identification

Learning about occupants' behaviour has been a long-standing issue in building research. Most of the previous studies used observations, interviews, and questionnaire surveys to record residents' activities when at

home. Data obtained through interviews or questionnaire surveys are based on the respondents' memory of previous activities. Very often, details are lost and do not always meet the required accuracy. The advent of RFID has made occupants' behaviour research easier, with improved accuracy and more detail.

In this research, an RFID real-time personal location system was installed with the test family: a retired couple. An RFID system is made up of a signal receiver (reader), a personal locator (tag trigger), a wristband (tag), software and a computer workstation.

Personal locators were installed in all functional rooms. Whenever a person entered a room, the locator triggered the wristband tag on this person, emitting a radio signal. This signal is picked up by the reader and sent to the computer workstation. The software automatically records the room (each locator has its own ID), the person (each wristband tag has its own ID) and the time the person entered and left the room.

Software was written with several functions. First, each locator has its own ID. The ID represents a specific function room. When an occupant's wristband (tag) goes to a certain locator, the software will identify which room the person has entered. Second, each wristband is assigned to a specific ID/person, i.e., wife or husband. The wristband should not be worn by a different person. Thus, the software can identify the person when he/she is in a specific room/locator.

The software only records the time a person enters and leaves a specific room. In this way, the recording database will not become too large to store in the disk. The software can automatically calculate the time a person stays within a locator's range i.e., a room, by simply subtracting the entering time from the leaving time.

Each family member's time spent in preparing and having food can then be retrieved from the recording database. Data analysis was carried out later to understand the occupancy behaviour in cooking and taking food.

One drawback of RFID is the locating capability. The locator's detection distance is stepped to 1.0 m diameter, 1.5 m diameter, and 3 m diameter. The locator's ability to detect the trigger's signal drops dramatically when the radio hits a concrete wall. When two locators' detection distances overlap, the software will record the presence of a trigger for both locators' ID. Thus, adjusting and locating the locator and avoiding signal overlap were two of the key activities in commissioning the system. On many occasions, the system needed to be re-commissioned.

Another drawback is the locating accuracy of the RFID. Ideally, a person's location in the kitchen should be recorded in very great detail, so that the different activities can be identified. These locations included, for example, the cooking area, wash basin, electric cookware area and the food preparation table. This required the system to locate a person at less than 0.5 m spacing. The RFID may not have been able to reach this level of accuracy. At the system selection stage, other locating systems, such as WiFi and LiFi, were also investigated.

A WiFi indoor locating system can locate active Wi-Fi devices throughout a coverage area with a higher accuracy than the Global Positioning System (GPS). The system enables the tracking of WiFi devices to a specific floor and room level, providing a similar level of accuracy to that of RFID. The system uses nodes, which are small devices, placed approximately within 30 m of each other to cover a three-dimensional space (site). A site may span a multi-storey building or multiple buildings on a campus. Nodes are simply plugged into standard electrical outlets for power. No wiring is necessary, as the nodes automatically configure themselves into a wireless mesh network. Once the nodes are set up, the system can locate and track

any WiFi-enabled smart phone or tablet, including iPhones, iPads, Android devices, BlackBerrys and Windows Mobile, as well as laptops.

Another recently developed and useful locating technology is LiFi. LiFi is a simple term for visual light communication (VLC), which can be applied for indoor positioning. LiFi uses the visible light spectrum instead of radio frequencies to enable wireless data communication. The integration of illumination and data services generates a measurable reduction in both infrastructure complexity and energy consumption. Philips introduced a system that connects in-store light-emitting diode (LED) lights with consumers' smart phones. Using a downloadable app, people are able to locate items on their shopping lists or acquire coupons as they pass products on the aisles. In return, retailers can locate customers within stores through an LED lighting system (LaMonica, 2014). LiFi is still at a trial stage in the industry. However, it will definitely be easy to adapt it to indoor positioning usage with a high level of accuracy.

As a result of budget and time constraints in this research, RFID was applied as a personal locating system. Figure 3-2 shows the installation layout of the RFID in the retired couple's home.

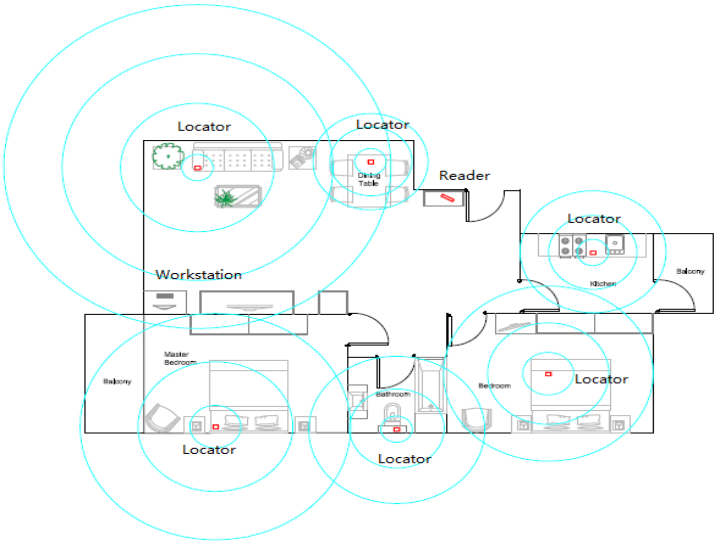


Figure 3-2: RFID system installed in the retired couple's home and the floor layout

3.4 $PM_{2.5}$ Measurement

Air pollution, particularly cooking fumes, is a major source of indoor air contamination. In the literature review, a wide range of published knowledge concluded that cooking fumes affect human health. In this research, air pollution, $PM_{2.5}$ cooking fumes in particular, was monitored and its impact on indoor air quality was tracked.

Test Equipment Selection

There are a variety of methods available for measuring the mass concentration of PM in the air. These include both direct reading instruments, which provide continuous measurements of particle concentrations, and filter-based gravimetric samplers that collect the particulate material onto a filter which must then be weighed in a laboratory. Commonly used methods include filter-based gravimetric samplers, tapered element oscillating microbalance (TEOM) analysers, optical analysers, the black smoke method and personal samplers (Air Quality Expert Group, 2005).

The advantages and disadvantages of each method are widely discussed in many research papers and textbooks. A short summary is provided in chapter 1: Introduction, Table 1-3. In this research, kitchen cooking fumes were measured. Particle sizes included small particles ($PM_{2.5}$) and large particles (PM_{10}). The first consideration was the portability of the monitor because the monitor was to be installed with the test family. When the recording finished, the family member would keep the monitor in a place other than the test area, which was near the gas cooker. During the testing, the monitor needed to be installed and moved to other places quickly and easily. Therefore, an optical analyser was selected.

An optical analyser, which is often used for workplace and indoor particle monitoring, is a portable, lightweight, battery-operated instrument that can easily be deployed for short-term measuring in a number of locations to build knowledge of particle distribution in both space and time. One type of this kind of equipment is the Dylos DC1700 laser particle counter (see Figure 3-3), which is of low cost and is used in research for utilizing the interaction between airborne particles and visible laser light to both count and size-classify PM. The advantage is that a single analyser can monitor particles of a range of sizes, including PM_{10} and $PM_{2.5}$, simultaneously. However, the particle counts need to be converted to mass by calculations using a range of assumptions, whose validity may vary due to the nature of the particles sampled.

The Dylos DC1700 has an internal battery which provides up to 6 hours of continuous use on a single charge. It can also be operated of alternating current (AC) using the wall socket power adapter included. The internal memory can store up to one week's worth of time-stamped data recorded every minute (about 10,000 samples). This means that the DC1700 can be left in a location to sample and then brought to a personal computer (PC), whereby the data can then be downloaded and loaded into Excel or other spreadsheet programs for analysis. This was particularly useful in reducing the disruption of testing during the family's daily life.



Figure 3-3: Dylos DC1700 $PM_{2.5}$ portable monitor

The literature review found that some researchers doubt the accuracy of

the Dylos DC1700 monitor because of its low cost. Low cost is normally associated with reduced accuracy in testing instruments in many cases. In this research, indoor particle concentration needed to be compared with outdoor particle concentration, so the equipment was preferred for having a certain accuracy level as an outdoor air quality monitoring station.

More research was conducted to identify a suitable air pollution monitoring instrument before purchasing. One of these research approaches was to study the Chinese government's choice. In China, the government air pollution monitoring station uses beta attenuation monitors (BAMs) to measure airborne particle matter. The main principle behind a BAM is based on the Bouguer (Lambert–Beer) law: the amount by which the flow of beta radiation (electrons) is attenuated by a solid matter is exponentially dependent on its mass and not on any other features (such as density, chemical composition or some optical or electrical properties) of this matter. Air is drawn from outside the detector through an 'infinite' (cycling) ribbon made from filtering material, so that the particles are collected on it. There are two sources of beta radiation: one placed before and one after the region where airflow passes through the ribbon leaving particles on it; there are also two detectors on the opposite side of the ribbon, facing the detectors. The intensity of the sources' and detectors' sensitivity being the same (or corrected with an appropriate calibration lookup table), the intensity of beta rays detected by one of the detectors is compared with that of the other. Thus, one can deduce how much mass the ribbon has acquired upon being exposed to the airflow; knowing the drain velocity, the actual particle mass concentration in the air can be assessed (Wikipedia, 2014d). The use of BAM was not applicable in this research because of its price. A piece of this equipment sells in China for 12,000 GBP. There are about 500 BAMs installed in China's major cities.

The Dylos DC1700 is a low-cost air particle monitor. The selling price in

China is about 200 GBP per unit. To test the accuracy of the Dylos, researchers installed one and compared the data with those from a BAM station. As shown in Figure 3-4 below, the two measured outputs trendline match each other very well (World Air Quality Index Project, 2013).

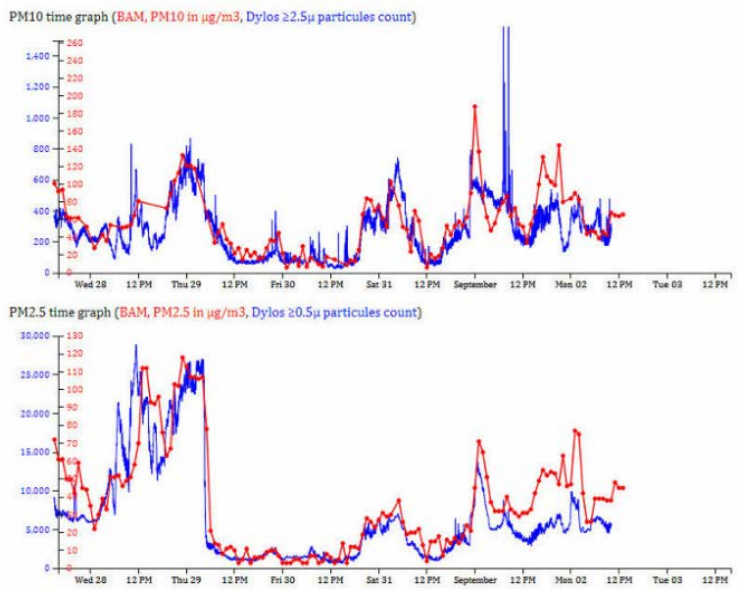


Figure 3-4: Comparison graph between a BAM station and a Dylos monitor of Beijing outdoor $PM_{2.5}$ concentration (Source: World Air Quality Index Project, 2013)

Other researchers have tried to compare the accuracy of the Dylos with other kinds of air particle counter to determine if the low-cost Dylos DC1700 can be used in homes to quantify pollution concentration. One group of researchers (Semple, Ibrahim, Apsley, Steiner, & Turner, 2013) used Sidepak AM510 Personal Aerosol Monitors (TSI, Minnesota, USA) as reference monitors. In their research, the cost of the AM510 was more than 2,500 GBP. The validation results from their study suggest that there was very good agreement between the two instruments when the regression equation was applied to the Dylos data. Approximately 3% of the measurements were outside the limits of agreement when an upper/lower bound of 1.96 standard deviation (SD) of the difference was applied. This suggests that the differences in the air quality information generated by the two instruments were generally small and the Dylos appears to be a valid

instrument for measuring $PM_{2.5}$ in household settings.

PM Monitor Location and Test Plan

In order to gain accurate and meaningful data for cooking fumes, two $PM_{2.5}$ monitors were used in the testing, although sometimes one monitor was adequate. Test plans were designed for three rounds of experiments: the first round was to test cooking fume concentration in the kitchen; the second was to test cooking fume concentrations of different cooking methods; and the third was to test the efficiency of the mechanical ventilation system. The locations of the test instruments are shown in Figure 3-5.

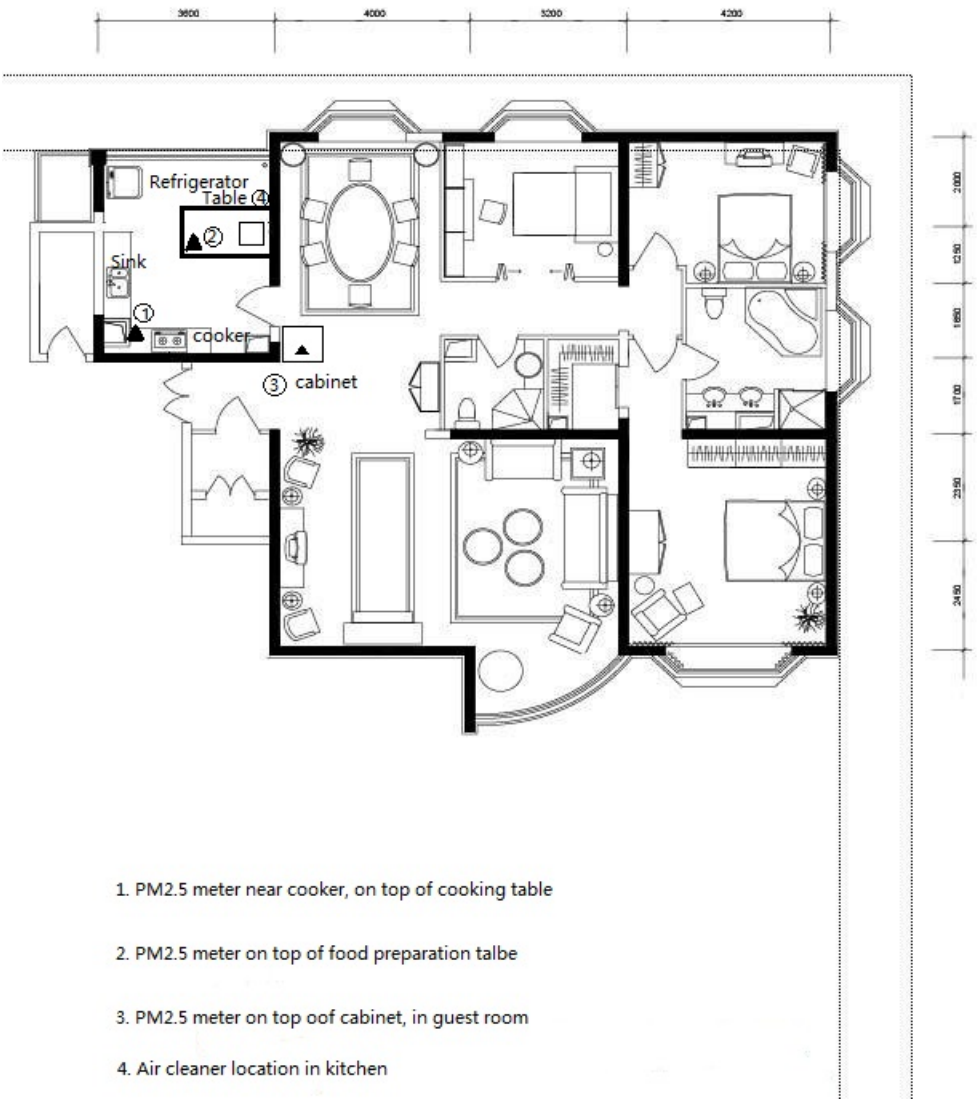


Figure 3-5: Kitchen floor layout and test instrument location

Cooking Fume Cleaner

In order to remove cooking fumes from the kitchen, an air cleaner was installed in addition to the mechanical ventilation/exhaust fan. As $PM_{2.5}$ is becoming a key concern in China, equipment which can be operated in a kitchen environment and has the capability to remove small air particles was installed in the home of the test family. The air cleaner uses water to clean the air. The water-wash type of air cleaner (see Figure 3-6) has the advantage of removing particles at the same time avoiding being blocked by sticky kitchen fumes, as happens with a traditional fibre filter.

A water-wash cleaner has a bundle of water disks installed in the airway. As the airflow moves through the water disk, a water stream falls from the upper side. The water forms a very thin water film on the disk surface that removes dust and small particles from the air. Clean air is, therefore, released into the room from the top outlet.



Figure 3-6: Beurer water-wash air cleaner

The removed air particles are dissolved in water. The dirty water is changed and the new, clean water can be used to clean the air again. Normal air cleaners that use fibre or an electrical magnetic field will either become blocked by sticky fumes or blanketed with a layer of oil on the magnetic panel surface.

PM Measurement and Test Plan

For the first test in this experiment, background combustion-generated $PM_{2.5}$ and PM_{10} were measured. This established the particle concentration baseline for further cooking fume testing. Data for kitchen exhaust fan efficiency, the mechanical ventilation system and air cleaner efficiency for removing combustion-generated PM were recorded. Eight rounds of tests were carried out, as shown in Table 3-1. The monitor was located near the burner and at breath height.

Table 3-1: PM baseline testing

	Cooker burner no. 1	Cooker burner no. 2	Exhaust fan	Air cleaner
Test 1	On	Off	Off	Off
Test 2	On	On	Off	Off
Test 3	On	Off	On	Off
Test 4	On	On	On	Off
Test 5	On	Off	Off	On
Test 6	On	On	Off	On
Test 7	On	Off	On	On
Test 8	On	On	On	On

In the tests that followed, different cooking methods and the particles generated were measured. The four most often-used Chinese cooking methods were selected. Each cooking method was carried out separately. Measurement started once cooking began and ended 5 minutes after the cooking.

Twenty tests were carried out, as shown in Table 3-2. The PM monitor was located near the burner and at breath height.

Table 3-2: PM release during different cooking methods

	Test 1	Test 2	Test 3	Test 4
Cooking method: Stir frying - Scrambled egg and tomato	Exhaust fan off/ air cleaner off	Exhaust fan on/ Air cleaner off	Exhaust fan on/ Air cleaner on	Exhaust fan off/ Air cleaner on
Cooking method: Steaming - Chinese steamed bun	Exhaust fan off/ air cleaner off	Exhaust fan on/ Air cleaner off	Exhaust fan on/ Air cleaner on	Exhaust fan off/ Air cleaner on
Cooking method: Boiling - Porridge	Exhaust fan off/ air cleaner off	Exhaust fan on/ Air cleaner off	Exhaust fan on/ Air cleaner on	Exhaust fan off/ Air cleaner on
Cooking method: Deep frying - Pan-fried cod fish	Exhaust fan off/ air cleaner off	Exhaust fan on/ Air cleaner off	Exhaust fan on/ Air cleaner on	Exhaust fan off/ Air cleaner on
Cooking method: Pan frying - Pancake	Exhaust fan off/ air cleaner off	Exhaust fan on/ Air cleaner off	Exhaust fan on/ Air cleaner on	Exhaust fan off/ Air cleaner on

3.5 Tracer Gas Experiment

Chinese families usually install a cooking fume exhaust fan in their kitchen. This type of fan has been a standard home appliance for a long time. Residents expect the exhaust fan to remove most of the cooking fumes in order to reduce the adverse impact on human health and keep indoor furniture/decoration clean. However, the efficiency of the exhaust fan is doubtful. Laboratory-based experiments on exhaust fan efficiency have been carried out by research institutes and manufacturers, the results of which vary to a wide range. One experiment is Lawrence Berkeley National Laboratory published results for the seven representative devices they tested. According to Chen (2012), the capture efficiency varied from less than 15% to more than 98%. Site measurement data in this area, particularly regarding Chinese cooking conditions, are rarely found in widely published material.

In this experiment, tracer gas was used to test cooking fume exhaust fan efficiency on site in the home of the Chinese family selected. As the first task, different tracer gas methods were investigated at the test preparation stage. In the published information, the tracer gas concentration decay method, constant concentration method and constant injection method are the most popular means of measuring indoor air change rate per hour (ACH). For all of these methods, a small amount of the tracer gas is first released into the room under study and its concentration is then recorded as a function of time. Subsequently, using appropriate evaluation algorithms, the ACH can be calculated from the data obtained. Heidt and Werner (1986) published the laboratory study results of a comparison between the constant injection method and the concentration decay method. They concluded that the constant injection method was more suitable for less airtight rooms, while the concentration decay method was more suitable for more airtight rooms. Baránkov, Naydenov, Melikov and Sundell (2004) and Naydenov, Baránková, Sundell and Melikov (2004) published their tests of exhaled human carbon dioxide (CO_2) as tracer gas in a laboratory study and field experiment in 2004. Their work concluded that room ACHs can be reliably determined by human carbon dioxide if the CO_2 in the air is mixed well and in a uniform matter. The use of CO_2 as a tracer gas to test room ACH then became an acceptable method.

In the past, a number of gaseous substances, such as helium, hydrogen, oxygen, carbon monoxide, methane, acetone, and the radioactive noble gases argon-41 and krypton-85, were studied and tested for the determination of ACH, mostly in comparison with other tracer gases. Today, the following tracer gases are mainly used in practice (Raatschen, 1995): nitrous oxide (N_2O), sulphur hexafluoride (SF_6), halogenated hydrocarbons, such as hexafluorobenzene (C_6F_6), and perfluorocarbons (PFCs). In the building industry in 1997, some researchers in China used CH_4 and SF_6 as

tracer gases to test building envelope airtightness and room space air change (Tian, Sun, & Liu, 2010; Xiaofeng & Yingxin, 1997). However, for safety reasons (CH_4 5-15% has the potential to explode), CH_4 is rarely used now. More recently, because CO_2 gas is easier to acquire and to measure by sensor, it has come to be commonly used as a tracer gas.

Laussmann and Helm (2011) gave a good review and proposal for using CO_2 as a tracer gas in their work on air change measurements using tracer gases. They mentioned that CO_2 is one of the gaseous organic compounds always detectable in indoor air. Since humans exhale metabolic CO_2 in considerable quantities, its concentration can increase to several thousand parts per million (ppm) (ml/m^3 room air) within a short time. CO_2 concentration is often used to assess the air quality of occupied rooms. In this context, CO_2 measurements are often used today for the determination of indoor ACH, because the measurement can be easily quantified and the required devices are reasonably priced and easy to operate. In practice, it is much better to derive ACH from a decay or build-up curve, as has already been shown (Beko, Lund, Nors, Toftum, & Clausen, 2010; Chao, Tung, & Burnett, 1997; Chung & Hsu, 2001; Guo & Lewis, 2007; Menzies, Schwartzman, Loo, & Pasztor, 1995; Roulet & Foradini, 2002; Sekhar, 2004; Shaw, 1984).

In this research, the CO_2 gas concentration decay method was applied. A CO_2 fire extinguisher was used as the source of CO_2 tracer gas. The CO_2 is compressed in a fire extinguisher cylinder. When the cylinder is placed in a room and CO_2 is released to the indoor air. About 30 seconds after release, the CO_2 in the room will reach 16,000 ppm. After stopping the release of CO_2 into the room, an infra-red CO_2 analyser detects the concentration of CO_2 gas in the form of its rate of decrease. By calculating based on empirical formulation, the air change in the room can be identified. Figure 3-7 shows the location of the fire extinguisher cylinder and CO_2 sensors on

site. The CO_2 sensors have an automatic logging function. Two sensors are located diagonally in the kitchen (Tian, Sun, & Liu, 2010). An electric household fan is used to mix the tracer gas with the room air quickly and evenly.



Figure 3-7: Fire extinguisher cylinder and electrical fan location

3.6 Field Study Summary

The first task of the field study was to select suitable test families. The testing needed to have a certain representative quality nationwide and the test data should be meaningful for academic publication. In the selection of test families, cooperation and a willingness to share family information were other important considerations. In air pollution testing, outdoor conditions also need to be considered. As a result, a young couple with a child and a retired couple were selected because these two groups of people often eat at home. Both of these families live in an apartment unit with a floor area of 80~90 m^2. The testing of indoor air quality should avoid the influence of outdoor air quality. Thus, winter was selected for the tests, as all windows are closed most of the time during that season.

Several rounds of tests were carried out in the research. These included tests used for home energy and indoor air pollution measurement.

With regard to home energy measurement, a plug-in energy meter, a gas meter, and a space heating calorie meter were installed to record home energy use. Severn categories of electricity end user data were recorded: entertainment, cooking, lighting, heating, hot water, cooling, and others. In order to record occupants' behaviour, an RFID system was installed to record the occupants' daily activities. The records included the entering and leaving times of the different functional rooms for each occupant.

For indoor air quality measurement, $PM_{2.5}$ and PM_{10} air quality monitors were installed. In order to remove cooking fumes, a water-wash cleaner was used in addition to a cooking fume exhaust hood. Tracer gas was used to measure the extent to which the kitchen envelope was airtight and the airflow of the cooking fume exhaust hood.

In the selection of the test instruments, pre-research was conducted on the accuracy of these instruments, such as the person-locating system and air quality monitor. Other considerations included cost and suitability. A list of the test instruments used is summarized in Table 3-3.

Table 3-3: List of test instruments

	Model	Manufacturer	Specification	Experiment
Plug-in energy meter	WF-D02A	WANF	160-280 V; 50 Hz; 15A; 0-9999 kWh	Energy measurement
Calorie meter	YG-RLM-15	Ningbo Yonggang Instrument Co. Ltd	DN:15 mm; Qn: 1.5 m^3/h; Q: 0.03~3 m^3/h; PN: 1.5 Mpa	Energy measurement
Gas meter	G4-OOOOO140	BUGM		Energy measurement
Water-wash air cleaner	LW110	Beurer	Airflow: 50-150 m^3/h Water container: 7.25 kg	$PM_{2.5}$ measurement
Air quality monitor logger	DC1700	Dylos		$PM_{2.5}$ measurement
Cooking fume hood	F05.90IX	VALENTI	Airflow: 1000 m^3/h; Pressure: 420 Pa	
Portable CO_2 fire extinguisher	MT/2	Lian YunGang City TianYi Fire Fighting Equipment Co. Ltd	CO_2 weight: 2 kg	Tracer gas
Household electrical fan	FT40-6B	Guangdong Midea Environment Electric Appliance Manufacturing Co. Ltd	50 W	Tracer gas
CO_2 concentration logger	EZY-1S	Beijing TianJian HuaYi Technology Co.		Tracer gas

Chapter 4: HOUSEHOLD COOKING ENERGY

4.1 Families in China: Household Energy

Introduction

Household energy used in Chinese families has been under detailed study for many years. Different publications depict sometimes quite different scenarios and findings. This conflict in the findings has been discussed in the literature review section of this work. The differences between the published data can be for the many reasons given below.

1. The advance of Chinese people's living standards has seen a fast growth in recent years. According to published statistics (National Bureau of Statistics of the People's Republic of China, 2014), from 2000 to 2013, the average annual income of an urban Chinese family increased from 6,280 to 26,955 RMB, while the average annual expenditure of an urban Chinese family increased from 4,998 to 18,023 RMB. The expenditure on home appliances per year increased from 375 to 1,208 RMB. This dramatic change has affected residents' energy consumption patterns a great deal and contributed to differences in the published data.

2. The climate's influence on building energy consumption was discussed in the literature review. Climate determines the amount of solar radiation and outside temperature to which a building is exposed; it also influences the amount of energy that is used for the heating and cooling of a building, and the amount of energy used for lighting (Haase, Amato, & Heiselberg, 2014). China has five climate zones: severe cold, cold, hot summer cold winter (HSCW), hot summer warm winter (HSWW) and temperate (Ministry of Construction, 2005a). The zoning is based on the

monthly average temperatures of the coldest and hottest months of the year (January and July, respectively), and the number of days on which the daily average temperature is below 5 °C and above 25 °C. Building energy consumption in the different climates varies in different ways. For example, regions below the Long River do not have heating systems and the year-round household energy consumption is low.

3. Building codes have tightened up building energy efficiency requirements since the 1980s. In 1986, the Ministry of Construction published the National Design Standard for Energy Efficiency of Residential Buildings (China Academy of Building Science, 1986). The standard required building thermal performance and mechanical design to reduce the physical building energy consumption by 30% compared with the 1981-1982 residential building energy consumption. In 1995, this standard was revised, requiring further reduction of building energy to 50% (China Academy of Building Science, 1995). In 2001 and 2003, two sub-climate design codes were published that followed the national standard: one was the Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone in 2001 (China Academy of Building Science & Chonngqing University, 2001); the other was the Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Warm Winter Zone in 2003 (China Academy of Building Science & GuangDong Province Academy of Building Science, 2003). These two climate zone standards were revised in 2010 (China Academy of Building Science, 2010) and 2012 (China Academy of Building Science & GuangDong Province Academy of Building Science, 2012), respectively. These standards affected building heating and cooling energy consumption in winter and summer all around China. Thus, building design and built dates vary in energy consumption because of the different building codes applied at the time.

4. Research methodology on building energy consumption applied in current Chinese industry can be classified into energy audits, energy modelling, energy measurement and surveys. Energy auditing is used to understand building operational energy use. The process can be from simple utility use and cost checking, walk-through investigations, to detailed audits of building facilities (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2004). In 2007, China published its own technical guidelines for energy audits (Long, Bai, & Ma, 2007). Energy measurement uses a meter or sub-meter to measure the energy use of a building or specific systems or equipment (US Department of Energy, 2002). The measurement method is defined by the International Performance Measurement and Verification Protocol (IPMVP). In many published papers, energy modelling is also used to depict building energy use. The argument for this method is the accuracy of the modelling. However, in the previously mentioned IPMVP, energy computer simulation, e.g., DOE-2, is classified as one of the acceptable energy measurement and verification methods. When it is used for new buildings, the model needs to be calibrated to the actual performance of the energy systems and an actual operational timetable. Energy surveys usually use trained interviewers to collect energy characteristics regarding housing unit, usage patterns, and household demographics. This information is combined with data from energy suppliers, such as the electric power bills for these homes, to estimate energy costs and usage for heating, cooling, appliances and other end uses. An energy survey can reach a large number of audience group in one round.

5. The use of passive design and renewable energy has affected building energy consumption a great deal since the promotion of green building nationwide in 2006. Passive design applies natural ventilation and

daylighting and adjusts building orientation with improved building envelope thermal performance and airtightness in order to reduce building energy consumption. The savings can vary from 10% to 20% (Hebei Academy of Building Science & CSTC, 2013). Renewable energy, especially solar hot water, is now widely used in solar-resource-rich provinces, such as Shandong Province, and coastal cities.

In view of the above parameters affecting building energy data, some important information needs to be recorded before energy data are collected. The information includes:

- The location of the building, particularly the climate zone in China.
- The completion date of the building and the energy efficiency code applied in that year.
- The date of the data collection due to changes in living standards.
- The methodology applied in the data collection.

In this research, energy measurement was selected as the methodology. The IPMVP was, therefore, used as the measurement protocol. In the IPMVP, four measurement options are recommended, as shown in Table 4-1 (IPMVP New Construction Subcommittee, 2006). Two options are for individual equipment measurement and the other two are for whole building energy measurement using metering or simulation.

Table 4-1: Measurement and verification options (Source: IPMVP Vol. III Part I)

M&V Option	How Baseline is Determined	Typical Applications
A. Partially Measured ECM Isolation Savings are determined by partial measurement of the energy use of the system(s) to which an ECM was applied, separate from the energy use of the rest of the facility. Some parameters are stipulated rather than measured.	Projected baseline energy use is determined by calculating the hypothetical energy performance of the baseline system under operating conditions during the M&V period.	Lighting system where power draw is periodically measured. Operating hours are stipulated.
B. ECM Isolation Savings are determined by full measurement of the energy use and operating parameters of the system(s) to which an ECM was applied, separate from the rest of the facility.	Projected baseline energy use is determined by calculating the hypothetical energy performance of the baseline system under measured operating conditions during the M&V period.	Variable speed control of a fan motor. Electricity use is measured on a continuous basis throughout the M&V period.
C. Whole Building Comparison Savings are determined at the whole-building level by measuring energy use at main meters or with aggregated sub-meters.	Projected baseline energy use determined by measuring the whole-building energy use of similar buildings without the ECMs.	New buildings with energy-efficient features are added to a commercial park consisting of buildings of similar type and occupancy.
D. Whole-Building Calibrated Simulation Savings are determined at the whole-building level by measuring energy use at main meters or sub-meters, or using whole-building simulation calibrated to measured energy use data.	Projected baseline energy use is determined by energy simulation of the Baseline under the operating conditions of the M&V period.	Savings determination for the purposes of a new building Performance Contract, with the local energy code defining the baseline.

Option B: ECM Isolation was chosen for this research. This option was the most effective to apply to the conditions as the parameters affecting energy use are not complex or excessively difficult or expensive to monitor.

Experiment Set-Up

Two test houses were selected for the experiment. One was built in 2003 with a construction area of 88 m^2. It is on the third floor of a six-storey multi-rise residential building. The unit comprises two bedrooms, one kitchen, one dining/guest room and one toilet. The floor layout is shown in Figure 4-1.

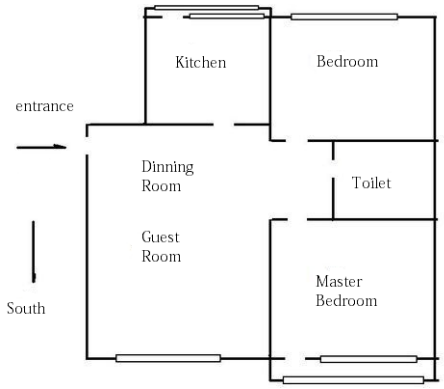


Figure 4-1: Unit layout of the test family – retired couple

An elderly retired couple in their 70s live in the unit. Their son and his family visit them at intervals of once every one or two weeks. The testing and data collection ran from November 2012 to December 2013.

The other selected building was built in 2011, with a construction area of 89 m^2. It is on the sixth floor of a six-storey multi-rise residential building. The unit comprises three bedrooms, one kitchen, one dining/guest room and one toilet. The floor layout is shown in Figure 4-2.

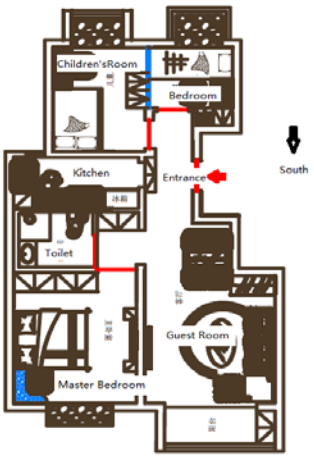


Figure 4-2: Unit layout of the test family – young couple

A young couple in their 30s live in the unit. Their young daughter (aged six) and her grandmother live with them in the unit. The testing and data collection ran from September 2012 to December 2012.

In order to collect the daily energy use for the two families, power plug-in meters were installed in every power socket. These meters measure and record the watt consumption of each plug-in home appliance. Power meter data were recorded every day manually on a form. The data were classified into several categories. The categories and associated electric home appliances are listed below.

For the retired couple:

- Air conditioning: there are two air conditioners installed in the unit: one is in the bedroom, the other is in the dining/guest room.
- Hot water: there is one electric water heater installed in the toilet for showering and hand washing.
- Entertainment: entertainment equipment includes a computer, VCD player, cable television, radio and hi-fi audio devices.
- In the bedrooms, there are lamps and a ceiling light tube.
- In the guestroom, there are lamps and ceiling light tubes.
- In the toilet, there is one light tube.
- In the kitchen, there are a ceiling light tube, a food preparation area task light, a kitchen hot water heater for dish washing, and home electric cooking appliances, including an electric rice cooker, an electric soya milk maker, an electric bread toaster, an electric micro-oven, and an electric pressurized cooker.

An excerpt from the manual family daily energy use recording form for the retired couple is listed in Form 4-1.

Form 4-1: Family accumulative daily energy use recording form for the retired couple (at 12 Dec. 2011)

Home appliances		Mon	Tue	Wed	Thu	Fri	Sat	Sun
Computer kWh	Computer	0.41	0.51	0.51	0.51	0.51	0.51	0.51
	Router							
Enter-tainment kWh	TV 1 Bedroom	34.45	34.62	35.14	35.94	36.42	37.58	38.07
	STB 1							
	DVD							
	TV 2 Guest room	36	36.4	37.11	37.35	37.8	38.83	39.28
	STB 2							
Freezer kWh		30.87	31.06	31.72	32.53	33	33.44	33.99
Hot water kWh	Kitchen heater	74.14	75.43	77.83	78.51	80.7	83.34	84.61
	Bathroom heater	44.67	44.67	50.65	51.02	51.02	51.02	51.02
Washing machine kWh		3.9	3.9	3.9	3.9	4.19	4.28	4.28
Air conditioner	AC 1							
	AC 2							
Cooking kWh	Fume exhaust fan	7.12	7.19	7.28	7.33	7.46	7.63	7.71
	Micro-oven	1.11	1.11	1.17	1.22	1.29	1.29	1.35
	Electric rice cooker	10.69	10.69	10.97	11.14	11.66	12.12	12.29
	Electric pressurized cooker							
	Soya milk maker	3.74	3.74	3.74	3.74	3.74	3.74	3.74
	Fruit juice maker							
Other plug-in load (kWh)								
Lighting (kWh)		4.27	4.38	4.65	4.79	4.93	5.2	5.38
Water (m^3)								801
Space heating kWh		1060.2	1074.1	1121.5	1160.6	1206.9	1256.3	1303.8
Gas (m^3)		1813.6	1814	1814.4	1814.7	1815.3	1816.6	1817.1

In the form above, space heating data were taken from the heating energy (calories) meter installed in the heating pipe shaft. Gas meter and water meter readings were also recorded. Gas is mainly for cooking. The family's hot water is heated by an electric water heater.

To relate energy use with cooking method, another form (see Form 4-2 below) was used to record the daily food menu of the test family. The form was completed daily by the test family. Food type, cooking time, cooking method and cooking utensils were all recorded. The information in this form, together with that in the energy use form, was combined for cooking energy analysis.

Form 4-2: Family daily food type, cooking method, cooking utensils and time form for the retired couple (the week of 12 Dec. 2011)

		Mon			Tue			Wed			Thu			Fri			Sat			Sun		
Meal		**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**
Staple food (number of people)	Rice		2			2						2			2			2				
	Steamed buns	2		2	2		2	2			2			2		2	2		2	2		2
	Noodles						1		2													
	Dumpling/Pancake									2			2								2	
	Porridge	2		2	2		1	2		2	2		2	2		2	2		2	2		2
	Soya milk																					
	Bread																					
	Chinese medicine			1			1						1			1			1			1
	Hot water	2		2	2			2			2			2			2			2		

		Mon			Tue			Wed			Thu			Fri			Sat			Sun		
Meal		**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**
Cooking method	Sweating																					
	Stir frying		v				v		v	v		v			v	v		v	v			v
	Steaming			v			v									v			v			v
	Boiling	v	v	v	v	v	v	v	v		v	v	v	v	v	v	v	v	v	v	v	v
	Stewing																					
	Frying									v			v									
	Roasting	v			v			v			v			v			v			v		
	Deep frying																					
	Soya milk maker																					

			Mon			Tue			Wed			Thu			Fri			Sat			Sun		
Meal			**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**
Cooking utensil and time (min.)	Iron pan							5			5		15	10					10	15			8
	Frying pan	Stainless pans	6	16		6			6	10	10	6			6	10	10	6			6		
	Steamer				20			15									15			10			8
	Boiler		8		10	8	20	8	8	8		8	8	15	8		10	8			10	15	10
	Kettle		15			15			15			15			15			15			15		
	Pressure cooker																						
	Electric pressure cooker				45						45			40			40			40			40
	Electric rice cooker			20			20									20			20				
	Soya milk maker																						
	Electric toaster																						
	Micro-oven																						
	Others																						

The young couple completed a similar form in the study and similar information was collected. It is not repeated here.

Data and Analysis

Household energy data acquired in the experiment from both the retired couple and the young couple are listed in the tables below. In Form 4-3, the data were recorded from 21 November 2011 to 21 November 2012. The power consumption of the computer, entertainment (television), freezer, household hot water, washing machine, air conditioner and electrical cooking facilities were measured using plug-in power meters. Lighting power consumption was read from the home power meter panel since the lighting power is supplied by separate power lines in the home and measured using a dedicated power meter in the panel. The other plug-in load was the number calculated by subtracting the measured plug-in power consumption from the consumption measured by the home power meter. Space heating energy consumption was measured by a direct reading from a heating energy (calorie) meter installed on the heating pipe which shows kWh. Home gas is for cooking only. In Beijing, cooking gas is natural gas from the oil field. The energy calorific value for Beijing natural gas is 1 m^3 natural gas = 9.86 kWh (National Development & Reform Commission, 2008). Form 4-3 summarizes the year-round energy use of the retired couple. Figure 4-3 is a pie chart showing the percentage of sub-categories of household energy use listed in Form 4-4. The sub-categories are in line with the mainstream classification method in China and internationally, thus comparison can be carried out at a later stage.

Form 4-3: Household whole-year energy use for the retired couple (from 21 Nov. 2011 to 21 Nov. 2012)

WHOLE YEAR HOUSEHOLD ENERGY USE		
Computer kWh	Computer	7.7
	Router	
Entertainment kWh	TV 1 Bedroom	231.42
	STB 1	
	DVD	
	TV 2 Guest room	275.06
	STB 2	
Freezer kWh	Freezer	249.32
Hot water kWh	Kitchen heater	431.6
	Bathroom heater	381.06
Washing machine kWh	Washing machine	24.49
Air conditioner kWh	AC 1	28.62
	AC 2	0
Elect. cooking kWh	Fume exhaust fan	54.44
	Micro-oven	4.45
	Electric rice cooker	116.98
	Elec pressurized cooker	
	Soya milk maker	16.01
	Fruit juice maker	
Other plug-in load Kwh	Other plug-in load	300.35
Lighting Kwh	Lighting	50.5
Home power meter kWh	Home power meter	2,172
Water m^3		84.95
Space heating kWh		5,815.9
* Gas m^3		220.1

*1 m^3 natural gas = 9.86 kWh

Form 4-4: Household whole-year energy use by category (from 21 Nov. 2011 to 21 Nov. 2012)

Total kWh	Space heating	Entertainment	Cooking	Hot water	Lighting	Cooling	Others
10158.12	5815.9	514.18	2362.1	812.66	50.50	28.62	574.16
115.43 /m^2*	66.09 /m^2	5.84 /m^2	26.84 /m^2	9.23 /m^2	0.57 /m^2	0.46 /m^2	6.38 /m^2

- Construction area: 88 m^2 (elderly couple)

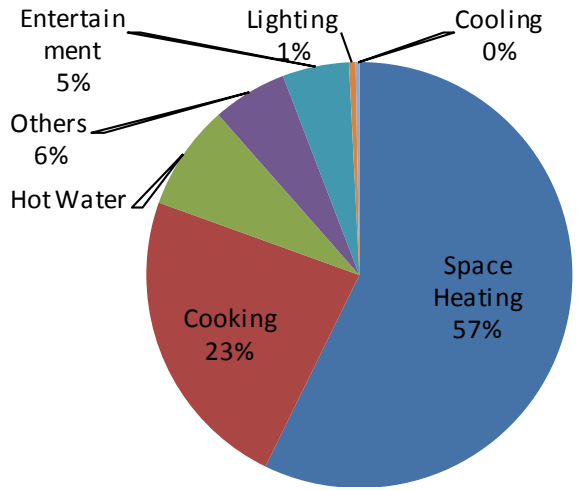


Figure 4-3: Household whole-year energy use by category (from 21 Nov. 2011 to 21 Nov. 2012)

Form 4-5 shows the energy consumption summary for the young couple with a child and her grandmother from 12 September 2012 to 24 December 2012. In the young couple's family, power consumption for the computer, entertainment, freezer, washing machine, air conditioner and electrical cooking facilities were measured using plug-in power meters. Lighting power consumption was taken from the home power meter panel. The lighting power was on separate power lines in the home and measured using a dedicated meter. Other plug-in load was the number calculated by subtracting the measured plug-in power consumption from the consumption measured by the home power meter. Space heating was taken from a direct reading of the heating energy (calorie) meter installed on the heating pipe which shows kWh. Home gas is used for domestic hot water and cooking.

Form 4-6 summarizes the year-round energy use of the young couple and their family. Figure 4-4 is a pie chart showing the percentage of sub-categories of household energy use listed in Form 4-5.

Form 4-5: Household energy use for the young couple with a child and her grandmother (from 12 Sep. 2012 to 24 Dec. 2012)

HOUSEHOLD ENERGY USE	Computer kWh	Entertainment kWh	Freezer kWh	Washing machine kWh	Electric fan kWh	Air conditioner kWh	Elect. cooking kWh	Other plug-in load kWh	Lighting kWh	Home power meter kWh	Hot water (inlet 15 °C	Water m^3	Grey water m^3	Space heating kWh	* Gas m^3
	11.53	110.97	73.43	19.07	6.01	21.96	138.04	176.88	125.4	683.29	29.86	53.03	9.14	946.26	153.01

* 1 m^3 natural gas = 9.86 kWh

Form 4-6: Household energy use category for the young couple with a child and her grandmother (from 12 Sep. 2012 to 24 Dec. 2012)

Total kWh	Space heating	Entertainment	Cooking	Hot water	Lighting	Cooling	Others
3132.4	946.26	122.5	1494.6	146.31	125.4	27.97	269.38
35.2 /m2*	10.63 /m2	1.38 /m2	16.79 /m2	1.65 /m2	1.41 /m2	0.31 /m2	3.03 /m2

* Construction area: 89 m^2 (young couple w/child)

As the record for the energy consumption of the young couple was not for a complete year, heating and cooling energy are excluded from Figures 4-4 and 4-5. Regardless of whether it concerned the retired couple or the young couple and their family, cooking energy was the largest energy end user, following by hot water, entertainment and lighting. In the following section, daily energy use profiles of the various home energy end users are depicted. Preliminary findings are also reported.

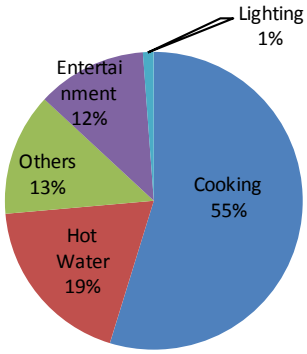


Figure 4-4: Household energy use for the retired couple without heating and cooling

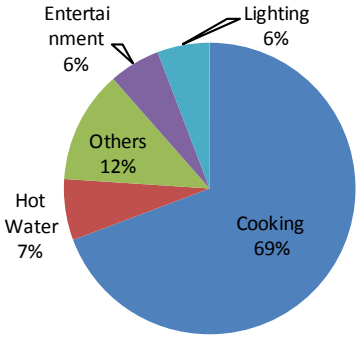


Figure 4-5: Household energy use for the young couple with child without heating and cooling

- Space Heating Energy

Space heating energy for both families was measured using a heating energy (calorie) meter installed in the heating supply and return water pipes. The energy meter measured the supply water temperature and return water temperature as well as the hot water flow in the pipeline. Heating energy was then calculated using chips embedded in the energy meter and displayed on an LCD screen on the body of the meter. Radiators are installed in both families' homes.

Data for the retired couple (Figure 4-6) show that the space heating energy use profile varied in the winter. Daily energy consumption was comparatively low at the beginning of the winter and increased as the

weather turned colder. Daily energy consumption decreased again as the temperature rose in spring.

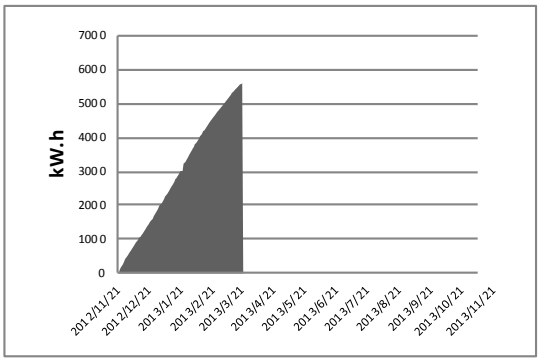


Figure 4-6: Accumulative Space heating profile of the retired couple (21 Nov. 2012 to 21 Nov. 2013)

Snapshots of the space heating energy consumption of both the retired couple and the young couple during the same period (from 14 to 23 December 2012) are presented in Figures 4-7 and 4-8, respectively. From the slope difference of the two profiles, we can conclude that the daily space heating energy for the young couple and their family is higher than that for the retired couple. There is not much difference in the construction floor area for the two families. The retired couple have a construction floor area of 88 m^2, while the young couple and their family have 89 m^2. Both units have south-facing and north-facing external walls. The largest difference is that the young couple and their family are on the top floor of a six-storey building, while the retired couple are on the third floor of a six-storey building. Heat loss through the roof requires extra energy for the young couple and their family to keep the unit warm and in an acceptable temperature zone.

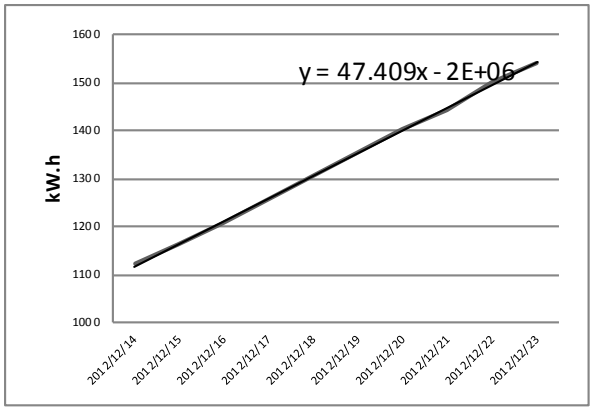


Figure 4-7: Space heating for the retired couple (from 14 to 23 Dec. 2012)

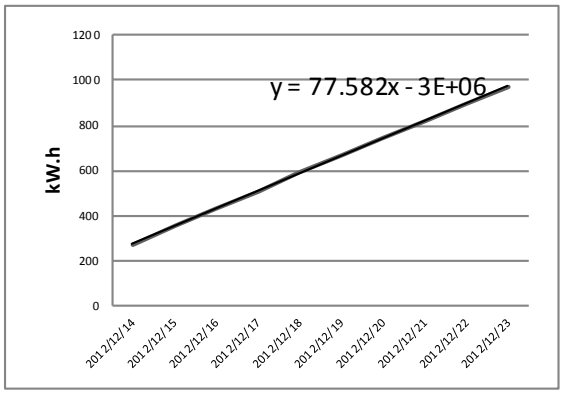


Figure 4-8: Space heating for the young couple w/child and her grandmother (from 14 to 23 Dec. 2012)

- Cooking Energy

As shown in Figure 4-9, cooking energy use in the retired couple's home shows a constant increase in a clear linear pattern during the measured year. The cooking energy use shown in the figure is made up of gas energy (dedicated to cooking use only) and the electrical power of the electrical cooking devices below:

- Micro-oven: used for reheating food
- Electric rice cooker: used for preparing rice
- Electric pressurized cooker: for making pork bone soup, softening beef

- Electric soya milk maker: for preparing breakfast
- Fruit juice maker: for preparing the afternoon tea break
- Cooking fume exhaust fan: turned on when frying or deep frying food

Common sense in China is that cooking energy rises during traditional long Chinese holidays, such as the Spring Festival (normally in early February), the National Holiday (1 October) and Chinese New Year. In these holidays, people prepare more food for celebration parties and family gatherings than they do the rest of the year. However, the retired couple's cooking energy use (figure 4-9) does not endorse this conclusion. The cooking energy trend line moves smoothly upwards with a constant ratio. This led the researcher to do more cooking energy recording in the different families to test this assumption. In a conversation with the retired couple, it was found that on traditional Chinese holidays, because of rising living standards, there is a trend to eat out more often in restaurants for parties and family gatherings. Restaurants provide more space and a greater diversity of food for family celebrations than eating at home. Thus, cooking energy does not increase in recent years as it had traditionally during these holidays.

Cooking energy for the young couple with a child and her grandmother shows a similar linear pattern to that for the retired couple (see Figure 4-10). However, the line climbs faster than that for the retired couple. The cooking energy use shown in the figure is made up of cooking gas energy and the power for the electrical cooking devices below:

- Micro-oven: used for reheating food
- Electric rice cooker: used for preparing rice
- Electric pressurized cooker: used for making pork bone soup, softening beef
- Electric stewing cooker: used for preparing soup

- Water purifier: used for purifying tap water
- Electric magnetic cooking pad: used for stir frying food
- Cooking fume exhaust fan: turned on when frying or deep frying food

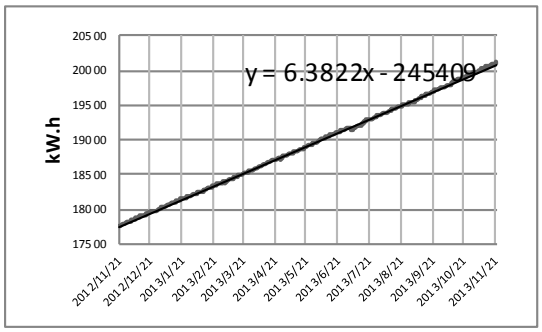


Figure 4-9: Cooking energy for the retired couple

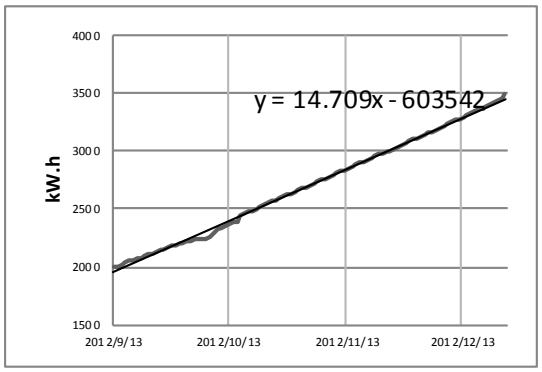


Figure 4-10: Cooking energy for the young couple w/child and her grandmother

- Hot Water Energy

Figure 4-11 shows the trend line for the hot water used by the retired couple. The hot water is for bathroom and kitchen use. It is understood that hot water energy use is high in the cold season and low in the hot season. Thus, the trend line has a sharp increase in winter and a slow increase in summer. The trend line shows a linear pattern in each sector.

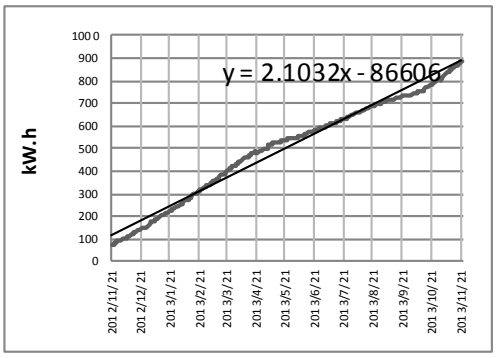


Figure 4-11: Hot water use for the retired couple

Figure 4-12 shows the trend line for the young couple with a child and her grandmother. Similar to the retired couple, the young couple's family trend line has two different slopes: one is a flat slope before October, the other is a sharp slope after October when the outdoor temperature becomes colder. The hot water for this family is for bathroom, shower and kitchen use.

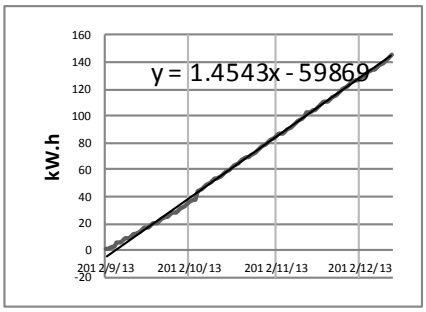


Figure 4-12: Hot water use for the young couple w/child and her grandmother

When we look at the slope of the hot water energy trend lines of the two families, we find that the retired couple used more hot water daily than the young couple, although the young couple and their family had double the number of family members. Detailed study was conducted to try to find the reasons behind these trend lines. Figures 4-13 and 4-14 show the partial energy use from 18 October to 18 November 2012 for the two families. In these two trend lines and in the site data collection, the following was found.

- First, the retired couple use an electric storage water heater for both the

bathroom and kitchen basins, while the young couple and their family use an instant gas water heater for both the bathroom and kitchen basins. Originally, the researcher assumed that the electric storage water heater in the bathroom had a high standby electrical power consumption, since it needs to maintain the water cylinder's temperature even when the water heater is not in use. However, the power consumption of the bathroom water heater shows that this is not the case. The retired couple's bathroom electric storage water heater does not have standby power consumption. This is because they turn off the water heater after each shower.

- Second, the researcher found that the kitchen basin water heater in the retired couple's home consumed more power than the bathroom water heater. After checking further with the retired couple, the researcher found that they cooked more often than the young couple and their family, and thus they also washed dishes and vegetables more often. Each time they washed dishes and vegetables they used hot water, since their skin is more sensitive to cold water than that of the young couple. Further, the kitchen electric water heater is a storage type. The retired couple did not turn off the kitchen electric water heater after each use. Thus, the standby energy consumption is needed for maintaining the required supply water temperature in the water cylinder.

- Third, for the young couple's family, the hot water energy trend line does not have a clear stepped increase because the young family members take showers more frequently than the elderly couple. This is because there are more people in the young couple's family: parents, a child and a grandmother. Thus, showers are taken on a daily basis. Since the kitchen hot water and bathroom hot water are all supplied by an instant gas water heater, there is no standby power consumption, as with the retired couple. The daily hot water energy consumption is less than that

for the retired couple.

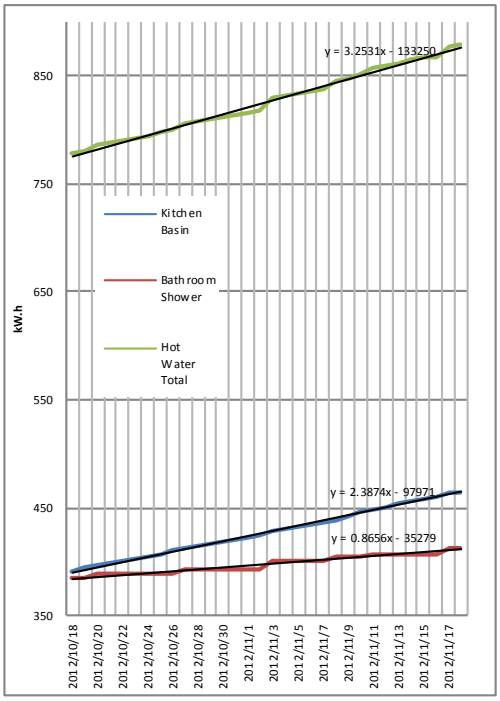


Figure 4-13: Hot water use for the retired couple (from 18 Oct. to 18 Nov. 2012)

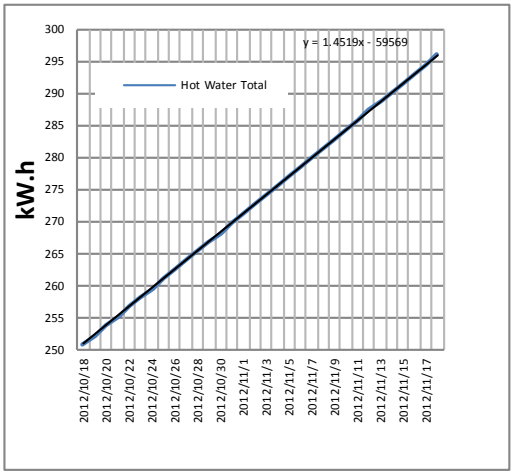


Figure 4-14: Hot water use for the young couple w/child and her grandmother (from 18 Oct. to 18 Nov. 2012)

- Entertainment Energy

Figures 4-15 and 4-16 show the entertainment power use for the retired

couple and the young couple's family, respectively. The figures show that the retired couple use more power for entertainment than the young couple. This is because the retired couple stay at home more than the young couple. The retired couple also watch television and listen to the Hi-Fi more often.

In the experiment, entertainment devices in the retired couple's home include televisions (two sets), a Hi-Fi and a computer. For the young couple and their family, entertainment devices include a television, computers (two sets), an electric piano for the child and a Hi-Fi. Looking at the details of the two trend lines, they show that in the summer (shorter night-time), daily entertainment energy use is less than in the winter (longer night-time). It is likely that, in summer, the occupants watch less television than they do in winter. The trend line in Figure 4-17 clearly shows that daily television power consumption is low in summer and high in winter for the retired couple. The trend line slope in Figure 4-17 shows that the retired couple's daily television energy use is higher than for the young couple and their family (Figure 4-18), which suggests that the retired couple watch television more often. The difference is almost as much as double.

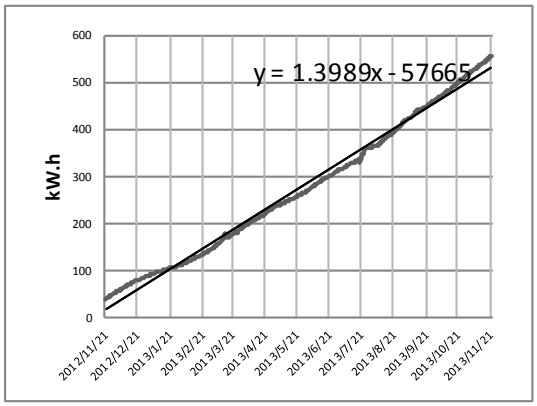


Figure 4-15: Entertainment for the retired couple

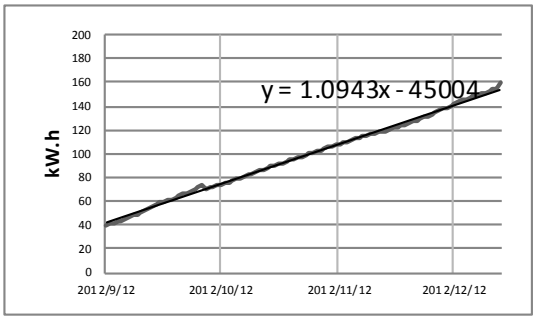


Figure 4-16: Entertainment for the young couple w/child and her grandmother

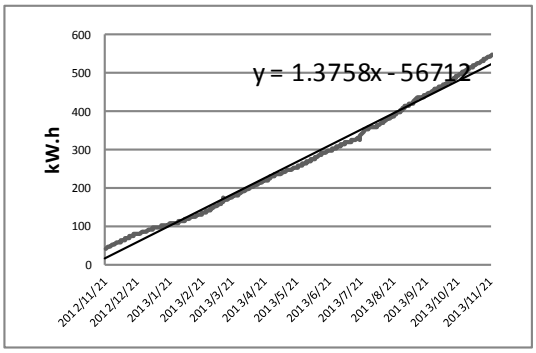


Figure 4-17: TV power consumption for the retired couple

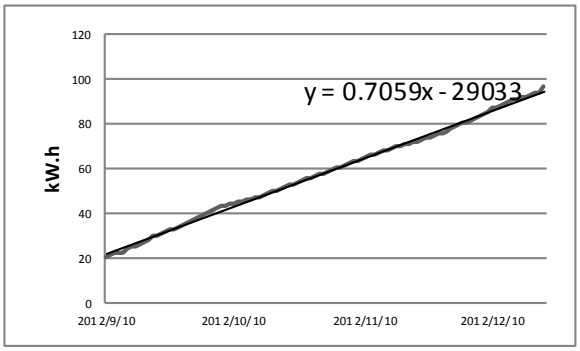


Figure 4-18: TV power consumption for the young couple w/child and her grandmother

- Lighting Energy

Figures 4-19 and 4-20 show the lighting power use for the retired couple and the young couple's family, respectively. The figures show that lighting power also has a seasonal character, as do the television and hot water power consumption. Daily lighting power use is high in winter and low in summer because of the longer and shorter night-times, respectively. The figures also show that the young couple's family uses much more daily

lighting power than the retired couple. An interview disclosed that once the young couple is at home, they turn on all the lights in the home. This is partially because of personal preference, partially because their child is afraid of the dark.

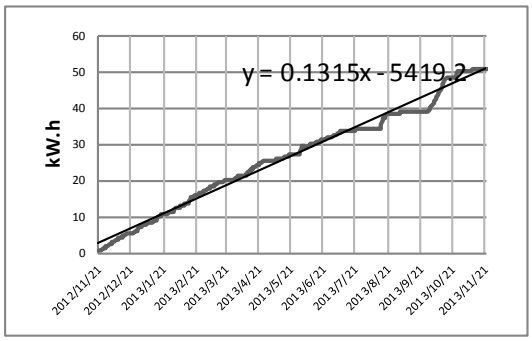


Figure 4-19: Lighting for the retired couple

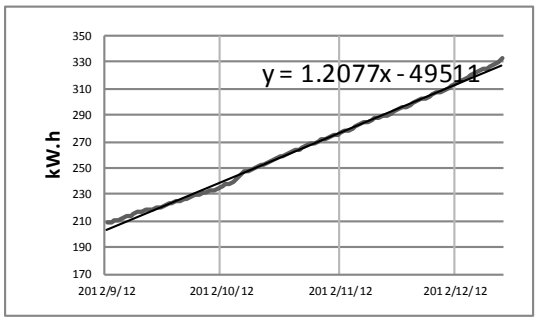


Figure 4-20: Lighting for the young couple w/child and her grandmother

- Total Household Energy

The following figures illustrate the energy use for both the retired couple and the young couple's family.

Total electric power consumption for the retired couple shows a linear pattern (Figure 4-21). However, the slope of the line changes along the year. This is because of the seasonal energy consumption by some home appliances, particularly electric water heaters, lighting and entertainment equipment such as televisions, consumes more energy in winter than in summer. These home appliances also consume a larger proportion of the electric power in the overall household energy consumption (Figure 4-5).

The young couple and their family used fewer entertainment devices, especially televisions, than the retired couple. They also used an instant gas water heater. Therefore, the total electric power curve (Figure 4-22) does not show seasonal changes, unlike that for the retired couple.

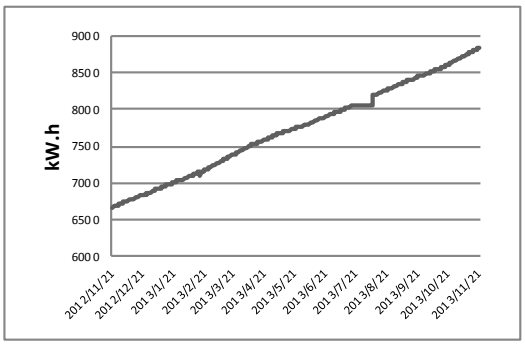


Figure 4-21: Total electrical power consumption for the retired couple

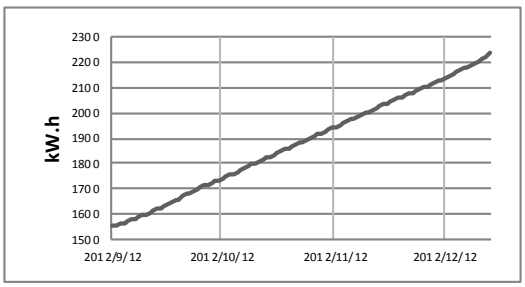


Figure 4-22: Total electrical power consumption for the young couple w/child and her grandmother

Total gas consumption for the retired couple shows a linear pattern (Figure 4-23). It does not show any seasonal changes. The gas is used only for cooking purposes. This illustrates that daily cooking energy consumption is constant in this family.

Gas consumption for the young couple and their family is for cooking and hot water, since they use an instant gas water heater. The slope of the line is flat in late autumn and becomes slightly steeper in winter. This reflects the family's need for more energy for bathroom shower hot water in the cold season.

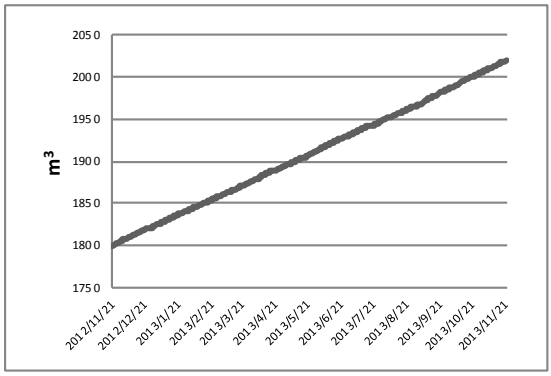


Figure 4-23: Total gas consumption for the retired couple

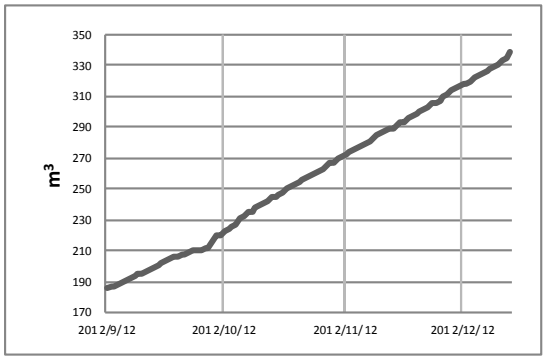


Figure 4-24: Total gas consumption for the young couple w/child and her grandmother

Total household energy for the retired couple is dominated by the space heating energy curve. This is because space heating energy is the largest energy end user in the household (Figure 4-25).

Total household energy for the young couple and their family is dominated by space heating and gas use. The gas use is for cooking and hot water, which rank the second- and third-highest energy end users in this family (Figure 4-26).

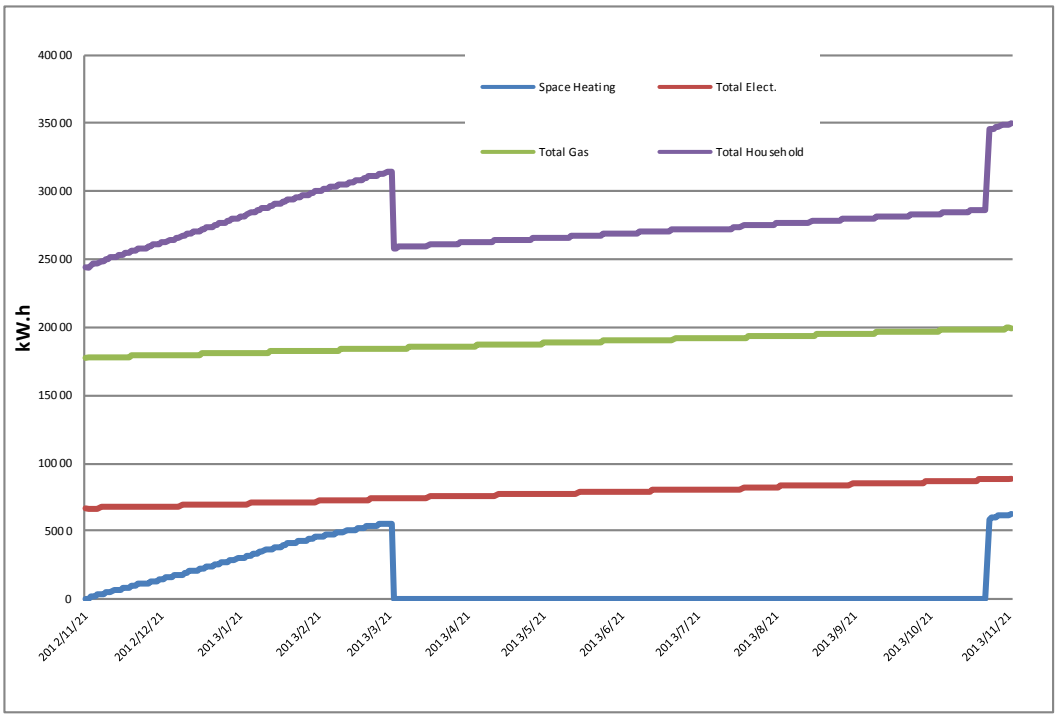


Figure 4-25: Total household energy consumption for the retired couple

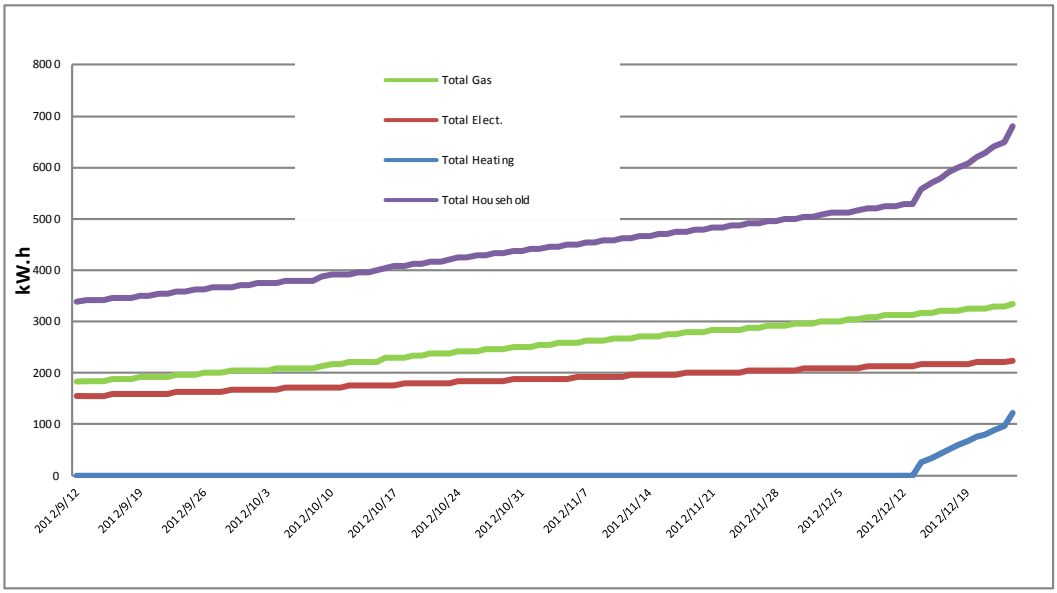


Figure 4-26: Total household energy consumption for the young couple w/child and her grandmother

Findings

The experiment for the two test families (the retired couple and the young couple and their family) revealed the following information, which either

reinforces existing findings or adds new knowledge to the current knowledge base.

- Space heating is the largest energy end user in northern China's residential buildings.
- Cooking is the largest energy end user in residential buildings if we exclude space heating.
- Hot water is the second-largest energy end user in residential buildings excluding space heating.
- Entertainment energy consumption takes a significantly large amount in residential buildings.
- Cooking, hot water and entertainment energy consumption are very different in different families, e.g., the retired couple and the young couple and their family.
- Hot water, lighting and entertainment energy consumption show a seasonal character i.e., daily consumption is low in summer and high in winter. This is because of the colder weather in winter (demanding more energy to heat water) and a longer night-time in winter (longer indoor entertainment time in the evening).
- Daily cooking energy consumption in a given family is almost fixed, although the difference between the families is large. This is discussed in a later section of this chapter.
- Electric storage water heater standby power is significantly large. Sometimes, it is greater than the energy used to warm up useable hot water. Instant water heaters are recommended in residential buildings because there is no standby energy.
- The retired couple showed much higher television energy consumption than the young couple and their family (Figure 4-27).

- Lighting energy has a clear seasonal character. The retired couple used less lighting energy than the young couple and their family.

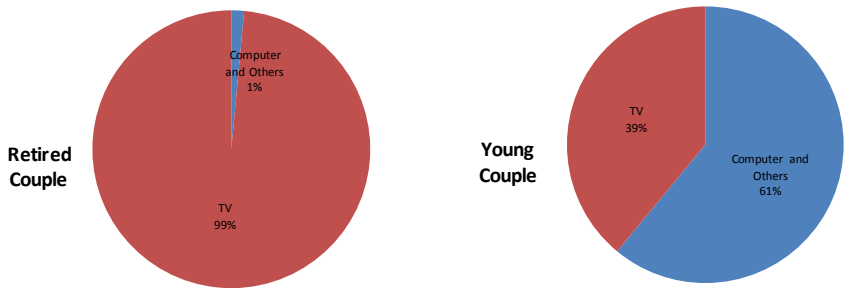


Figure 4-27: TV and other entertainment devices' power consumption percentage comparison

The character of the differences in cooking energy is discussed in more detail in the following section.

4.2 Chinese Household Cooking Energy

Introduction

The study of Chinese household energy has revealed that cooking energy is ranked as the second-largest category of energy consumption for a family in China. The level of consumption has the following characteristics, which require further exploration.

- Cooking energy is different from family to family. Further study needs to discover the underlying reasons for this difference.
- Cooking energy in a given family follows a linear pattern i.e., daily cooking energy consumption is at a constant rate. Further study needs to identify the underlying reasons for this.
- Cooking energy is indifferent to seasons. The daily cooking energy consumption is at a constant rate.
- Cooking energy is one of the largest household energy end users. Further study needs to identify strategies to reduce this.

Data Collection

In the experiment, in addition to measuring daily household cooking energy consumption, family daily food type, cooking method and cooking utensil data were also recorded. Form 4-7 shows the data for the retired couple who took part in the experiment.

The data were collected from 28 November 2011 to 28 January 2013. The staple foods for breakfast, lunch and dinner were recorded and included the following:

- Rice: steamed or boiled rice is one of the most common staple foods in a Chinese family for lunch and dinner.
- Steamed buns: steamed buns are another of the most common staple foods in a Chinese family for breakfast, lunch and dinner, especially in northern China.
- Noodles: boiled noodles are a common staple food in a Chinese family for breakfast, lunch and dinner.
- Dumplings: boiled dumplings are a common staple food for a Chinese family.
- Pancakes: baked pancakes are a common staple food for a Chinese family.
- Porridge: boiled porridge is one of the most common staple foods for breakfast in China.
- Soya milk: occasionally, the retired couple had soya milk instead of porridge for breakfast.
- Bread: occasionally, the retired couple took bread instead of steamed buns for breakfast.
- Chinese medicine: the retired couple took Chinese medicine almost

every morning.

- Hot water: hot water is another very energy-consuming drink item in the record list.

The number of people served was also recorded. For example, at breakfast, the family might have two servings of porridge, two servings of steamed buns, and two servings of hot drinking water.

Cooking methods were also recorded on the form. These records indicate the way staple foods and other dishes were prepared. Cooking methods included deep frying, roasting, frying, stewing, boiling, steaming and stir frying.

Cooking utensils and cooking times (in minutes) were also recorded on the form. For example, on Mondays, the total cooking time for breakfast is 29 minutes. This time includes 15 minutes using the kettle to boil the hot water, 8 minutes using a saucepan to prepare the porridge and 6 minutes using a frying pan to cook Chinese steamed buns. The recording of food type, cooking method, utensil, and duration is a time- consuming and boring process. The following analysis will break down the daily cooking energy into details relating to food type and cooking method.

Data and Analysis

In the Cooking Energy section of this chapter, Figures 4-9 and 4-10 show that the daily cooking energy consumption for the retired couple and the young couple with a child is at a constant rate. The rate is 6.38 kWh/day and 14.7 kWh/day, respectively. It seems safe to conclude the following:

> **Conclusion 1: If the number of family members (family size) remains constant, the daily cooking energy consumption is constant.**

Conclusion 2: If the number of family members (family size) increases, the daily cooking energy consumption increases.

The researcher gained more data from another test family. The data were collected from 9 January 2015 to 8 February 2015 for a full month. Before 3 February 2015, the family members included a working couple, their 5-year-old daughter and two of the child's grandparents. After 3 February 2015, the grandparents took the young daughter to the grandparents' house. The family members in the test house were then only the young working couple. Figure 4-28 shows the change in cooking energy during this period. It was found that the daily cooking energy rate was 12.86 kWh/day before 3 February 2015 and 7.682 kWh/day after 3 February 2015.

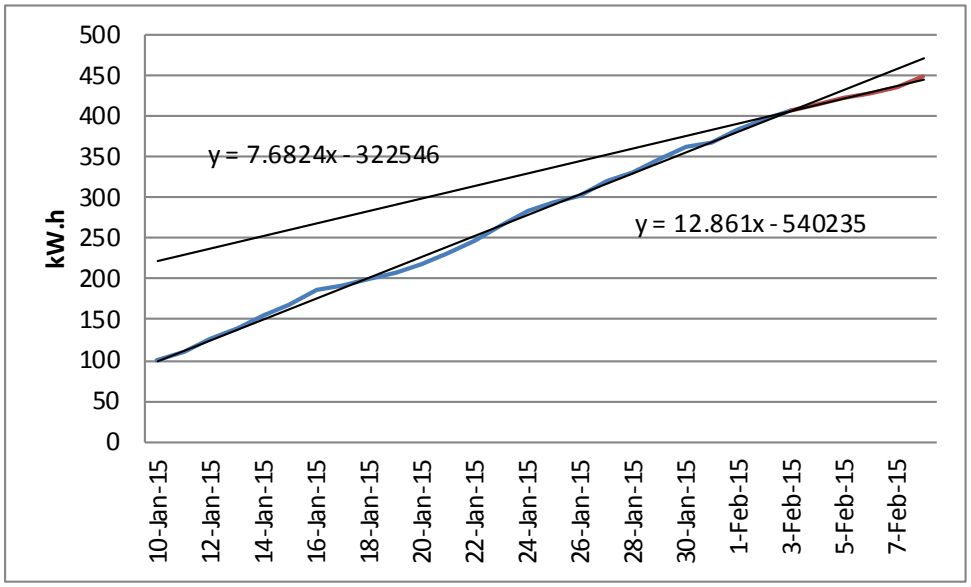


Figure 4-28: Accumulative daily cooking energy consumption with a change in family members

This change in the cooking energy daily rate raises an interesting discovery that the cooking energy daily rate not only seems to be related to the number of family members (Conclusion 2), but also relates to family structure and life cycle. Before 3 February 2015, the family was one with three generations; however, after 3 February, it was similar to a newly married couple's family. Therefore, it seems reasonable to conclude:

Conclusion 3: Family cooking energy consumption relates to family structure/life cycle.

- Family Life Cycle and Cooking Energy

Family energy use and its relation with the family life cycle is not a new topic in much of the academic research on this topic. Previous investigations have shown energy use to be related to family income (Newman & Day, 1975). However, several of the following studies have focused on additional characteristics of the household in an attempt to explain energy consumption patterns. Fritzsche (1981) suggested that the family life cycle construct could delineate more clearly the energy consumption patterns of a family unit for the following reasons. First, the income effect should be included, as income fluctuates over the family life cycle. Second, family size changes over the stages of the life cycle and the children's maturity can be incorporated into the cycle. Third, as family demands have been shown to change during the family life cycle, the demand for energy is also likely to change over the cycle. Fourth, as the family unit moves through its life cycle, the number of family ties to outside organizations, as well as the number of social and political activities engaged in by the household change. Finally, the construct is familiar to marketers and is thus easily understood. At the end of Fritzsche's research, he concluded the following. First, households in the Young Single stage of the family life cycle consumes the least amount of energy of any stage, with the exception of petrol consumption. Second, the Middle-Aged Married With Children household consumes the most total energy and the most energy of each type, with the exception of fuel oil, wood and coal. Young and Middle-Aged Singles With Children are low energy consumers with the exception of fuel oil, wood and coal, of which they tend to be relatively high consumers, along with households in the latter stages of the family life cycle. Greater amounts are spent on gas and oil for vacations by households in stages which are likely to have greater

amounts of discretionary income and thus able to afford such expenditures: Young Married Without Children and Middle-Aged Married Without Children.

Fritzsche (1981) focuses on total household energy expenditure, including the energy used for home heating, hot water, lights and appliances, and petrol. Another study, carried out by Zimmerman (1981), evaluated household demand for transportation energy across the family life cycle. Zimmerman found petrol consumption peaked during middle-life cycle stages where children were in their late teens. Once out of the workforce, household consumption declined drastically. Frey and LaBay's (1983) study on the household energy consumption across the family life cycle revealed that heating energy expenditure showed a positive linear relationship whereby higher costs were associated with elderly consumers. This is because households in the middle stages of the family life cycle, in which one might expect family size and dwelling size to peak, show conservation behaviours above the mean and heat costs very close to the mean. Early stages of the life cycle, which exhibit little interest in conservation, also seem to have low expenditures. Where the head of the household is over 65, no significant difference in seen in dwelling size compared to other childless households, but significantly higher thermostat settings are reported. This may explain the increase in heat cost.

It is obvious that family life cycle is a relevant way of explaining household energy consumption. In the above-mentioned literature, both overall household energy and sub-categories such as heating and transportation energy have a clear relation between energy use and family life cycle. In this research, Conclusion 3 contains the observation that, in Chinese family cooking circumstances, there is also an observed relation between cooking energy and family life cycle. However, one aspect that needs to be considered is the difference between the Western family life cycle and the Chinese family life cycle.

- Chinese Family Life Cycle

The family life cycle is a kind of population statistic method to study family behaviour based on income, age, members and consumption needs. Marketing and consumer behaviour researchers use the family life cycle to clarify market segments. This concept was originated in 1903 by Rowntree (1903). In 1950, the idea of the family life cycle was introduced to marketing study. It was widely used in studying family income and consumer behaviour (Wagner & Hanna, 1983). Lansing and Morgan (1955) carried out a study on housing and durable goods by clarifying the family life cycle into seven stages. Wells and Gubar (1966) further expanded Lansing and Moran's family life cycle stages into nine stages. They paved the foundation for the notion of typical family life cycle stages. All the later studies in this area are mostly based on Wells and Gubar's model. Table 4-2 shows Wells and Gubar's family life cycle and its nine stages.

Table 4-2: An overview of the family life cycle (Source: Wells & Gubar's 1966 model)

Family life cycle stages	**Bachelor stage**; young single people not living at home	**Newly married couples**; young, no children	**Full nest I**, youngest child under 6	**Full nest II**, youngest child 6 or over 6	**Full nest III**; older married couples with dependent children	**Empty nest I**; older married couples, no children living with them, head in labour force	**Empty nest II**; older married couples, no children living at home, head retired	**Solitary survivor**, in labour force	**Solitary survivor**, retired
Financial characteristics	Few financial burdens	Better off financially than they will be in the near future	Home purchasing at a peak	Financial position better	Financial position still better	Home ownership at a peak	Drastic cut in income	Income still good but likely to sell home	Drastic cut in income

Yu and Liu (2007) pointed to four key differences between the Chinese and Western family life cycles after they studied 320 Chinese families in a survey. These key findings include:

- Chinese families are larger than American families: the statistics show that, in 1996, the average number of family member in China was 3.7, while in the US this was 2.65.
- In China, the family is made up of three, four or five family members, while in the US the family is made up of one, two, or three members.
- In China, the divorce rate was 1.8 ‰, while in the US the divorce rate was 4.4 ‰ in 1996.
- In China, many families still have three generations, while in the US this kind of family is very rare.

In a summary of Yu and Liu's (2007) research, a Chinese family is generally larger than in the US and a family with three generations living together is common. Yu and Liu proposed a revised Chinese family life cycle with 10 stages. This family life cycle model covered 96.53% of Chinese families in the 2006 China population survey statistics:

- Young couple (13.56%).
- Middle-aged couple (4.73%).
- Elderly couple (1.27%).
- Couple living with parents (5.68%).
- Full nest I: young couple with a dependent child, dependent child under 6 (18.61%).
- Full nest II: young couple with a dependent child, dependent child over 6 (12.62%).

- Full nest III: middle-aged couple with a dependent child over 12 (22.71%).
- Key family I: a three-generation family, with the youngest dependent child under 6 (12.62%).
- Key family II: a three-generation family with the youngest dependent child over 6 (3.47%).
- Key family III: a three-generation family with a dependent child (4.73%).

To explore the potential relationship between family cooking energy and family life cycle, a survey was conducted in April 2016 as part of this research. The survey was designed to ask a wide variety of questions about family life cycle, gas consumption (mainly for cooking), time of eating at home, cooking utensils, food types and cooking methods. The survey was expected to collect sufficient data to enable each household to be classified by a stage in the family life cycle. Slight deviations were made in the classifications of the life cycle. First, Yu and Liu's (2007) stages in the Chinese family life cycle were adapted, along with Wells and Gubar's (1966) model. Second, since the study is on cooking energy, only the gas consumption of the families studied was collected. In the study, it was found that some families used a gas water heater for showering and hand-washing purposes. The frequency of shower-taking was recorded, since previous research revealed that home hot water use followed a linear pattern. The amount of energy consumption was small compared with cooking energy. Home hot water energy was also related to the family life cycle. It was assumed that including hot water energy in the cooking energy would not affect the conclusion of the study regarding the relationship between family life cycle and cooking energy. However, in the data analysis part, hot water gas consumption was deducted from total gas consumption.

Cooking energy trend lines for two family life cycles are shown in graph form

in order to explain the analysis details. Cooking energy for other family life cycles is summarized in Table 4-3. Figure 4-29 shows the collected gas consumption for retired couples (Elderly couple – 1.27%). Figure 4-30 shows families with two generations (Couple living with parent – 5.68%), usually, a middle-aged couple with the single parent of one of them.

From the 40 responses, the gas usage from March 2015 to February 2016 for six retired couples is plotted in Figure 4-29. The slopes of these trend lines show a strong similarity. The slopes range from 0.31 to 0.51. This confirms that families in the same family life cycle have the same cooking energy consumption.

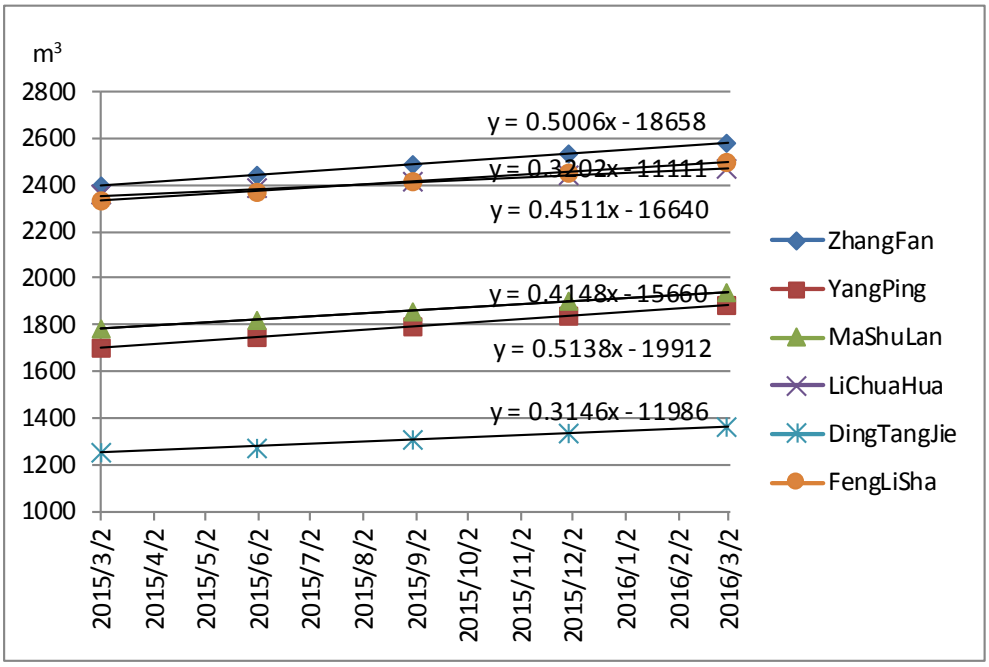


Figure 4-29: Gas use trend lines for six elderly couples

From the 40 responses, another significant group in the surveyed residential quarter was middle-aged (35~60 years old) couples living with a parent. A middle-aged couple, in employment or retired, taking care of their elderly parent, normally a solitary survivor, is not uncommon in China. Unlike the typical situation in Western countries, a Chinese solitary survivor often lives with his or her child. This is because in the current Chinese welfare system, organizations taking care of elderly people are imperfect.

Pension houses or assisted senior living houses are not sufficient in most cities. Elderly people tend to live with their son or daughter.

The gas usage of six such families from March 2015 to February 2016 is plotted in Figure 4-30. The slopes of these trend lines also show a strong similarity. The slopes range from 0.51 to 0.88. This shows the cooking energy is higher than for the elderly couple group, which indicates more frequent eating at home, larger family sizes and probably different cooking methods when catering for an elderly single parent.

Further investigation indicated that elderly single parents need softer food. This means longer cooking times, with more boiling and steaming of food. Previous research shows boiling and steaming consume more energy than baking or frying. The average gas use (m^3 per day) per head shows that middle-aged couples living with their single parent (0.6893) consume more than elderly couples (0.4192).

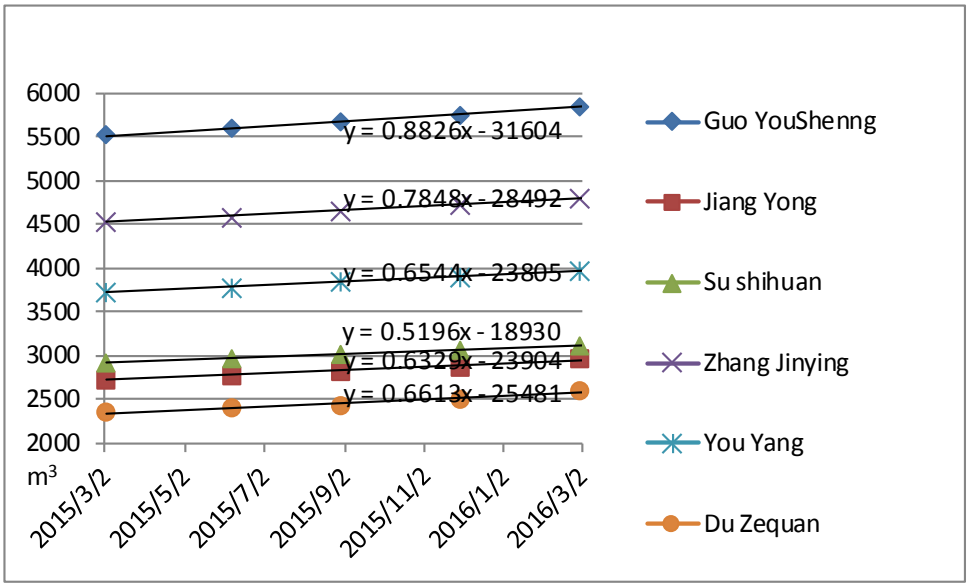


Figure 4-30: Gas use trend lines for middle-aged couples living with their single parent

Table 4-3 shows the results of the analysis of the cooking energy consumed by households in the survey sample. The table entries consist of the cooking energy use deviations from the grand mean adjusted for stages of the family

cycle. Yu and Liu's (2007) classification is used in the table.

Table 4-3: Cooking energy consumption by stage of family life cycle (Source: Yu and Liu, 2007 model)

Stage of family life cycle	Cooking energy kWh/day
Young couple, < 35 years old (13.56%)	Various
Middle-aged couple, 35~60 years old (4.73%)	5.1
Elderly couple, > 60 (1.27%)	4.13
Couple staying with parents (5.68%)	6.8
Full nest I: young couple with dependent child, dependent child under 6 (18.61%)	Various
Full nest II: young couple with dependent child, dependent child over 6 (12.62%)	Various
Full nest III: middle-aged couple with dependent child, over 12 (22.71%)	6.51
Key family I: three-generation family, with the youngest dependent child under 6 (12.62%)	12.86
Key family II: three-generation family, with the youngest dependent child over 6 (3.47%)	N.A.
Key family III: three-generation family, with dependent child (4.73%)	8.13

The data in Table 4-3 show the findings of the family cooking energy survey. There is a relation between family life cycle and home cooking energy. This relation is stronger than that for family size that most people previously assumed, i.e., home cooking energy is less related to cooking energy used per family member/headcount. The survey also revealed that, in China, Key family I, i.e., a family with three generations living together with the youngest child under 6, consumes the most cooking energy for a minimum four-person family (12.9 kW/day). Key family II, i.e., a family with three generations living together with a dependent child over 12, consumes the second-highest amount of cooking energy, for a minimum four-person family (8.13 kWh/day). The third group is that of solitary survivors living with a middle-aged couple in a three-person family (6.8 kWh/day). The fourth group is middle-aged couples with a dependent child over 12, a three-person family (6.51 kWh/day), followed by middle-aged couples (5.1

kWh/day) and elderly retired couples (4.13 kWh/day).

The survey also indicates that young couples, except those with a child under 6 years old, show great uncertainty in their daily cooking. The data vary dramatically. This is because young couples, younger than 35 years old, tend to eat out often (Jiang, He, & Wang, 2014). Even after they have children, they take their children when eating out.

- Lock-in Effect of Energy

It was observed and concluded that the daily home cooking energy for families in the same family life cycle in China seems constant. This kind of lock-in effect is not unusual in the recent energy conservation field. Carbon lock-in, which is a term often heard in the energy and climate change field, refers to the self-perpetuating inertia created by large fossil-fuel-based energy systems that inhibits public and private efforts to introduce alternative energy technologies. The concept is most used in relation to the challenge of altering the current energy infrastructure to respond to global climate change (Wikipedia, 2015b). In buildings, the lock-in problem originates from the fact that if moderate (i.e., not low enough) performance levels become the standard in new and/or retrofitted buildings, it can either be impossible or extremely uneconomic to further reduce energy consumption in such buildings for many decades to come and, in some cases, for the entire remaining lifetime of the building. In other words, if, during a refurbishment or new construction, a holistic optimization of the building envelope and technologies is not followed, the later installation of even the highest efficiency equipment or building materials will not be able to capture all the savings otherwise attainable in a comprehensive refurbishment.

In the home cooking energy survey conducted in April 2016, 40 response families showed a strong correlation between family life cycle and

household cooking energy. At a certain stage of the Chinese family life cycle, the cooking energy is constant. In other words, the data also disclose a similar lock-in effect for cooking energy. This can be defined as the inertia created by a certain reason or set of reasons that inhibit change in family cooking energy. In the survey and observation, the lock-in effect comes from the eating culture, cooking culture and lifestyle of different families in different family life cycles.

In order to understand the details of the lock-in effect for household cooking energy, especially the underlying driving forces of the lock-in effect, a further survey was conducted online in August 2016 using the WeChat survey tool So Jump. So Jump company was established in December 2005 in Shanghai in China with a focus on the development and operation of a primary questionnaire service site. So Jump is dedicated online, self-designed questionnaire software.

In two days, the survey received 162 responses from 24 provinces, including Shanghai, Beijing, Tianjin, Chongqing and Hong Kong. Most response families were singles (32.7%), singles staying with parents (24.7%), new married without children (12.96%), and new married with children under 6 years old (11.73%). The survey showed that 69.7% of the 162 response families often ate at home. The meals most often eaten at home were supper (64.81%) and breakfast (40.74%).

In the survey, it was found that 66.05% of the families had a fixed family member do the cooking. The most preferred cooking method was stir frying (54.94%). Stewing was in second place.

Household cooking energy lock-in driving factors are observed when we start to see the relation between family life cycles, culture and other factors influencing cooking behaviour.

1. The survey showed that most families keep a relatively constant

cooking menu for two key reasons: one is that it saves time because it becomes very efficient to follow the same cooking menu; the other is culture related. Culture-related factors include family taste and parents' cooking influence. There are some families who are concerned about the healthiness of their food and others who use a special menu because of allergies (Figure 4-31).

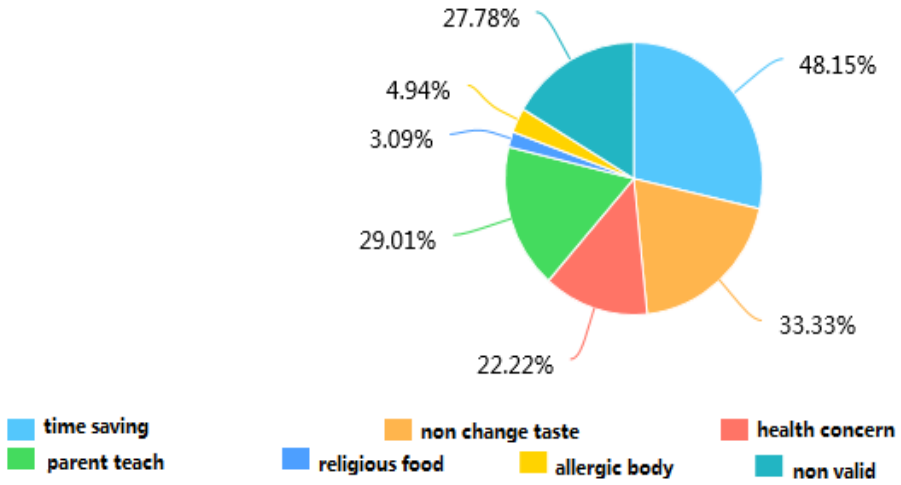


Figure 4-31: Lock-in driving factors in Chinese cooking behaviour

2. It was also found in the survey that families in different family life cycle stages have a unique constant cooking menu. Married couples without children, families with young children less than 12 years old, and three-generation families ranked time saving as the first priority in choosing a cooking menu. Single, staying with parents, parents with children and retired families reported acquired taste as the key reason for keeping an unchanged menu in these families. In reviewing these findings, time saving and culture were key factors in keeping a constant cooking pattern in families but this varied in different family life cycles (FLCs) (Figure 4-32).

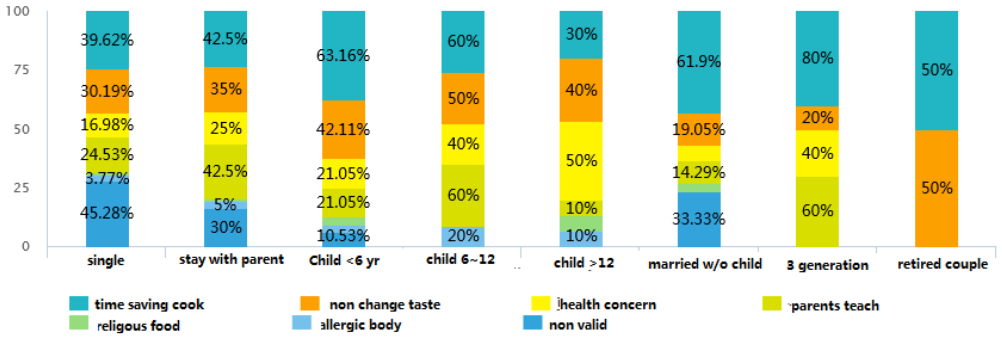


Figure 4-32: Lock-in driving factors across Chinese FLCs

3. It was reported in the survey that the most preferred cooking method in Chinese families is stir frying in all family life cycle stages. Stewing was in second place. Boiling was another preferred cooking method spreading across almost all family life cycles (Figure 4-33).

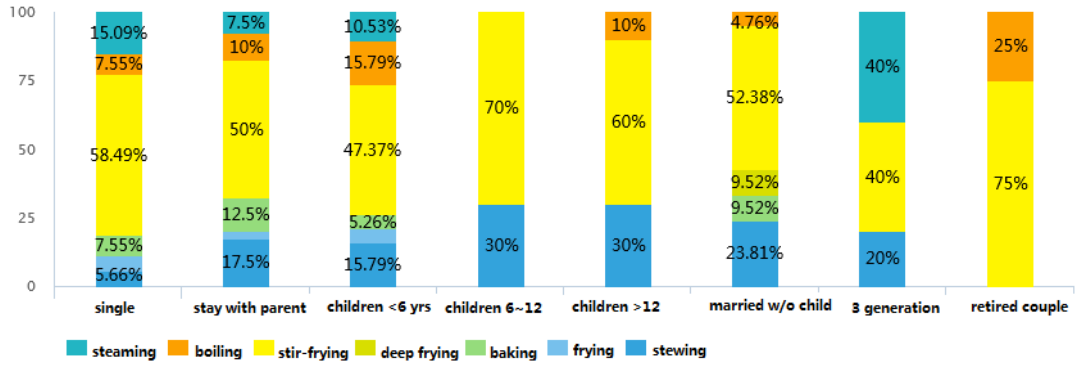


Figure 4-33: Preferred cooking methods in Chinese FLCs

In summary, the online survey reflected that there is a lock-in effect in family cooking behaviour. This lock-in effect on cooking behaviour further locks the cooking energy of these families in their respective FLCs. A summary of the underlying lock-in effect driving forces is given in Table 4-4. It seems safe to conclude that time saving in cooking, fixed taste and parents' menu are underlying reasons for the cooking lock-in effect. Stir frying, steaming and boiling are the cooking methods that consume the largest portion of

household cooking energy.

Table 4-4: Cooking patterns and methods across Chinese FLCs

Cooking method	Cooking pattern	FLC
Stir frying/steaming	Time saving/taste	Single
Stir frying/stewing	Time saving/taste	Staying w/parent
Stir frying/stewing	Time saving/ taste	Married w/children < 6
Stir frying/stewing	Time saving/parent influence	Married w/children 6-12
Stir frying/stewing	Time saving/health concerns	Married w/children > 12
Stir frying/stewing	Time saving/parent influence	Married w/o child
Stir frying/stewing	Time saving/parent influence	3 generations
Stir frying/boiling	Time saving/taste	Retired couple

Cooking Energy Use Intensity

Like other building-related energy consumption, such as space heating and cooling, cooking energy also needs to have a way to trace it.

In space heating and cooling, the most widely used way to estimate heating/cooling energy demand is to use energy intensity for a specific functional building in a certain climate zone. Energy intensiveness is simply energy demand per unit area of a building's floor plan, usually in square metres or square feet – sometimes called energy use intensity (EUI). Once the climate zone and building function are confirmed, year-round energy use can be estimated by multiplying floor area by energy intensity, which is denoted as kWh/year.m^2. Although the estimation is different from building to building because buildings have their own characteristics, such as low

energy buildings or green buildings, this method has been applied in the HVAC industry for a long time and is used in many cases.

Building EUI is a particularly useful energy performance metric for the design energy modelling and assessment of building energy performance, so it is commonly used throughout the building industry for setting energy use benchmarks and goals for codes, standards and incentive programmes, and as benchmarks for building operations (Peterson & Crowther, 2010). For example, Energy Star measures EUI to examine the national median building energy performance for various property types, and consequently set the industry benchmark and reference values. EUI is useful for comparing the performance of buildings across sizes, types, and locations.

Depending on the measurement scope, EUI can express completely different meanings. The EUI used to measure building energy consumption refers to site EUI, which only considers the amounts of electricity and fuel that are used on site. However, in order to assess life cycle energy efficiency in a building, we need to look at source EUI, which represents the total amount of raw fuel that is required to operate the building. Source EUI incorporates all transmission, delivery, and production losses (Energy Star, 2016).

EUI is also widely used by programmes such as Energy Star and the 2030 Challenge to set goals and references for different building types, from education and healthcare to retail and services. In a survey of US national median EUI conducted by Energy Star, restaurants had a source EUI of 432 kBtu/ft^2.yr (1362 kWh/m^2.yr) and a site EUI of 224 kBtu/ft^2 .yr (706 kWh/m^2.yr), while single-family residences had a source EUI of 68 kBtu/ft^2.yr (215 kWh/m^2.yr) and a site EUI of 46 kBtu/ft^2 .yr (145 kWh/m^2.yr) (Energy Star, 2014). (Please note: kBtu = British thermal units.)

EUI can be used to measure various building and space types, not just

regular offices and commercial and residential buildings. By changing the numerator and denominator, the energy use can be evaluated for certain building types more precisely. For instance, the information technology industry develops metrics for measuring data centre energy efficiency, by dividing the amount of power entering a data centre by the power used to run the computer infrastructure within it (Peterson & Crowther, 2010). This energy efficiency measurement is called power usage effectiveness (PUE).

Similar strategies can be taken to develop a metric specifically for energy use in domestic kitchens and restaurant kitchens. The key issues in proposing cooking energy use intensity (CookEUI) are the data collection, the unit and the conditions. In this research, large-scale data collection was not in the research scope. However, a framework was developed by the research. Some key questions that need to be solved in order to develop the CookEUI include:

- Should the CookEUI be measured in kWh/m^2.year or in another unit?
- In what conditions can the CookEUI be applied in order to achieve a certain level of accuracy?
- What is the best way to express CookEUI?

In the study of the retired couple's cooking energy use, the cooking energy was recorded for one year. The source of cooking energy was natural gas and electric power. The electric power for the daily use of cooking-related home appliances and gas (only used for cooking) was recorded and plotted in Figure 4-9. The trend line moves steadily upwards for the whole year and follows a linear regression. The intercept is 6.28 kWh/day. Looking at Figure 4-10 for the young couple living with their 5-year-old daughter and her grandmother, the trend line follows the same pattern with an intercept at 14.7 kWh/day. This shows an interesting discovery that the cooking energy use is relevant to family life cycle, number of family members (family size)

and the relation is linear when family life cycle and family size remain constant.

Figure 4-28 showed the change in family members (size) and its impact on cooking energy. Before 3 February 2015, the family was made up of five family members: a 5-year-old child, parents and grandparents. After 3 February 2015, the family had changed to two family members: the parents. The change in family size led to a change in daily cooking energy, from 12.86 to 7.68 kWh/day. If we allocate this changed cooking energy to household headcount, we find that 12.86/5 = 2.57 kWh/day.head and 7.68/2 = 3.84 kWh/day.

The difference between the daily cooking energy per household headcount before and after 3 February 2015 raises the need for further study. As shown in the literature review in the Data and Analysis section of this chapter, the existing knowledge points to a relation between family cooking energy and family life cycle. Before 3 February 2015, the family was in the life cycle of middle-aged couples, with children, staying with parents. This five-person family is part of 16.88% of China's families, based on Yu and Liu's (2007) study. After 3 February 2015, the family was in the life cycle of middle-aged couples, no children, living independently. This two-person family is reflected by 20.31% of China's families.

In order to confirm the provisional conclusion regarding the relation between cooking energy and family life cycle, a survey was conducted in a residential quarter, as mentioned in the Data and Analysis section of this chapter. The survey shows a strong relation between family life cycle and family cooking energy. The survey also supported the conclusion of the lock-in effect that daily family cooking energy will not change if the family life cycle does not change.

Cooking Energy and Behaviour

The large difference in cooking energy use, as shown in Table 2-2 (Household energy use comparison for China, Japan and America) in the literature review chapter, raised the interest of the researcher. In further research, very little published knowledge was found on this area in China. Some overseas papers, especially those in India, reveal that the amount of cooking energy is related to cooking behaviour and cooking equipment.

In this research, by carrying out energy measurement, an occupant behaviour study (RFID) and a survey, it was found that there was a relation between Chinese household cooking energy use, residents' behaviour and Chinese cooking techniques. The current study on cooking energy use can be classified into three categories: cooking behaviour, cooking equipment and cooking energy in household energy use. Although this classification seems simple, it covers most of the known knowledge in academic circles. From time to time, some random publications, such as on the relation between energy use and food type, are available.

- Cooking Techniques, Staple Food Type and Cooking Energy

The data recorded in this research include the cooking techniques applied and staple food types used in two families. According to the records, the cooking techniques most often used in both families are boiling, steaming and stir frying.

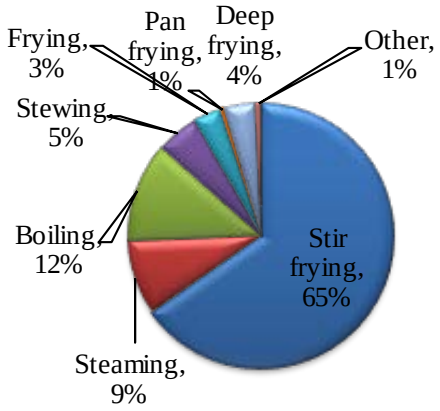


Figure 4-34: Young couple and their family - cooking techniques

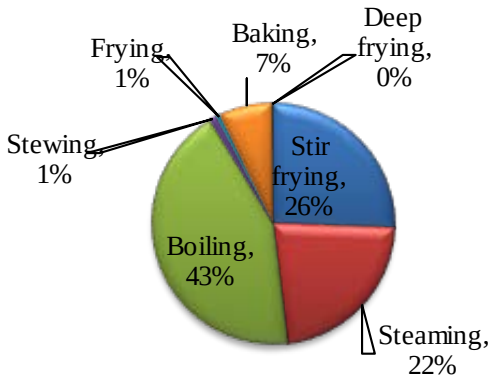


Figure 4-35: Elderly couple - cooking techniques

The staple foods most often cooked by both families are as follows.

Young couple and their family:

- Milk
- Porridge
- Steamed bread
- Steamed rice

Elderly couple (Figure 4-36):

- Noodles

- Porridge
- Steamed bread
- Milk
- Steamed rice

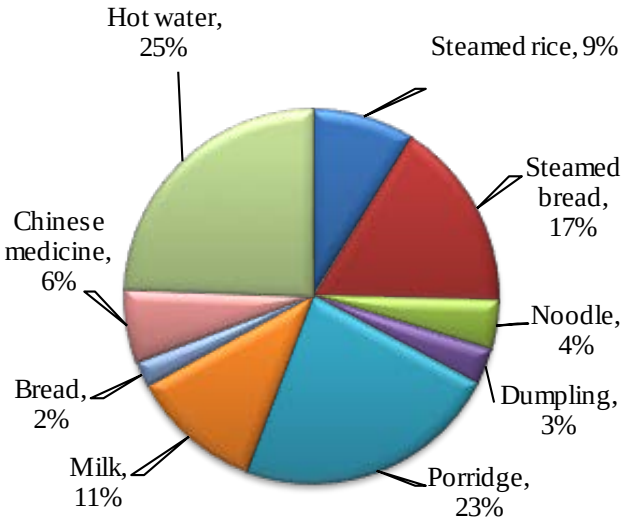


Figure 4-36: Elderly couple - staple food types

The data indicate that, unlike Western families, Chinese families use more boiling and steaming cooking techniques when preparing staple foods. These staple foods include noodles, porridge, steamed bread and steamed rice. For side dishes, stir frying is the cooking technique used most often.

These data explain the reason for Chinese families using more cooking energy than Western families, as identified in the literature review. This is because the most preferred staple foods, such as noodles, porridge, steamed bread and steamed rice, require water and steam as cooking media for applying boiling and steaming cooking techniques. In contrast, Western households use baking as one of the main cooking techniques.

- Cooking Heat Transfer Principles

In cooking, there is typically a heating element (such as a fire), a heat transfer medium (oil, water, air, a pan, etc.), and the food itself. The heat

moves from the element through the medium to the food. In cooking, there are three general ways that heat can be transferred from one material to another: conduction, convection, and radiation. All three play a role in cooking but, depending on the cooking method, only one or two may be important. The other important aspect of moving heat is how much the temperature of a material changes when you move a certain amount of heat into it. Heat capacity refers to how quickly a material's temperature changes with the addition of heat. As heat is added to a material with a high heat capacity, the temperature will increase more slowly than for a material with a lower heat capacity.

The thermal properties of cooking media (Table 4-5) reveal that steam and water have their limit for temperature heating up to 100 ^{o}C, while air (used in baking and roasting) and cooking oils have almost no temperature limit or can go up to several hundred degrees centigrade. The higher the temperature, the faster the cooking, the less energy used. Further, as listed in Table 4-5, the heat capacity of water is high. This means that water requires more energy than air and oil to reach a certain temperature or when it becomes steam.

Table 4-5: Thermal properties of common cooking media

Cooking media	Heat capacity (J/g-K)	Thermal conductivity (J/sec-m-K)	Effective temp. range (°C)
Air	1	0.02	No limit
Steam	2	0.02	100 °C*
Water	4.2	0.6	0-100 °C
Cooking oils	2	0.2	5-230 °C

*Higher temperatures possible with pressure cookers

Table 4-6 illustrates the relationship between cooking techniques and the heat transfer principles of these techniques.

Table 4-6: Common cooking methods and heat transfer principles

Method	Conduction	Convection	Radiation
Steaming	High	High	Low
Boiling	High	Moderate	Low
Deep frying	High	Moderate	Low
Sautéing	High	Low	Low
Broiling	Moderate	Low	High
Baking	High	High	Moderate
Grilling	Moderate	Moderate	High
Microwaving	Low	Low	High

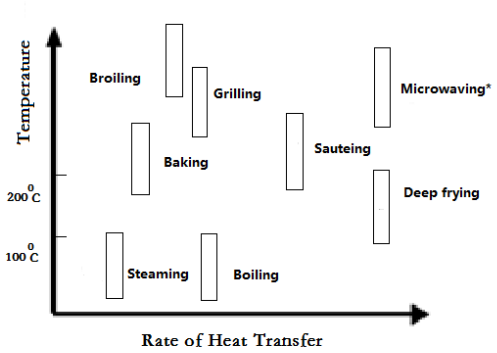


Figure 4-37: Maximum temperature and rate of heat transfer matrix in cooking

In Figure 4-37, the temperatures are qualitative illustrations only, since most cooking methods span a broad temperature range. Since we are discussing temperature as it relates to heat transfer, microwaves and infrared waves are listed as 'high temperature' because they can transfer heat into even very hot foods.

On-site measuring of the cooking energy consumption for daily Chinese dishes in the research confirmed these cooking principles. Figure 4-38 shows the real data for Chinese cooking practices. Boiling (soups) and stewing (slow boiling) rank high for energy consumption, while frying is ranked low.

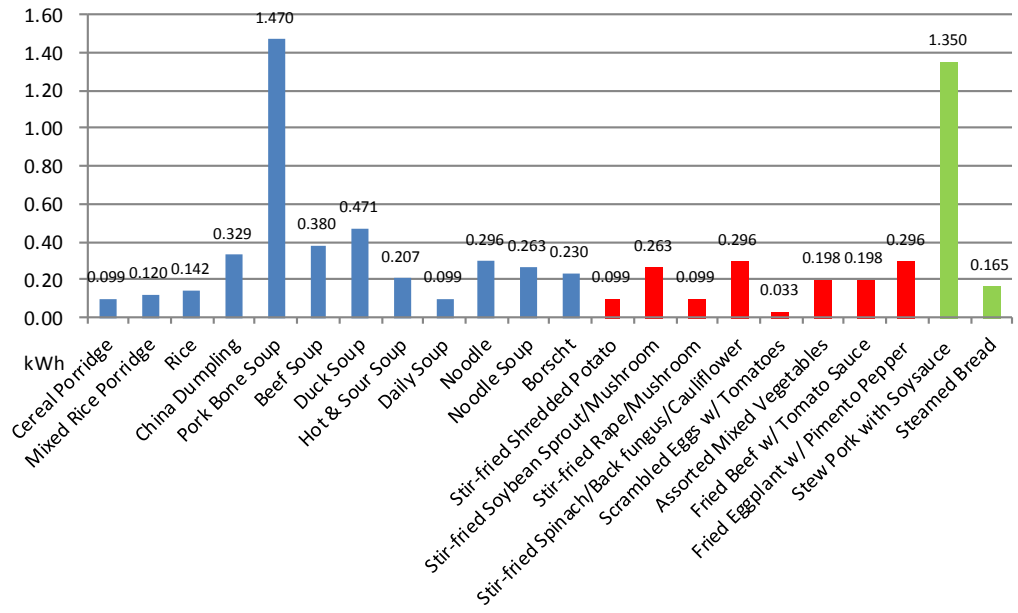


Figure 4-38: Chinese dishes and their related energy consumption

The above information is useful in understanding why Chinese family cooking energy is higher than in Western households. This is because the most cooking method for staple food is boiling and steaming. Chinese also prefer have a soup in the supper and lunch. The water based cooking food needs more energy than oil based cooking and backing/roasting. Below is the ingredients of these measured food.

Food Name	Portion	Ingredients weight (gram)
Cereal porridge	2 persons	Cereal (150g) + Water (750g)
Mixed rice porridge	2 persons	Rice (52g) + Millet (6g) + Water (1058g)
Rice	2 persons	Rice (70g) + Water (1000g)

China dumpling	2 persons	Dumpling (962g) + Water (1000g)
Pork bone soup	2 persons	Upper part of a leg of pork (1320g) + Water (2600g)
Beef soup	2 persons	Beef (300g) + Water (1000g)
Duck soup	2 persons	Roast duck bone (200g) + Water (1000g)
Hot & sour soup	2 persons	Bamboo shoot (80g) + Egg (1 piece) + Mushroom (100g) + Peanut Oil (20g) + Water (800g)
Daily soup	2 persons	Egg (1 piece) + Water (761g)
Noodle	2 persons	Noodle (250g) + Water (1000g)
Noodle soup	2 persons	Noodle (250g) + Water (1000g)
Borscht	2 persons	Beef (150g) + Potato (235g) + Tomato (280gx2) + Onion (240g) + Carrot (222gx2) + Water (1000g)

Stir-fried shredded potato	2 persons	Potato (235gx3 pieces) + Peanut oil (40g)
Stir-fried soybean root w/ mushroom	2 persons	Soybean root (300g) + Mushroom (200g) + Peanut oil (40g)
Stir-fried rape w/ mushroom	2 persons	Rape (200g) + Peanut oil (40g) + Mushroom (200g)
Stir-fried spinach w/ black fungus & cauliflower	2 persons	Spinach (250g) + Black fungus (80g) + cauliflower (150g)
Scrambled eggs w/ tomatoes	2 persons	Egg (1 piece) + Tomato (280g x 2) + Peanut oil (40g)
Assorted mixed vegetables	2 persons	Rape (300g) + Peanut oil (30g)
Fried beef w/ tomato sauce	2 persons	Beef (300g) + Peanut oil (500g) + Tomato sauce (50g)
Fried eggplant w/ pimento pepper	2 persons	Eggplant (212g) + Pepper (152g) + Peanut oil (40g)

Stew pork w/ soya sauce	2 persons	Pork (400g) + Water (1331g)+ Soya sauce (115g)
Steamed bread	2 persons	Steamed bread (200g) + Water (2000g)

The findings can also be used to alter the method and change the cooking behaviour of Chinese cooking practice in order to achieve lower carbon emissions. For example, beautiful golden-brown Beijing duck is one of the most welcome items of Chinese cuisine. However, it normally takes more than 1 hour to roast in a traditional duck roasting oven (Figure 4-39). An alternative method is to use a pressurized frying oven to cook the duck. Deep frying transfers heat much faster than roasting, and pressurized oil temperature can be as high as 230 ^{o}C in a fryer, so the duck will be cooked in under half an hour. The moderate temperatures of frying (compared with roasting) also mean the meat will stay golden brown, not burned, on the outside.



Figure 4-39: Electric pressure fryer and a traditional duck roasting oven

- Cooking Utensils and Occupant Behaviour

Further study explored the cooking utensils used by Chinese families. Figure 4-40 depicts the frequency of use of different cooking ware by the

retired elderly couple.

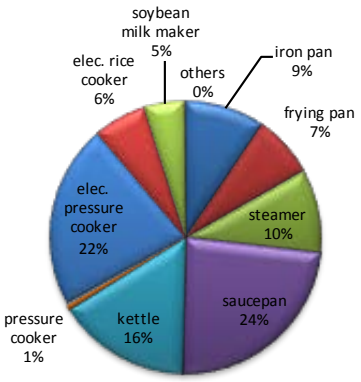


Figure 4-40: Frequency of use of cooking utensils by the retired elderly couple

It was found that the most frequently used cooking method in this family was to use water to heat food. A steamer was used to heat water until the water turned to vapour, which was then used to heat the food. A saucepan was used to boil food directly. A kettle was used to boil the water for making drinks. A pressure cooker was used to prepare food in a pressurized closed space using water. A rice cooker also used water to cook rice. Based on Figure 4-40, 79% of the cooking utensils used by the retired couple were for steaming and boiling purposes, which creates a low temperature and slow heat transfer. This also partially explains why Chinese cooking consumes more energy than its Western counterpart.

In order to understand more about Chinese household energy consumption, a daily record of occupants' cooking behaviour was necessary and RFID was used together with cooking energy measurement. RFID is an automatic method of recording occupants' behaviour in a home. It was used to record a week of test family activities. Taking no account of sleeping hours, the overall family member daily activity time and male/female daily activity time are illustrated in Figures 4-41 to 4-43. The data show that a Chinese family spends a large proportion of their time cooking. The elderly couple spent 28% of their active time (excluding sleeping) in the kitchen and at the dinner

table. This is the longest time in their everyday life at home. Outdoor activities took about 34%. An interesting finding was that the elderly man spent more time in the kitchen, although his work in the kitchen was on food preparation. Although the elderly woman spent less time in the kitchen, she was the person using the cooker to heat food.

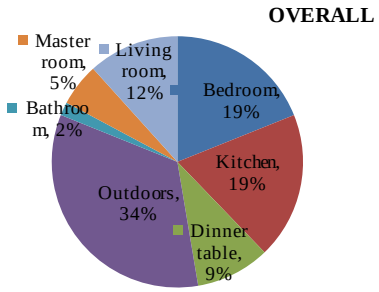


Figure 4-41: Active time spent at home by the elderly couple

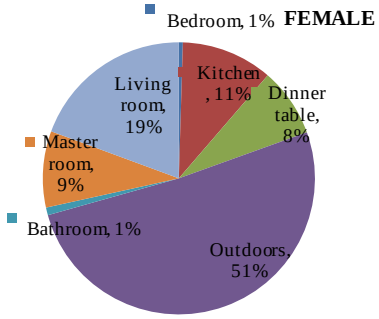


Figure 4-42: Active time spent at home by the elderly woman

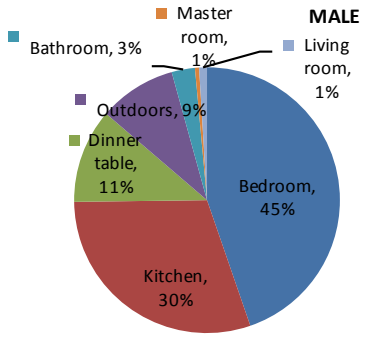


Figure 4-43: Active time spent at home by the elderly man

Findings

Research on family cooking energy shows interesting findings. The underlying heat transfer principles explain why Chinese family cooking energy consumption is higher than in Western and Japanese families, as shown in the literature review (Table 2-2). A summary of the findings includes the following.

Food preference and cooking method: Chinese people prefer hot food. Most staple food needs to be prepared by steaming or boiling e.g., porridge, steamed bread, noodles, steamed rice and milk. Figure 4-36 showed the percentages of daily staple foods taken by a typical retired couple. Most side dishes are prepared by frying or deep frying. Based on the thermal properties of the cooking media summarized in Table 4-5, water has a higher heat capacity and the upper limit on temperature is 100 ^{o}C. On the other hand, cooking oil has the lowest heat capacity than water, which means that oil can heat up very quickly and the highest temperature can be up to 230 ^{o}C. Thus, cooking using water/vapour is among the most energy-consuming cooking methods.

Utensil type: Since Chinese people prefer to steam and boil staple foods and fry side dishes, the frequency of use of boiling and steaming cooking utensils is high. As shown in Figure 4-38, saucepans, steamers, rice cookers and pressure cookers are the most often used utensils in a Chinese family. Iron pans and frying pans, which are used for preparing side dishes, are also among the frequently used utensils in the family.

As a result of food preference, cooking method and utensil type usage preference, Chinese cooking has, according to Figure 4-35, high energy consumption embedded in it. However, in Western families, fresh food and grilling/baking are more often preferred. Grilling/baking consumes less

energy in preparing food because of the good thermal properties of air as a cooking medium.

In theory, frying and deep frying have the advantage of saving cooking energy because of the use of oil as a cooking medium. Cooking oil has the advantage of better thermal performance in terms of heat capacity and high boiling temperature. However, most published health articles state that eating fried food is an unhealthy habit. Medical research demonstrates that frying food raises the incidence of severe chronic disease. A compromise between food preference, cooking method and cooking energy is the use of pressurized cooking utensils, such as the pressurized rice cookers that are already widely used by Chinese families.

Research on family cooking energy shows a strong relation between family life cycle and family cooking energy. Data support the conclusion that there is a lock-in effect that, once the family life cycle remains unchanged, daily cooking energy consumption is constant. In the same family life cycle, the daily cooking energy consumption remains constant even as family members change in that family life cycle.

Thus, in this paper, the researcher proposes energy use intensity for measuring Chinese family cooking energy consumption, i.e., cooking energy use intensity (CookEUI). This EUI has the following characteristics:

- It is related to the family life cycle.
- The unit of measurement is the daily cooking energy consumption: kWh/day.FLC (family life cycle).

For example, based on Yu and Liu's (2007) Chinese family life cycle classification and the results of this research, CookEUI can be noted as:

Family Life Cycle (Middle-aged couple, 35~60 years old): CookEUI = 5.1 kWh/day

Family Life Cycle (elderly couple, > 60): CookEUI = 4.13 kWh/day

Family Life Cycle (couple staying with parents): CookEUI = 6.8 kWh/day

This method of clarifying CookEUI is an easy way to estimate family cooking energy. In many of the prevailing pieces of energy modelling software, such as IES and eQuest, family cooking energy is classified as a process load. The process load is calculated based on kW/m^2 or a fixed number. The discovery of the family life cycle/cooking energy relationship and the lock-in effect not only points out the mistake of floor-area-based cooking EUI, but also proposes the direction, at least in family cooking, of how to calculate cooking energy.

Young couples with or without children are a unique sub-group in cooking energy use. It is various greatly in the collected cooking consumption energy data. This is mainly because of the frequency of eating-out among this group. The complexity of this issue, relating to lifestyle, income level and other factors, makes it worthy of separate research but is out of the scope of this study.

4.3 Summary

Household cooking energy is a missing part of energy use research in China. Even in the rare publications, household energy use is often depicted in quite different scenarios. The differences come from many reasons. Some are because of the fast advances in Chinese people's living standards, particularly the increasing expenditure on home appliances in recent years. Some are because the studies were carried out in different climate zones. Some are due to changing building codes, leading to differences in building

envelope performance. Some are because of different research methodologies being applied, such as energy audits or modelling, and some are due to the use of advanced technologies, such as renewable energy.

In order to gain first-hand cooking energy data, the researcher selected two typical apartment units with a floor area of about 80~90 m^2. This is the size of most occupied city residential units for Chinese families. The two test families selected are from the segment most likely to cook at home, i.e., a retired couple and a young couple with a child and her grandparents. Power plug-in meters were used to measure energy end-user consumption, which was grouped into seven categories: air conditioning, hot water, entertainment, bedroom, guest room, kitchen, and toilet. The measurement standard used was IPMVP option B: ECM Isolation Method. In order to collect occupants' behaviour data, RFID equipment was installed. Signal receivers were installed in different rooms and wrist taggers were worn by each family member. A site computer automatically recorded the times each occupant entered and left each room, so that the amount of time spent in different functional rooms was acquired for each family member. Manual records are essential even with automatic instruments. In this study, one set of forms recorded family daily food type, cooking methods, cooking utensils used and time of cooking. Another set of forms recorded the daily food menu. All data were recorded from November 2012 to December 2013 for the retired couple, and from September 2012 to December 2012 for the family composed of the young couple with one child and her grandparent.

First-round data analysis confirmed the literature review conclusion that cooking energy is the largest household energy end-user in China, other than space cooling in the south and space heating in the north of the country. Some household end-user energy consumption varies between different families, such as that used for cooking, entertainment and hot water. Some

end-user energy consumption shows seasonal differences, such as for hot water, entertainment and lighting. Some end-user energy consumption remains constant year-round in a given family, such as that for cooking.

The assumption that cooking energy is directly related to number/size of family members looks reasonable in the first viewing of the collected data. However, further analysis of a family during the Chinese Spring Festival found that cooking energy is related more to family structure i.e., family life cycle. During the Chinese Spring Festival, the test family structure changed from one with three generations to one that was more like a newly married couple. The cooking energy observed changed but was constant before and after the change. This led to further study of the relation between family life cycle and household cooking energy.

Previous studies have shown the relation between household energy and family life cycle. For example, Fritzsche (1981) delineated total household energy as being affected by family income, family size, energy demand and frequency of attending social activities outside the family. His research concluded that the Young Single stage of the family life cycle consumed the least amount of energy, with the exception of petrol consumption. A middle-aged, married with children household consumed the most total energy, with the exception of fuel oil, wood and coal. Zimmerman's (1981) research on transportation energy across the family life cycle concluded that middle-life cycle stages in which children were in their late teens consumed the most petrol. Frey and LaBay's (1983) study revealed that heating energy expenditure was high for elderly consumers because of the significantly higher thermostat settings in their houses. All these researchers showed that it is obvious that family life cycle is a relevant way of explaining household energy consumption.

Western scholars' studies on the relationship between family life cycle and household energy rely on Well and Gubar's (1966) classification of nine

family life cycles. In 2007, Yu and Liu pointed out that Chinese families are generally larger than those in the US and a family with three generations living together was common. They proposed a revised Chinese family life cycle with 10 stages. This family life cycle model covered 96.53% of Chinese families in the 2006 China population survey.

The researcher carried out a survey to explore the relationship between family cooking energy and family life cycle using Yu and Liu's (2007) model. The survey was designed to ask a wide variety of questions about family life cycle, gas consumption (mainly for cooking), time of eating at home, cooking utensils, food types and cooking methods. From the 40 responses, a strong relation between family life cycle and home cooking energy was found. The survey also revealed that, in China, Key family Type I, i.e., a family with three generations living together with the youngest child under 6, consumed the most cooking energy for a minimum four-person family (12.9 kW/day). Key family Type II, i.e., a family with three generations living together with a dependent child over the age of 12, consumed the second-highest amount of cooking energy for a minimum four-person family (8.13 kWh/day). The third group is that of solitary survivors living with a middle-aged couple in a three-person family (6.8 kWh/day). The fourth group is middle-aged couples with a dependent child over 12, a three-person family (6.51 kWh/day), followed by middle-aged couples (5.1 kWh/day) and elderly retired couples (4.13 kWh/day).

The survey also indicated that young couples, except those with a child under 6 years old, showed great uncertainty in their daily cooking, as the data vary dramatically. This is because young couples, i.e., those younger than 35 years old, often tend to eat out (Jiang, He, & Wang, 2014). Even after they have children, they take their children when eating out.

Reasons or underlying driving forces of the observed constant cooking energy in certain given family life cycles were, therefore, examined further.

A lock-in effect for household cooking energy was therefore concluded in the research. The lock-in effect 'locks' the cooking energy of these families in their respective family life cycles. Key driving forces of the lock-in effect include time saving in cooking, fixed tastes and the influence of the parents' menu. Stir frying, steaming and boiling are the cooking methods that consume the largest portion of household cooking energy.

At the end of this chapter, the researcher proposed energy use intensity as a means of measuring Chinese family cooking energy consumption, i.e., cooking energy use intensity (CookEUI). CookEUI has the following characteristics: it is related to the family life cycle; and the unit of measurement is the daily cooking energy consumption: kWh/day.FLC (family life cycle).

The CookEUI proposed in this paper points out the missing part of floor-area-based cooking EUI used in several pieces of energy modelling software, for example, IES and eQuest. In this software, cooking energy is treated as a process load. The process load is calculated based on kW/m^2.yr or as a fixed number, which is obviously inaccurate.

This chapter also pointed out that the reason Chinese household cooking energy is higher than that in Western households is that the preferred staple foods, such as noodles, porridge, steamed bread and steamed rice, require water and steam as cooking media for applying boiling and steaming cooking techniques. In contrast, Western households use baking as one of the main cooking techniques. Heat transfer principles indicate the higher the temperature, the faster the cooking, the less energy used. Water requires more energy than air and oil to reach a certain temperature or to become steam. Thus, Chinese household cooking needs more energy than that in Western cooking because Chinese cooking uses boiling and steaming more often, while Western households are more likely to use baking.

Chapter 5: COOKING AIR POLLUTION

5.1 Cooking Air Pollution and $PM_{2.5}$

See and Balasubramanian (2006) state that the average mass concentration and average number of fine particles ($PM_{2.5}$) rocket by a factor of 12 and 85, respectively, during cooking hours compared with non-cooking hours. They also revealed that the amount of the total particle count deposited within the body was elevated from 58% during non-cooking hours to 71% during cooking hours. In addition, ultrafine particles (UFPs, diameter < 100 nm) accounted for about 80%-90% of PM in terms of particle counts (See & Balasubramanian, 2006; Wallace, Emmerich, & Howard-Reed, 2004), and have been shown to be more toxic than larger particles since their smaller size and larger surface area can absorb more mutagenic pollutants. Wallace et al. (2004) also found that cooking activities would lead to a higher concentration of UFPs by a factor of 10.

PM emitted from cooking oil fumes has been associated with respiratory problems, lung cancer, cervical intraepithelial neoplasm, and cardiopulmonary deaths (Boldo et al., 2006; Pope III & Dockery, 2006; Wu et al., 2004). Chiang Wu and Ko (1999) have successfully identified four PAHs (B[a]P, DB[ah]A, B[b]FA, and B[a]A) from COF, which were indicated by the US Environmental Protection Agency (EPA) as being probable human carcinogens (US Environmental Protection Agency, 1999). Exposure to these kinds of PAHs is very likely to increase the risk of contracting lung cancer. Tung et al. (2001) observed that exposure to 200 μg/ml COF generated from heated rapeseed oil could induce oxidative stress in CL3 lung epithelial cells and significantly reduce the growth of lung epithelial cells within 96 hours. Wu et al. (2004) examined the relationship between COF and cervical intraepithelial neoplasm (CIN) in women. Their study found that 20- to 40-year-old women who cooked once a week without

the presence of a fume extractor had a 2.29 times higher risk of developing CIN than those who did not cook, and had a 2.47 times higher risk of developing CIN than those who cooked with fume extractors switched on.

Overall, a human health risk assessment performed by See and Balasubramanian (2006) calculated the estimated non-carcinogenic risk to be 50% higher than the acceptable level, and the estimated carcinogenic risk to be two orders of magnitude higher than the acceptable level. In the current research, COF released in actual home cooking conditions and particle dissemination patterns was closely monitored and recorded in the experiment. Test results are summarized in this section.

Particle Release Monitoring for Three Continuous Days

Indoor $PM_{2.5}$ and PM_{10} and outdoor $PM_{2.5}$ concentrations for three continuous days were monitored from 10 to 13 February 2015 in real kitchen cooking circumstances in Beijing. All the kitchen windows were closed during the monitoring time. Table 5-1 summarizes the cooking menus during these test days. The PM concentrations shown in Figure 5-1 demonstrate that indoor PM_{10} was rarely affected by outdoor air quality, while $PM_{2.5}$ was clearly influenced. Moreover, both indoor $PM_{2.5}$ and PM_{10} concentrations were affected by cooking. In addition, since breakfast cooking uses the steaming method, it released less $PM_{2.5}$ than lunch and supper cooking. The findings for the three continuous days of monitoring are:

- Indoor $PM_{2.5}$ concentration was more greatly affected by cooking than indoor PM_{10}.
- Cooking Chinese breakfast releases less $PM_{2.5}$ and PM_{10} than cooking Chinese lunch and supper.

Table 5-1: Cooking menus from 11 to 13 February 2015

Date	Day	Meal	Cooking time	Cooking menu	Exhaust hood fan
11 Feb.	Wednesday	Breakfast	7:40~8:10 am	Steamed buns; fried eggs	1 speed
11 Feb.	Wednesday	Lunch	12:00~12:15 pm	2 stir-fried vegetables, 1 soup and rice	1 speed
11 Feb.	Wednesday	Dinner	5:10~6:10 pm	3 stir-fried vegetables, 1 soup, rice and steamed buns	3 speed
12 Feb.	Thursday	Breakfast	7:40~8:10 am	Steamed buns; fried eggs and pancake	1 speed
12 Feb.	Thursday	Lunch	12:30~12:55 pm	2 stir-fried vegetables, 1 wonton soup	2 speed
12 Feb.	Thursday	Dinner	5:30~6:00 pm	1 stir-fried vegetable, 1 steamed meatball	2 speed
			7:00~7:10 pm	1 stir-fried vegetable, 1 soup	2 speed
13 Feb.	Friday	Breakfast	7:40~8:10 am	1 fried eggs, 1 steamed bun	1 speed
13 Feb.	Friday	Lunch	11:45~12:10 pm	1 stir-fried vegetable, 1 soup, 1 steamed meat	2 speed
13 Feb.	Friday	Dinner	5:40~6:00 pm	Braised string bean with noodle	2 speed

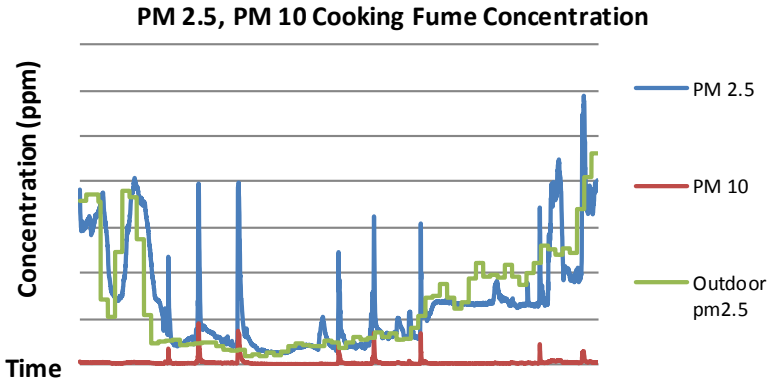


Figure 5-1: $PM_{2.5}$ and PM_{10} cooking oil fume concentration from 11 to 13 February 2015

Particle Release of Different Chinese Cooking Methods

$PM_{2.5}$ and PM_{10} release for different Chinese cooking methods was monitored and recorded in separate tests. Table 5-2 summarizes these cooking methods and shows the corresponding $PM_{2.5}$ and PM_{10} particle release graphics and cooking operation details, as well as the on/off status of the exhaust fan and air cleaner.

Table 5-2: Summary of cooking methods and cooking conditions

Menu	Exhaust fan	Air cleaner	Reference figures	Cooking process
Braised string beans with noodle	Off	Off	Figure 5-2	Stir frying shredded pork first
Braised croaker	20:45 on/speed 2	19:20 on	Figure 5-3	Deep frying croaker first
Pork hock soup	17:54 on/speed 2	Off	Figure 5-4	Boiling
Steamed buns with fillings	Off	8:44 on/speed 3	Figure 5-5	Steaming
Fried eggs	Off	7:54 on/speed 3	Figure 5-6	Frying

Figures 5-2 to 5-10 all show a noteworthy increase in $PM_{2.5}$ particle concentration in a very short time. It only took 1~2 minutes for the particle concentrations to reach the peak once the monitor sensed the release of particles. The concentration then dropped by the time the cooking oil was used up.

However, in Figures 5-2, 5-4 and 5-6, the particle numbers climbed again in the descending period when the cooking burner had already been turned off. This was because the downflow of cold air brought the high-level $PM_{2.5}$ particles to the low level where the monitor was located.

$PM_{2.5}$ particle concentration climbed fast when boiling water, the fundamental procedure used for boiling and steaming, as shown in Figures

5-4 and 5-5. It then dropped as the air in the kitchen became hot and raised the $PM_{2.5}$ particles to a high level below the ceiling.

In Figure 5-3, the sharp and abrupt trough indicates a significant impact of window ventilation on indoor $PM_{2.5}$ concentration, while that on PM_{10} was less.

Based on this series of tests, the results indicated that the emission of $PM_{2.5}$ can be ranked from deep frying (Fig. 5-3), frying (Fig. 5-6), stir frying (Fig. 5-2) to boiling (Fig. 5-4). This supports the conclusion in See and Balasubramanian's (2008) research. In See and Balasubramanian's research, it was revealed that the total mass concentration of fine particles increased by more than five times in a kitchen during cooking compared with the background levels. It was also observed that the deep-frying method emitted the largest mass of particles, followed by pan-frying, stir-frying, boiling, and steaming. The same trend was found for most of the chemical components of $PM_{2.5}$, i.e., carbonaceous particles.

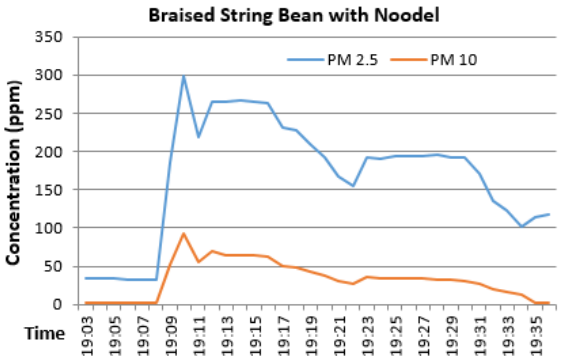


Figure 5-2: Braised string beans with noodles - particle emissions

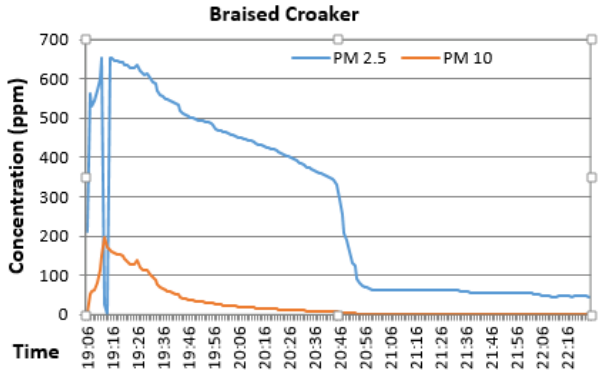


Figure 5-3: Braised croaker - particle emissions

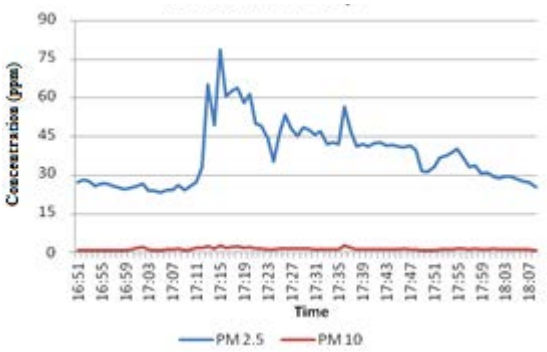


Figure 5-4: Pork hock soup - particle emissions

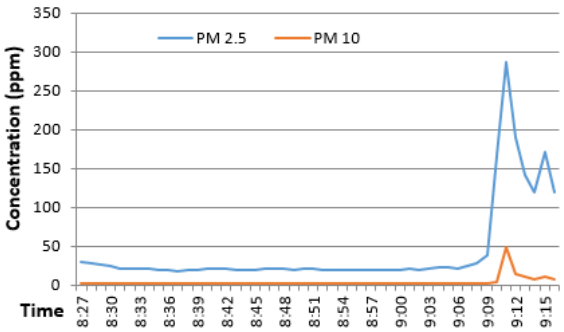


Figure 5-5: Steamed buns with fillings - particle emissions

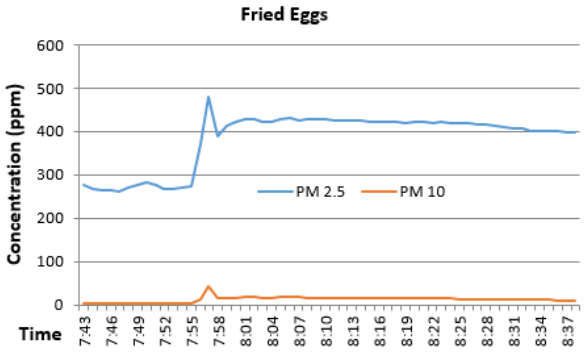


Figure 5-6: Fried eggs - particle emissions

Particle Removal by Air Cleaner and Exhaust Fan

Fried eggs are the most popular breakfast dish among Chinese families. Thus, in the research, frying eggs was chosen as the test cooking to collect experimental data. Cooking oil is usually rapeseed oil and the egg is cooked in a pan. Three tests were carried out to try to find an effective way of removing cooking $PM_{2.5}$.

The first test was to cook eggs in the kitchen with both door and windows closed. The exhaust fan and air cleaner were both turned off. $PM_{2.5}$ climbed to the maximum concentration of 3,200,000 particles per cubic foot (ppcf) in 50 seconds (one indicator denoted 5 seconds in this test), as shown in Figure 5-7. Then the emission of particles dropped because the cooking oil was used up. The fried egg was ready.

Two comparison tests were carried out in the same cooking conditions. One was with only the exhaust fan on, and the other was with only the air cleaner on. In both cases, the equipment was turned on at the beginning of the test. In these two tests, one indicator denoted 1 minute. It was clear that the exhaust fan reduced $PM_{2.5}$ concentration significantly.

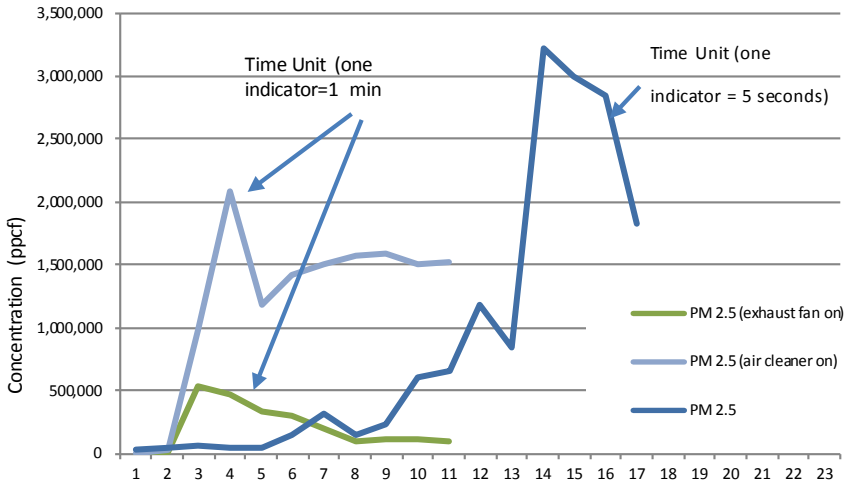


Figure 5-7: Particle removal by air cleaner and exhaust fan

In the tests referred to above, the following interesting findings were observed.

- Mechanical ventilation by exhaust fan is the most efficient way of removing cooking $PM_{2.5}$ fumes.
- The concentration of $PM_{2.5}$ particles bounded up because the high-level particles moved down with downward air movement to a low level, where the PM monitor was located, after the cooking burner was turned off.
- The air cleaner reduced $PM_{2.5}$ fume particle concentration.

5.2 Fume Exhaust Fan and Efficiency

Kitchen Ventilation

In the above $PM_{2.5}$ and PM_{10} measurements, it was revealed that indoor $PM_{2.5}$ was affected by airflow in two ways: first, outdoor air pollution infiltration affected the indoor air pollution in a much more significant way than PM_{10}, as shown in Figure 5-1; second, ventilation, both natural and mechanical, will change indoor $PM_{2.5}$ concentration in dramatic ways. This was observed in the experiment and shown in Figures 5-3 and 5-7. As a result, the air change in the kitchen and the ventilation flow rate of the kitchen exhaust hood were checked further. The purpose of measuring the air change in the test kitchen was to see how deeply the airflow, both natural and mechanical ventilation, affected $PM_{2.5}$ concentration during the test.

In order to establish the air change rate when mechanical ventilation was off i.e., the natural ventilation air change in the kitchen, the first test was carried out by injecting CO_2 into the kitchen when the cooking exhaust hood was off. The window and kitchen door were closed. Two CO_2 sensors were placed diagonally in the kitchen to acquire the average CO_2 concentration

in the kitchen. Background CO_2 concentration was measured first and is used in later data analysis.

The airflow of the kitchen hood was measured in two conditions: the first was with the door and window open, the second was with the door and window closed. In both measurements, speed 2 of the exhaust fan was used (the medium speed between the slow and fast speeds). Figure 5-8 shows the CO_2 concentration change for the two-day tracer gas test.

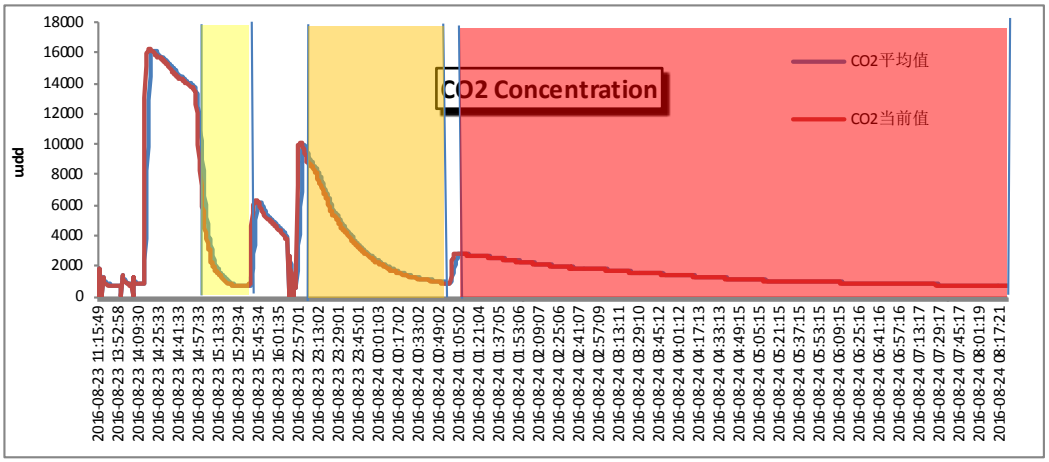


Figure 5-8: CO_2 decay lines for three conditions (from the left: window and door open/fan on; window and door closed/fan off; and window and door closed/fan off)

In Figure 5-8, the yellow area trend line shows the data when the exhaust hood was on with the kitchen door and window open. The orange area trend line shows the data when the exhaust hood was on and the kitchen door and window closed. The red area trend line shows the data when the exhaust hood was off and the kitchen door and window closed.

All three trend lines show a CO_2 decay curve that follows an exponential course. Based on empirical concentration decay function (M.H. Shearman, 1990), the trend lines can be described as

$$C(t)=(C_0-C_a)*e^{-\lambda *t}+C_a$$

Where

C_0 is the initial concentration

C_a is the concentration in the ambient air (i.e., background concentration)

λ is the air change of the kitchen

Enlarged CO_2 concentration decay trend lines and regression equations are shown in the figures below. The volume of the kitchen is measured as 24.51 m^3.

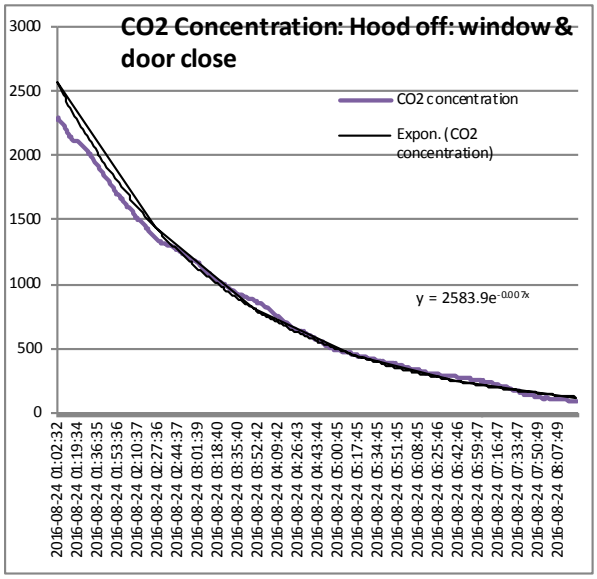


Figure 5-9: CO_2 decay regression line: hood off; window and door closed

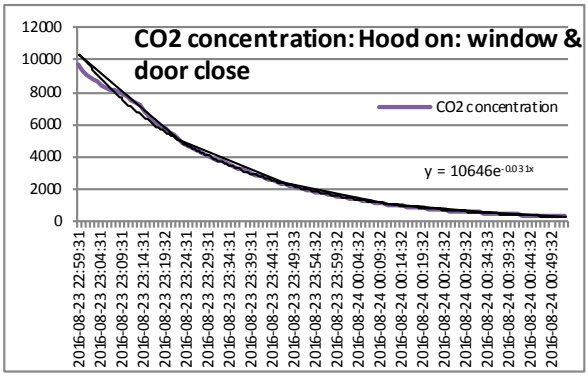


Figure 5-10: CO_2 decay regression line: hood on; window and door closed

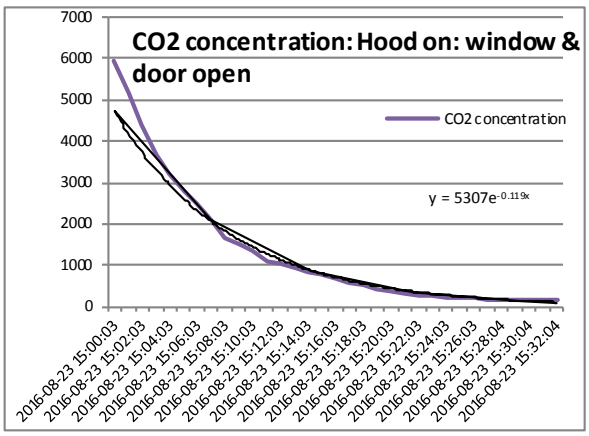


Figure 5-11: CO_2 decay regression line: hood on; window and door open

The CO_2 concentration decay time was recorded in minutes. Thus, the air changes in the kitchen in each measurement condition were:

Kitchen fume exhaust hood off; widows and door closed: 0.42 ACH

Kitchen fume exhaust hood on; windows and door closed: 1.86 ACH

Kitchen fume exhaust hood on; windows and door open: 7.14 ACH

The volume of the kitchen was measured as 24.51 m^3. Thus, the airflow when the kitchen fume exhaust hood was on was 46 m^3/h (window and door closed) and 175 m^3/h (window and door open), respectively.

The tracing gas experiment was conducted in two days. Many field experiences were built in the first day of experiment, including measurement, data recording and data analysis. For the first day of measurement, the recording time period for natural ventilation was only for 1 hour. Therefore, the data did not show the whole decay trend line; only the beginning of the line. This caused the experiment to fail. On the second day, based on the experiment for the first day's data, the natural ventilation measurement time increased to 6 hours. At the end of the measurement, CO_2 concentration tended to reach the outdoor level and became constant. This coincided with ASTM E 471-00 (American Society for Testing and Materials, 2001) recommendations and VDI (Messen von

Innenraumluftverunreinigungen, 2001) research shown in Table 5-3 for minimum time spans between first and last sampling.

Table 5-3: Sampling intervals (Source: VDI, 2001) for air change measurement with the decay method

Air change rate [ACH]	Minimum time span of tracer gas measurement [hours]	Air change rate [ACH]	Sampling interval [min]
0.05	20		
0.125	8		
0.25	4	< 0.5	30 - 40
1	1	0.5 to 1	20 - 30
2	0.5	1 to 2	10
4	0.25	2 to 5	5
10	0.1	> 10	< 2

Another experience built into the data analysis was the equation applied. In the first round of data analysis, the equation used was

$$C(t)=C_0*e^{-\lambda *t}$$

Where

C_0 is the initial concentration

λ is the air change of the kitchen

This equation was the one most often used in tracer gas testing. In many cases, the tracer gas applied is CH_4 and SF_6. However, unlike other tracer gases, CO_2 has the particularity that there is always a certain amount of CO_2 in the outdoor air, meaning that the background concentration cannot be ignored. In general, the outdoor air concentration of CO_2 is between 350 and 450 ppm or even higher, depending on the season. In this experiment, the background CO_2 was 680 ppm. Thus, the CO_2 decay curve will not decline to zero. Instead, the CO_2 concentration decreased to values which were near to that of the outdoor air, as shown in the trend lines. This must be taken into account when analysing CO_2 decay curves. The above equation cannot be applied; thus, the ACH must be determined using the following equation:

$$C(t)=(C_0-C_a)*e^{-\lambda *t}+C_a$$

The difference in applying different equations in this study was as large as 20% ACH.

The kitchen fume exhaust hood installed for the family is rated as having 800 m^3/h airflow rate on the nameplate. However, in real measurements, even when the door and windows were both open, the maximum flow rate was only 175 m^3/h. This reveals that there is a large airflow difference between the factory nameplate and real performance. Since the previous finding discovered that $PM_{2.5}$ is affected by airflow in a significant way, enhancing the air change of the kitchen hood is an important factor for removing kitchen air pollution.

The reason for the airflow difference between that stated on the nameplate and real operational performance was investigated, since the difference is significant. Figure 5-12 shows the airflow experiment equipment for Chinese fume hood factory testing (Zishuo, Shuixiang, & Songhe, 1999).

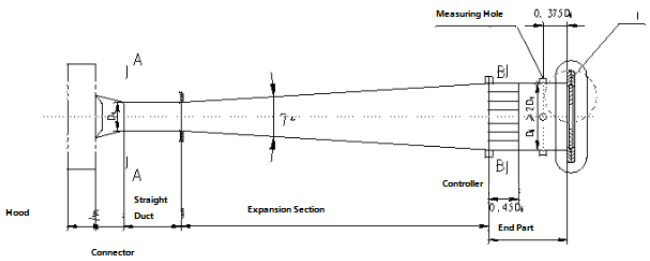


Figure 5-12: Factory testing equipment for cooking fume hoods (Source: Zishuo, Shuixiang & Songhe, 1999)

Factory testing equipment includes a connector to connect the test fume hood with the equipment, a straight tube to stabilize the air current in the tube, and an expansion section to reduce airflow speed and increase pressure at the outlet of the tube and the end. The end includes a measuring section and flow control valve. The whole piece of equipment is in a large room and the air circulates from the end to the inlet of the equipment. In this

condition, the pressure loss along the testing equipment is very low. However, in real kitchen conditions, the inlet side is sometimes in a small enclosed kitchen with all the windows and the door closed; sometimes with the windows and door open. The outlet of the fume hood has a long exhaust duct comprising a duct in the kitchen and a structural vertical air shaft. The resistance on both sides is much higher than in laboratory conditions. This causes the hood airflow in real conditions to be much lower than that rated on the factory nameplate.

Computer Simulation

In this research, it was observed that $PM_{2.5}$ particles were affected by airflow in a significant way. Natural ventilation and upward and downward airflow were all determinants of $PM_{2.5}$ concentration. In the discussion of the test results, an assumption was put forward: the $PM_{2.5}$ particle weight is so light that it could simply be ignored. In other words, the $PM_{2.5}$ particle was assumed to be weightless. If the assumption is correct, it is more important to provide a large volume of airflow to remove particles than to provide a velocity adequate to overcome gravity.

ANSYS Fluent (2014). Particle Force Balance - predicts the trajectory of a discrete phase particle (or droplet or bubble) by integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written as Eq. 1 (A. D. Gosman and E. Ioannides (1983)):

$$\frac{d\vec{u}_p}{dt} = \frac{\vec{u} - \vec{u}_p}{\tau_r} + \frac{\vec{g}\left(\rho_p - \rho\right)}{\rho_p} + \vec{F} \qquad \text{(Eq. 1)}$$

Where

$\vec{F}$ is an additional acceleration,

$\frac{\vec{u}-\vec{u}_p}{\tau_r}$ is the drag force per unit particle mass,

$\tau_r=\frac{\rho_p d_p^2}{18\mu}\frac{24}{C_d \mathrm{Re}}$ is the particle relaxation time,

$\vec{u}$ is the air velocity,

$\vec{u}_p$ is the particle velocity,

ρ is the air density,

ρ_p is the density of the particle,

$Re\equiv\frac{\rho d_p|\vec{u}_p-\vec{u}|}{\mu}$ is the relative Reynolds number,

d_p is the particle diameter, and

μ is the molecular viscosity of the air.

A CFD model was built to test the assumption. It was made with fine grid mesh with around 10,000,000 cells and the simulation was undertaken at unsteady state until reaching 1 minute close to steady condition. The first simulation was carried out when the fume exhaust fan was off. Figure 5-13 shows the temperature distribution pattern while frying eggs. Figure 5-14 shows the air movement while frying eggs. It is clear that the air movement pattern is similar to the temperature distribution, since, when the exhaust fan is off, the air movement is mainly maintained by air buoyancy.

Two rounds of simulations were undertaken on $PM_{2.5}$ and PM_{10} in the above cooking circumstance i.e., frying eggs in a frying pan, and the exhaust fan was off. Figures 5-15 and 5-16 illustrate the $PM_{2.5}$ and PM_{10} particle distribution pattern. More PM_{10} sank compared with $PM_{2.5}$. This suggests that $PM_{2.5}$ is very much less affected by gravity. Its distribution pattern is close to the air movement/velocity.

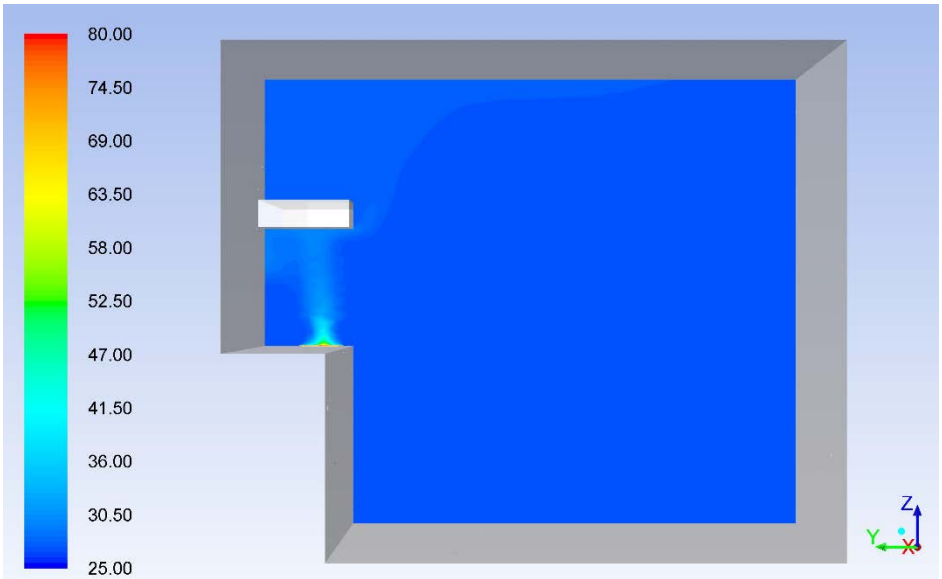


Figure 5-13: CFD simulation of the temperature distribution pattern while frying eggs at 1 minute close to steady state

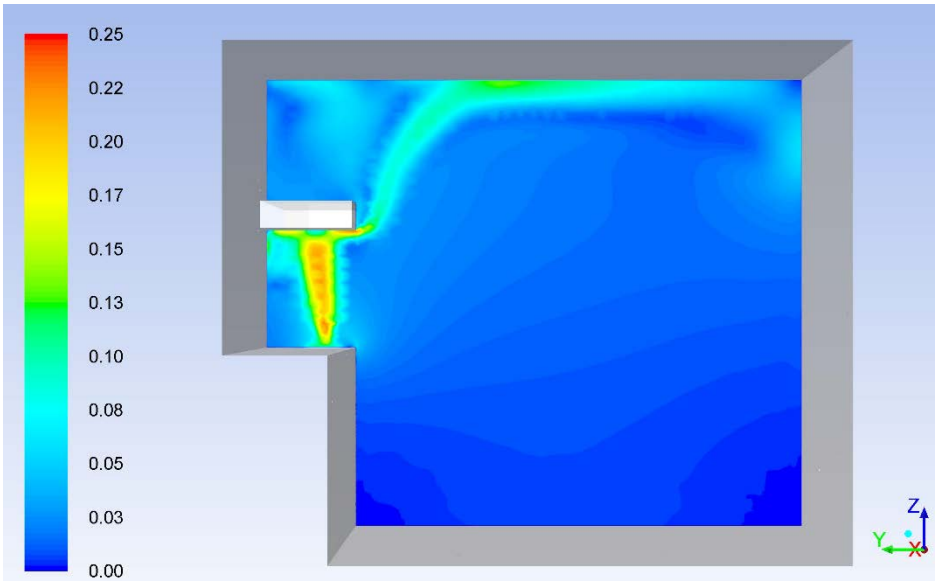


Figure 5-14: CFD simulation of air velocity distribution pattern while frying eggs at 1 minute close to steady state

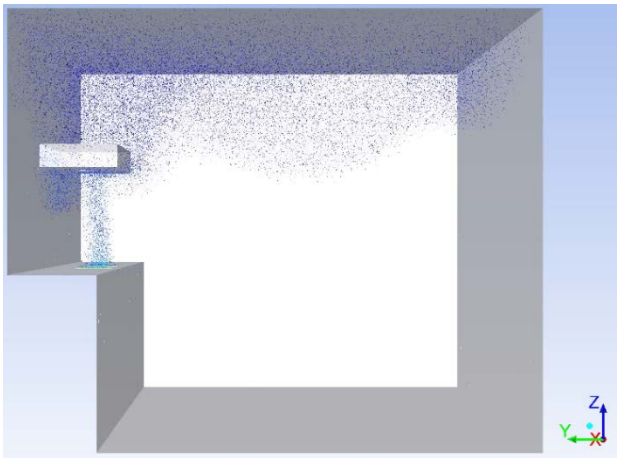


Figure 5-15: CFD simulation of PM2.5 distribution pattern while frying eggs at 1 minute close to steady state

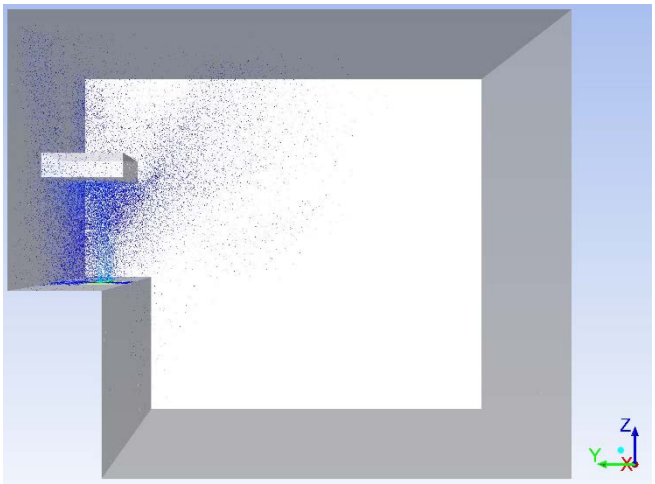
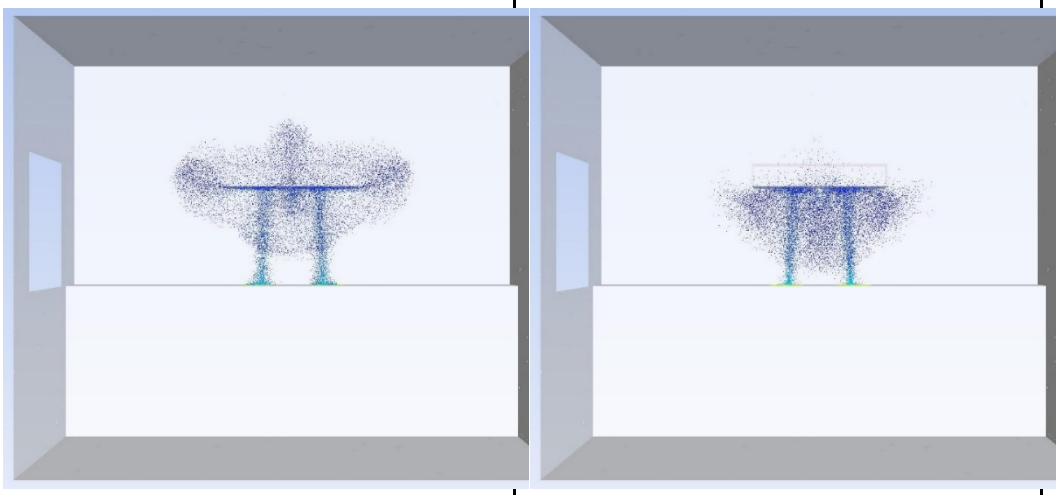


Figure 5-16: CFD simulation of PM10 distribution pattern while frying eggs at 1 minute close to steady state

Figures 5-17 to 5-20 show the particle distribution pattern for different time intervals when ventilation is turned off. Most of the $PM_{2.5}$ appeared near the ceiling, while the PM_{10} appeared near the ventilator.

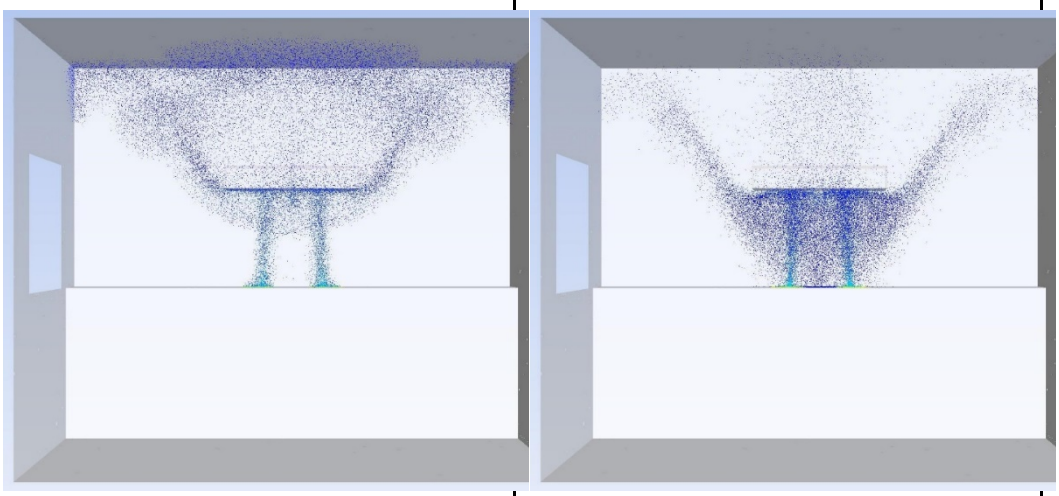
The hot stove induced an upward convection current in the air by buoyancy. Although PM_{10} experiences a larger upward force compared with $PM_{2.5}$ (in relation to area ratio), the gravity acting on PM_{10} is larger than that on $PM_{2.5}$ (in relation to volume ratio). Therefore, $PM_{2.5}$ appeared in a higher position

than PM_{10}.



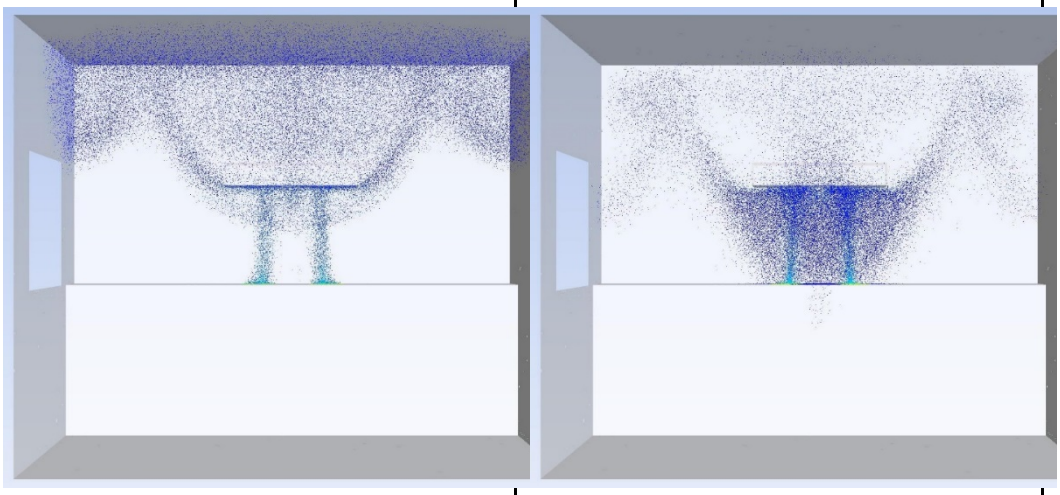
$PM_{2.5}$	PM_{10}

Figure 5-17: Particle distribution pattern at time = 15 s (ventilation off)



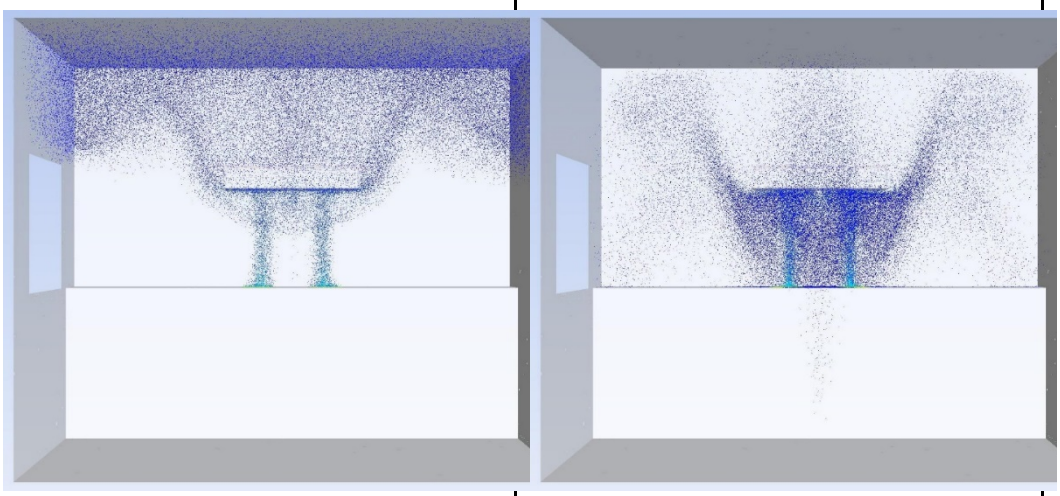
$PM_{2.5}$	PM_{10}

Figure 5-18: Particle distribution pattern at time = 30 s (ventilation off)



$PM_{2.5}$	PM_{10}

Figure 5-19: Particle distribution pattern at time = 45 s (ventilation off)



$PM_{2.5}$	PM_{10}

Figure 5-20: Particle distribution pattern at time = 60 s (ventilation off)

The second simulation was carried out when the fume exhaust fan was on. Figures 5-21 and 5-22 show the vector diagram and particle distribution for $PM_{2.5}$ and PM_{10}, respectively. The magnitude and direction of the air are represented by the vector arrows, while the distribution of the particulates is represented by the red dots. The distribution of the particulates is coherent with the direction of the vectors. This means the particulates from the stove are being transported by the air movement towards the exhaust fan.

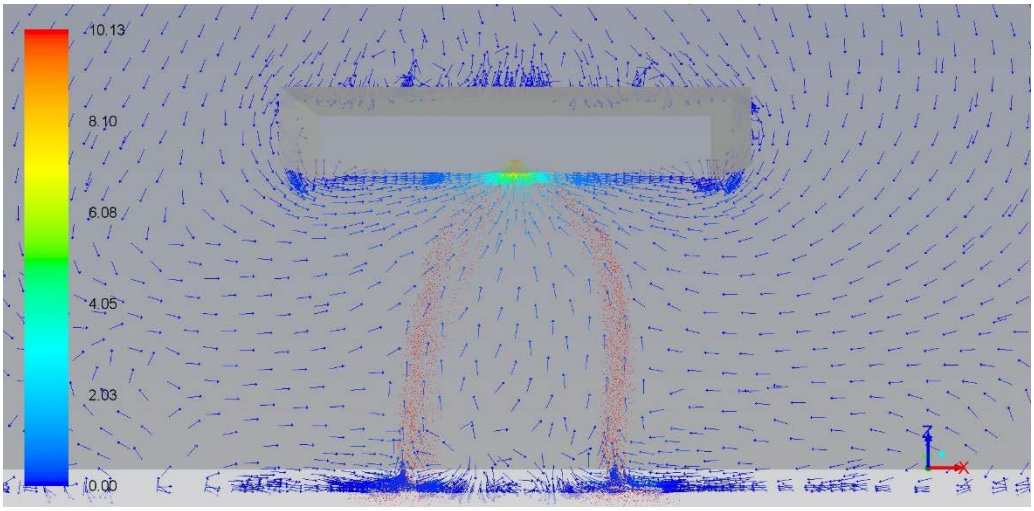


Figure 5-21: Velocity vector diagram and particle distribution for $PM_{2.5}$ (ventilation on)

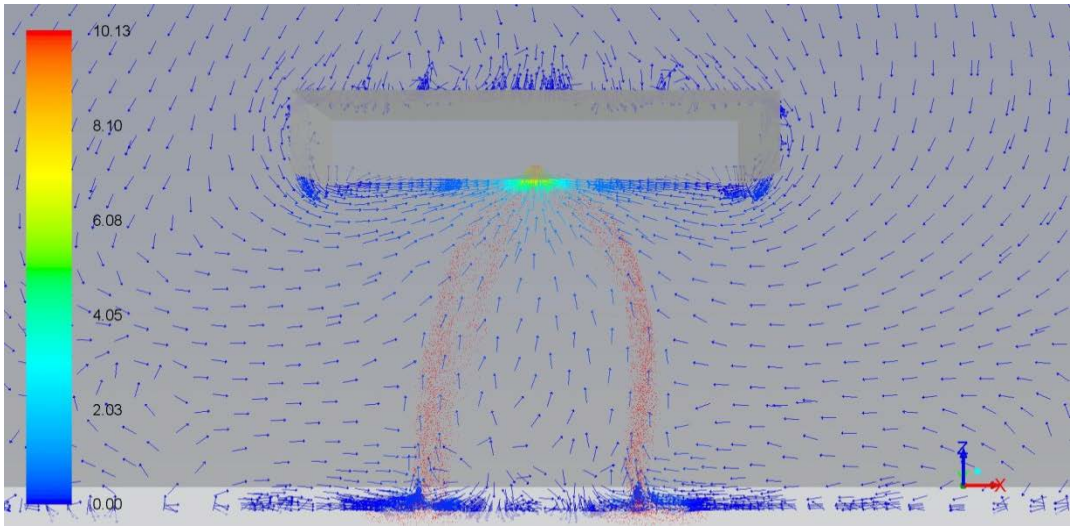


Figure 5-22: Velocity vector diagram and particle distribution for PM_{10} (ventilation on)

The dominant acceleration in this case is the drag force, which is the drag

provided by the suction of the ventilation fan. Therefore, the velocity (speed and direction of movement) of the particle would be very similar to the air velocity and the particle distribution pattern (Figure 5-15 refers) can be implicitly identified by the velocity pattern.

5.3 Data and Analysis

Chinese Cooking Methods: Water/Oil-based Cooking Methods

Seven Chinese cooking methods were very often used by the test family. UFPs include cooking oil fumes and water steam. It was clearly found that oil-based cooking emitted much more $PM_{2.5}$ than water-based cooking methods. Oil-based cooking methods refer to stir frying, deep frying, and frying. All these methods use cooking oil as a medium to heat food. Since oil has a high boiling point and a low specific heat, it can heat food in a short time compared with using water to boil or steam food. On the other hand, the boiling point of water is 100 °C. The heat transfer principle is conduction in both boiling and steaming, so water usually uses longer cooking times than oil-based cooking methods.

It has been observed that Chinese families prefer oil-based cooking methods for the sake of short cooking times. On the other hand, water-based cooking methods are used for making food soft, such as when steaming Chinese buns and porridge.

COF Dissemination Pattern Characteristics

Both oil- and water-based methods show the pattern of a quick climb of $PM_{2.5}$ concentration at the beginning and a sharp drop after reaching the peak. For oil-based cooking, this is because the oil is consumed quickly so that it is used up quickly. For water-based cooking, $PM_{2.5}$ is related more with water steam. Once the water has boiled, the steam concentration increases at the $PM_{2.5}$ monitor level (table-top burner). The detected $PM_{2.5}$

value then decreases when the steam rises to a higher level (unlike oil-based cooking, water is not used up in boiling and steaming).

In several tests, it was observed that once the burner was turned off, there was a small surge in $PM_{2.5}$ concentration. This was because the air had cooled down after turning off the burner. Consequently, $PM_{2.5}$ at a high level started to descend due to lacking the buoyancy of hot air, increasing the concentration of particles at low level. A typical $PM_{2.5}$ concentration at table-top level for the test family is shown in Figure 5-23. This applies to both oil-based and water-based cooking methods.

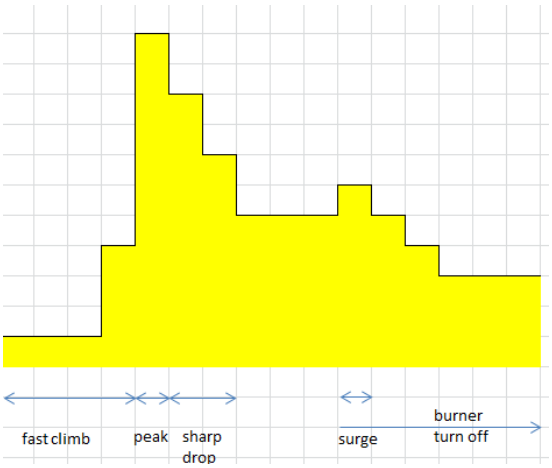


Figure 5-23: Typical COF pattern in the cooking for both oil-based and water-based cooking

Other Factors Influencing COF

- Natural Ventilation

Natural ventilation, such as an open kitchen window, affects $PM_{2.5}$ concentration swiftly. In Figure 5-3, showing the PM result for cooking braised croaker, the kitchen window was accidentally opened during cooking and the $PM_{2.5}$ concentration dropped immediately. When the window was closed again, the concentration returned to the original level.

- Aerostatic Buoyancy

Aerostatic buoyancy affects the airborne $PM_{2.5}$ pattern in a significant way. In oil-based cooking methods, once turning off the burner, the high-level airborne $PM_{2.5}$ moves downward and increases the low-level concentration. This leads to the small surge in COF pattern shown in Figure 5-6. In water-based cooking methods, once the water is boiled, the heat raises low-level $PM_{2.5}$ particles to a high level, thus reducing low-level $PM_{2.5}$ concentration. This causes a sharp drop in COF pattern.

Summary

The monitoring of UFP in actual Chinese kitchen cooking conditions reveals interesting findings. Many of the findings support the discoveries of previous research, such as the UFP concentrations demonstrated by Zhang et al. (2010) and See and Balasubramanian (2008). Some of the findings of the present research are not discussed in previous studies. These new findings include:

1. Chinese breakfast cooking releases less $PM_{2.5}$ than lunch and supper cooking because it uses more water-based cooking methods, such as steaming and boiling.

2. $PM_{2.5}$ emission patterns are similar in both oil-based and water-based cooking methods. Both patterns reveal a quick climb in $PM_{2.5}$ concentration in the early stage, a sharp drop after the concentration reaches the peak, followed by a small surge in concentration at low levels after turning off the burner.

3. Oil-based cooking releases much more $PM_{2.5}$ than water-based cooking. This is extremely harmful to human health, and oil-based cooking was the technique most often used by the test family.

4. Natural ventilation, even a very short period of having the window open, reduces $PM_{2.5}$ in a significant way.

5. Air cleaning or water-washing type cleaning is less effective than an exhaust fan at reducing $PM_{2.5}$ concentration. However, it is still useful in reducing $PM_{2.5}$ concentration.

6. The gravity of $PM_{2.5}$ has little impact on its airborne character.

The above discoveries led to innovative thinking on kitchen design and COF removal. First, it is critical that Chinese kitchens have operable windows. Western-type kitchens that are located in the inner zone of the dining room in most condominium designs are not recommended in Chinese house design. Second, control of $PM_{2.5}$ during the cooking period should be focused on the fast climbing stage. It is suggested that the fan is at full speed for 2 minutes and can be slowed down afterwards. This can remove COF more efficiently and save energy. Third, there is a small surge after the cooking burner is turned off at chest level. This is because of the cold air taking high-level particles to a lower level. Thus, an exhaust at low level and on the table top is also important in removing COF. Fourth, deep frying has the most $PM_{2.5}$ particles escaping in the cooking process. In order to reduce $PM_{2.5}$ concentration, a pan cover is necessary. Cooking habits should be cultivated by more education on the harm of COF to human beings.

5.4 Conclusion

1. Kitchen hood and fume exhaust fan systems are very much less efficient in a real kitchen system. Unlike what is rated on the manufacture's nameplate, in real kitchen conditions, an exhaust fan system runs on very low airflow and far less than expected. In the tracing gas test in a real home kitchen, the airflow of the kitchen hood was about 175 m^3/h, which is only about 1/4 of the airflow listed on the nameplate, even when all kitchen windows and the door were open. When the windows and door were closed, airflow was 45 m^3/h i.e., 6% of the airflow stated on the nameplate. The key reason for this is that the operating conditions

are different. In factory testing, there is no inlet and outlet resistance when rating the airflow on the nameplate. However, in real kitchen conditions, there is a discharge duct taking air from the kitchen to the rooftop. In addition, when the door and windows are closed, the kitchen is in a very airtight condition, with only a 0.41 ACH. All these factors build up the resistance of the cooking exhaust fan and bring down its performance.

2. $PM_{2.5}$ concentration is very much affected by natural ventilation, the mechanical ventilation system and the kitchen airflow pattern. A traditional hood and fume exhaust fan system is not efficient at removing $PM_{2.5}$. The trend for addressing current kitchen fumes is to increase fan pressure, which is not very efficient since in real kitchen conditions the resistance on both the inlet and outlet sides can reduce airflow to 1/4 of the airflow listed on the nameplate. Reducing resistance and/or enhancing airflow rate, but not increasing fan power, could be ways to improve $PM_{2.5}$ removal efficiency. A makeup air system is recommended for removing $PM_{2.5}$ and larger particles in real kitchen conditions. The makeup air, which ultimately originates as outside air, replaces an equal volume of air removed from the kitchen.

3. Other solutions include equipment that can remove $PM_{2.5}$ as well as larger particles but which is easy to clean when it becomes clogged by kitchen-fume oil. In recent years, fan manufacturers have started to explore ways to combine the function of a filter and a fan in a single piece of equipment. The benefit is reduced energy consumption in the filter; however, there is a risk of increased operation and maintenance complexity.

In the field study, one of this kind of equipment was used: the water-wash filter/fan. The water-wash filter uses a rotatable plaque which has a thin water film on the plaque surface to absorb cooking fumes when air goes

through it. The experiment showed that it helps in reducing $PM_{2.5}$ concentration but with limited efficiency.

Another type of equipment under development is that which combines the fan and filter function and can be used in a kitchen environment. The mop fan, developed by the University of Nottingham, utilizes a brush disk, instead of bladed impellers, within a centrifugal fan casing (Riffat & Shehata, 2001). It is a fan, filter, and humidifier, an all-in-one air-cleaning device that fulfils the triple function of de-dusting gas streams, the removal of particulate and gaseous pollutants, and gas circulation. The mop fan was applied for the control of pollutants released to the atmosphere from industrial (especially chemical) and agricultural processes, and its efficiency at removing airborne particulates was tested to approach 97% (Shehata, Riffat, & Shao, 1997).

As the mop fan develops, the flexible fibre mop, which is commonly mounted in a centrifugal fan casing, is coated with a photocatalyst, titanium dioxide. The flexible fibre mop acts as an air impeller as well as a filter for the removal of particulate pollutants. Titanium dioxide (TiO_2), a semiconductor oxide, together with ultraviolet A (UVA) photons in the presence of oxygen and water vapour produce hydroxyl radicals under irradiation. This process is called photocatalytic oxidation (PCO), which is highly effective for the destruction of gaseous pollutants, especially organic air pollutants. Airborne moulds, spores, bacteria and viruses can also be deactivated. Riffat and Zhao's (2007) study concluded that increased mop fibre diameter and quantity, as well as enhanced light source intensity, benefits the dynamic and photochemical performance of the mop cleaning system. Moreover, increasing the airflow rate and reducing the pollutant-generating rate can significantly reduce pollutant concentration in a room.

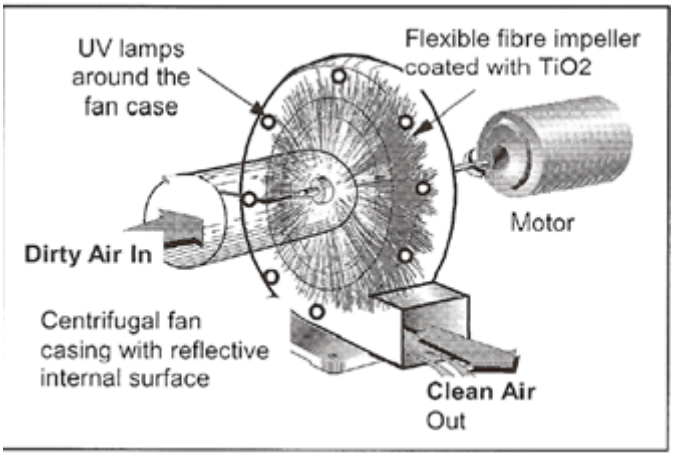


Figure 5-24: MOP fan system operation (Source: Riffat and Zhao's, 2007)

Further research (Riffat & Ma, 2013) has tested the fluid dynamic characteristics, energy consumption, and pollutant degradation effect of the novel mop fan system. It was found that the system has very low energy consumption and is very effective at destroying diesel fumes, a micro-particulate pollutant. Therefore, Riffat and Ma (2013) stated that the novel mop fan system is suitable for any indoor environment to clean the air by removing particulates, odours, viruses, bacteria and volatile organic pollutants due to its high pollutant degradation efficiency, low energy consumption, good appearance, and cost-reduction characteristics.

The mop fan has the advantage of both ease of maintenance and low operation cost because of its low energy consumption. It is suitable for removing kitchen cooking fume $PM_{2.5}$ and larger particles. However, the fan is still in the laboratory prototype testing stage. Once it leaves the laboratory, field testing in real kitchen cooking circumstances can be carried out.

5.5 Summary

Researchers have demonstrated the adverse effect of cooking fumes on human health. See and Balasubramanian (2006) and Wallace (2004) stated

that the average mass concentration and average number concentration of fine particles ($PM_{2.5}$) rocket by a factor of 10 to 85. The literature review showed that Chinese housewives spend, on average, 3.4 to 4 hours in the kitchen every day preparing and cooking meals, i.e., 1/4 of their daily activity (Lai, 2005). A comfortable and healthy cooking environment is, therefore, very important.

Cooking methods, cooking oils, cooking temperature and cooking fume hoods are all critical to fume generation and removal. Among the different frying methods, deep frying shows the largest increase (a 24-fold rise) in the amount of $PM_{2.5}$ concentration compared with the background concentration, followed by pan frying and stir frying (See & Balasubramanian, 2008). Chiang, Wu and Ko (1999) successively tested nine commercial oils heated at 250 °C for 30 minutes, and found the amount of fume particulates generated were in the sequence of soybean > peanut oil > safflower > lard > vegetable > corn > mustard > olive > coconut. In addition to cooking oils, the amount of smoke and grease produced during the cooking process depends on the fat content of items. Foods with a higher fat content tend to release more smoke and grease, regardless of the type of cooking process. Tseng and Chen (2013) measured the variations in particle concentration and size distribution with temperature for cooking oil. The results showed that, in general, from 180 °C to 210 °C, every 5 °C rise in oil temperature would result in a 20~50% increase in ultra-fine particle number concentration. Gao et al. (2013) measured the dynamic concentration of $PM_{0.1\sim10}$ and the inhaled particles fraction under different door and window conditions. It was found that the degree of natural ventilation of a kitchen space also had a certain influence on the capture efficiency of exhaust systems.

Air pollution measurement in a real Chinese kitchen conducted by the researcher revealed that indoor $PM_{2.5}$ concentration is more greatly affected

by cooking than indoor PM_{10}. The measurement also confirms that, in Chinese cooking, the emission of $PM_{2.5}$ can be ranked from deep frying, frying, stir-frying to boiling. Total mass concentration of fine particles increased by more than five times in a kitchen during cooking compared with the background levels. Both oil- and water-based cooking methods showed a similar pattern of a quick climb of $PM_{2.5}$ concentration at the beginning and a sharp drop after reaching the peak. Once the burner is turned off, there is a small surge in $PM_{2.5}$ concentration because the air has cooled after turning off the burner. Therefore, $PM_{2.5}$ at a high level started to descend due to lacking the buoyancy of hot air, increasing the concentration of particles at table-top level.

Tracer gas testing of mechanical kitchen ventilation revealed that kitchen hood and fume exhaust fan systems are very much less efficient in a real Chinese kitchen. There is a large gap in airflow between real kitchen conditions and the nameplate of the ventilation device. This is because in factory testing, there is no inlet or outlet resistance when rating the airflow given on the nameplate. However, in real kitchen conditions, there is a discharge duct taking air from the kitchen to the rooftop and the kitchen is usually airtight, with only 0.41 ACH. All these build the resistance of a cooking exhaust fan and lower its performance.

Computer CFD simulations illustrated that $PM_{2.5}$ is very much less affected by gravity. Its distribution pattern is close to the air movement/velocity. Thus, an increase in airflow, not velocity (needing more motor power) as an effective way of removing $PM_{2.5}$.

Chapter 6: REDUCING COOKING ENERGY AND REMOVING COOKING FUME FINE PARTICLES IN A CHINESE FAMILY KITCHEN

6.1 Reducing Cooking Energy

Existing knowledge indicates that cooking energy takes a large portion of home energy consumption. Comparison studies indicate that in Western countries residential buildings consume more of the national energy than all other types of buildings. However, cooking takes a smaller percentage of household energy (Yang & Jiang, 2007) than its counterpart in China. In a Chinese family, cooking energy takes 35% of the total family energy use, while in Japan and the US this figure is about 7.4%. A Chinese study indicates that, from 1996 to 2011, although cooking energy was reduced from 60% to 31%, the increased efficiency was due to the change in cooking fuel from coal to natural gas (Tsinghua University's Building Energy Research Centre, 2013). There is little research on the relation between cooking energy and Chinese cooking style, cooking utensils, eating culture and cooking culture. However, it is an accepted view that cooking energy is the second-largest energy end user in Chinese families, apart from space heating in the north and space cooling in the south of the country. China is experiencing a fast growth in its urban population and, each year since 2000, the average floor area added to the existing building stock is 219,532,000 m^2. This makes home energy saving, including cooking energy saving, an immediate challenge.

In this research, the cooking energy use was measured in real Chinese families. The cooking utensils and cooking and eating habits were recorded and a summary of findings is listed below.

1. Cooking was ranked the second-largest family energy use in the test families apart from space heating.

2. In a Chinese family, the family members spend a great amount of time cooking. Taking the example of the retired couple, they spent an overall 19% of non-sleeping time in the kitchen preparing morning, noon and evening food and another 9% at the dinner table.

3. The frequency of different foods taken by the test families was also studied. A Chinese family often uses boiling and steaming cooking techniques in preparing staple foods. These staple foods include noodles, porridge, steamed bread and steamed rice. For side dishes, stir frying is the most often used cooking technique.

4. Cooking energy is related to cooking methods. On-site measurement showed that boiling and stewing (slow boiling) ranked high for energy consumption, while frying was ranked low.

5. The most frequently used utensils in the test families were those using water to heat food. A steamer was used to heat water until the water turned to vapour and the water vapour further heated the food. A saucepan was used to boil food directly. A kettle was used to boil the water for drinking purposes. A pressure cooker was used to prepare food in a pressurized closed space by using water. A rice cooker also used water to cook rice. Based on the study, 79% of the cooking utensils used by the retired couple were for steaming and boiling. Since water, as a cooking medium, creates a low cooking temperature and transfers heat slowly, it increases the energy used in the cooking process.

6. The research also discovered the relation between cooking energy consumption and family life cycle. These two parameters had a closer relation than cooking energy consumption and family size. The research also found that the cooking energy of the families in a certain

FLC was similar. This is because of the lock-in effect. The lock-in effect indicates that there are underlying reasons, such as culture and cooking time, in families in the same FLC that keep cooking energy constant.

In the light of the above discoveries, one way to reduce Chinese family cooking energy could be through one of the following areas or the combination of some of the areas listed below.

1. Reducing cooking-related time in Chinese families.
2. Changing the eating culture to take more food that requires less energy to prepare, such as fried food (although the impact on body health would need to be evaluated).
3. Changing cooking utensils to more energy-efficient cooking ware. Table 6-1 shows the energy required for cooking 296 g of presoaked rice under normal condition were 23 minutes and 623 kJ. Energy requirement for cooking presoaked rice reduced by _35% during controlled cooking compared to normal cooking. Mori (1983) reported that a microcomputer‐controlled rice cooker offers higher thermal efficiency by holding down evaporation to a minimum. Thermal efficiency improved by 19% when rice was cooked in a microcomputer-controlled cooker compared to ordinary type electric rice cooker.

Table 6-1: Energy consumption of rice using different types of cooking method (Source: Das et al., 2006)

Table 3
Energy consumption during normal and controlled cooking of presoaked rice using different types of cooking method

S. no.	Type of cooking	Normal				Controlled			
		Energy (kJ)	Duration		Water evaporation loss (g)	Energy (kJ)	Duration		Water evaporation loss (g)
			On time (min)	Total (min)			On time (min)	Total (min)	
1	Electric rice cooker	621	23	23	125	405	15	26	17
2	Pressure cooker-Electrical								
	(a) Open cooking	2340	25	25	321	1260	13	30	62
	(b) Pressure cooking	1440	14	24	34	1080	11	30	25
3	Pressure cooker-LPG								
	(a) Open cooking (high flame)	1749	20	20	259				
	(b) Open cooking (high + low flame)	1391	10 + 13	23	90	1132	10 + 6.5	32	39
	(c) Pressure cooking (high flame)	1180	13.5	23.5	79				
	(d) Pressure cooking (high + low flame)					1137	10.5 + 5.5	32	19

In the research, it was found that Chinese people prefer fried side dishes and boiled/steamed staple foods. Since boiling and steaming use water as heat media, they have the disadvantage of reaching high temperatures and increasing the temperature quickly compared with cooking oil. Thus, cooking oil is a better cooking medium than water to heat food more quickly and save energy. However, a number of research results have proven that eating fried food is unhealthy. This is not only with regard to eating fatty food and gaining weight, but also in terms of fried food being carcinogenic. A cross-sectional study of the dietary intake of 33,542 Spanish adults was conducted by the European Prospective Investigation into Cancer and Nutrition (EPIC) to assess the relationship between fried food and obesity. The logistic regression analysis demonstrated that fried food was positively correlated with general and central obesity among people in the highest quintile of energy intake from fried food (Guallar-Castillón, et al., 2007).

Further, carcinogens, including heterocyclic amines (HCAs), PAHs and acrylamide were identified in carbohydrate-rich foods cooked at high temperatures and under low moisture conditions (Johansson & Jagerstad, 1993; Thiebaud, Knize, Kuzmicky, Hsieh, & Felton, 1995; Wang, Lee,

Shuang, & Choi, 2008). In addition to HCAs and PAHs, which are common cooking oil fume carcinogens, acrylamide has also been classified as a group 2A carcinogen, which means that it is probably carcinogenic to humans, by the International Agency for Research on Cancer (1994). When cooking temperature exceeds 120 °C, hot oil heats the surface of the dough, initiating the formation of acrylamide, and then the Maillard reaction changes the colour of the dough to a golden brown and produces acrylamide (Wang et al., 2008). Moreover, Wang et al. suggested that larger specific surface areas of food generally showed higher acrylamide levels.

Breaking the Lock-in Effect and Changing Food Preferences

The lock-in effect was confirmed in the research by a large-scale survey. In different FLCs, there exist certain cooking patterns and cooking method preferences. These preferences keep the cooking method and cooking menu constant in Chinese families, further fixing the cooking energy consumption. For example, stir frying and steaming consume the largest proportion of household cooking energy.

The energy consumption of various cooking methods, including baking, roasting, broiling, boiling, frying, and stewing, is dissimilar due to different applications of heat and duration (Karel, Fennema, & Lund, 1975). In roasting, food is heated in an oven at 100-300 °C; the heat is simultaneously transferred by a combination of convection (air), radiation (oven walls) and conduction (roasting tin). In frying, fat or oil is used as the heat transfer medium, in direct contact with the food. Deep frying submerges food in hot oil. The heat transfer mechanism includes the conduction of the pan and the convection of the liquid. Pan frying cooks food in a thin layer of fat and transfers heat through conduction (Karel, Fennema, & Lund, 1975).

Roasting requires pre-heating of the oven to reach the desired temperature. A vast amount of energy is consumed to heat the entire volume of the air in

the oven to a temperature of about 200 °C. In contrast, during the frying process, food is in direct contact with hot oil at about 160-180 °C (Berk, 2013). Its heat transfer is fast and the cooking time is short compared with roasting and is thus more energy efficient. According to California's energy efficiency campaign, the energy cost of electric/gas ovens, approximately $0.30-$0.60/$0.05-$0.11 per hour, is much higher than that of electric/gas ranges, which is at a range of about $0.07-$0.30/$0.04-$0.08 per hour (McGruther, 2009). In Hager and Morawocki's (2013) review of residential cooking energy consumption, they compared the efficiencies of electric, natural gas, and liquefied petroleum gas stoves and ovens. The results show that using stoves is more energy efficient than using ovens, in terms of energy consumption per serving, regardless of the type of fuel.

Although the lock-in effect is an obstacle to a change from traditional cooking to a more energy-efficient way of cooking, new ways to cook food that are energy efficient, in other words, economical, have been observed in recent years. Some of the cooking methods have even changed food preferences. This makes breaking the lock-in effect possible; the transition from roasting to frying is happening.

One of the examples of a new cooking method is roast mutton shashlik. This food was introduced from Xingjiang Province and has become popular in coastal provinces in the past 20 years. Traditionally, mutton shashlik stands on a specially designed U-shaped trough and is heated by a wood fire from below. It normally takes 10 minutes to be ready. Recently, small restaurants have discovered that deep frying a piece of mutton is faster than roasting and just needs 2 minutes to be ready. After adding some flavours, customers have accepted deep frying as a way of preparing mutton shashlik. This saves a lot of energy.

Another example is roast duck and chicken. Beijing roast duck has been one of the most welcome items in Chinese cuisine since the Han Dynasty.

However, it normally takes more than an hour to roast this dish in a traditional duck roasting oven. An alternative method is to cook the duck in a pressurized frying oven. Deep frying transfers heat much faster than roasting, and the pressurized oil temperature can be as high as 230 °C in the fryer, so the duck will be done in under half an hour. Moreover, frying can retain the golden-brown appearance and moistness of the meat.

Berk (2013) discussed frying and roasting cookery in his book *Food Process Engineering and Technology (Chapter 24: Frying, baking, roasting)*. During frying, several phenomena, including cooking, dehydration, changes in fat content and in texture and structure, take place simultaneously. The steep temperature gradient at the food and oil interface, together with a coating of batter and breadcrumbs, leads to the creation of the characteristic dual structure of a dry, crisp, golden crust and a moist centre. Roasting can achieve a similar crisp taste by increasing radiation to enhance heating, browning and drying of the surface for the formation of the crust.

Fried food may contain up to 40% oil. Oil intake is mainly decided by the nature of the food surface and the viscosity of the oil. Frying causes dehydration of the molecules at the surface, and thus is more suitable for the absorption of lipids. Oil uptake by the fried product is an important nutritional and organoleptic issue.

Regardless of what kind of cooking methods people use, they can always save cooking energy by increasing appliance efficiency and enhancing their behaviour as consumers during cooking, as these are two major factors influencing end-use cooking energy consumption (Hager & Morawicki, 2013).

The composition, size and shape of cookware all greatly influence energy efficiency and energy consumption. For example, frying mainly uses

conduction to transfer heat, so pans comprising more conductive metals, such as those with a copper base, can be heated on the stove much more efficiently due to the high thermal diffusivity. In contrast, radiation is the primary heating mechanism for roasting, so glass and ceramic dishes can be significantly more efficient than all-metallic cookware, due to their high emissivity (or reflective) property (Amann, Acakerly, & Wilson, 2013).

Pressurized Cooking and Utensils

In order to achieve both healthy cooking methods and low cooking energy consumption, pressure cooking utensils such as pressure cookers are suggested to be used by Chinese families. Since the boiling point of water is 100 °C, boiling and steaming food is less likely to meet the condition of producing carcinogens mentioned above. Moreover, Kim, Yu and Chung (2015) compared the changes in the contents and profiles of various nutrients and bioactive compounds when soybean and rice were cooked together using either an electric rice cooker or an electric rice pressure cooker. The results showed that, compared with the soybean-rice mixture cooked by electric rice cooker, the total content of phenolics, tocopherols and soyasapogenols decreased less when cooking with an electric rice pressure cooker.

Das et al. (2006) conducted an investigation of the energy consumption, water evaporation loss, and total duration time of cooking pre-soaked rice using pressure cookers in open mode and pressure mode (Table 6-2). The results showed that when using electrical pressure cooker, the power-ON time of pressure cooking mode, decreased from 25 minutes to 14 minutes, and the water evaporation loss dropped from 321 g to 34 g, saving energy to the extent of 38.5% compared with using the open cooking mode. The savings in energy can be as high as 44% when cooking unsoaked rice. Moreover, the research also found that in addition to pre-soaking and

pressure cooking, controlled energy input was another optimizing method of utilizing energy for cooking. Monitoring and keeping the cooking temperature at about 100 °C prevents excessive evaporation of water, resulting in energy saving and food not getting scorched.

Cooking Energy Use Intensity

It was found in the research that there was a cooking energy use intensity imbedded in family cooking energy use which is related to the FLC. This intensity is locked-in by the food cultures and cooking habits which have developed in China in the long history since the Tang Dynasty. Over time, different cooking methods were developed based on the technology level, such as the large-scale making of rapeseed oil and the keeping of domestic fowl. The level of cooking technology defined food preferences and cooking methods at certain periods of history. Rule by non-Han Imperials brought in non-traditional foods and cooking methods, such as baking and roasting. The influence of the historical factor on food preferences and cooking methods has locked-in the use of cooking energy in Chinese families. The cooking energy lock-in effect was also discovered in different family life cycles in this research.

Cooking EUI was revealed in this research. The term is borrowed from building energy use intensity, which is measured in $kW/m^2.yr$. Building EUI is a fast tool for estimating annual building energy use before building and even heating and cooling equipment selection. Historically, there is a lack of fast ways to estimate home cooking energy. In most energy simulation software, cooking energy is considered as a process load, which is measured by construction floor area. This research found that cooking energy has no relation to construction floor area. Common sense may indicate that cooking energy has a direct relation with family size, i.e., the number of people in a family. However, the research found that the relation

is weak compared with the connection to family life cycle.

Based on the research, a cooking EUI has been developed which is based on family life cycle. A cooking EUI table is shown below (Table 6-2). The family life cycle is based on Yu and Liu's (2007) research on the Chinese family life cycle, which is different and has more life cycle classifications than that presented in Wells and Gubar's (1966) model.

Table 6-2: Cooking energy use intensity of families in different FLCs

Stage of family life cycle	Cooking energy kWh/day
Young couple, < 35 years old (13.56%)	Various
Middle-aged couple, 35~60 years old (4.73%)	5.1
Elderly couple, > 60 (1.27%)	4.13
Couple living with parents (5.68%)	6.8
Full nest I, young couple with dependent child, dependent child under 6 (18.61%)	Various
Full nest II, young couple with dependent child, dependent child over 6 (12.62%)	Various
Full nest III; middle-aged couple with dependent child over 12 (22.71%)	6.51
Key family I, three-generation family, with the youngest dependent child under 6 (12.62%)	12.86
Key family II, three-generation family, with the youngest dependent child over 6 (3.47%)	N.A.
Key family III, three-generation family, with dependent child (4.73%)	8.13

This research has indicated that most Chinese families' cooking EUI is related to the family life cycle. However, uncertainty exists in the three family life cycle stages containing the highest number of people: young couple, full nest I and full nest II.

Young couples', i.e., newly married couples, cooking EUI shows a great difference between different families. Since young couples frequently eat out in current Chinese society, their home cooking energy is very difficult to define. The data collection showed insignificant cooking energy used in this group. Similar eating-out-often characteristics are appearing in the other two family life cycle stages: couples with children below 6 years old and

6~12 years old. As young couples often eat out, their cooking energy varies in different ways. It is suggested that further research should be carried out with married and unmarried young couples to measure the relation between the frequency of eating out and home cooking energy.

As mentioned before, most examples of energy simulation software currently use process load to handle cooking energy. Figure 6-1 shows a standard eQuest process load input datasheet. The input power of home electrical appliances, such as refrigerators and washing machines, is key and is considered in the simulation. However, because of the lack of a cooking energy database, cooking energy is frequently ignored. In eQuest energy simulation software, the previous way to calculate cooking energy was to treat it as equipment. A fixed energy kW is given as the cooking energy and this equipment is selected in the calculation.

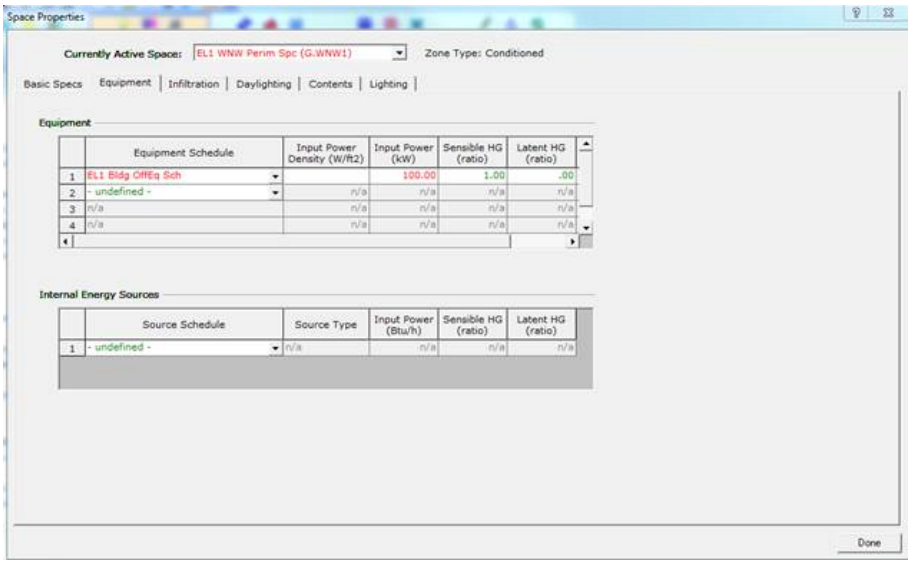


Figure 6-1: Process load input sheet from eQuest

Based on the result of this research and the data listed in Table 6-2, a cooking energy database was built into the energy simulation input sheet illustrated in Figure 6-2. The input sheet shows family life cycle related to cooking energy. The radiant fraction is set up as 0.6, which means 60% of cooking energy changes to space cooling/heating load (CIBSE, 2006).

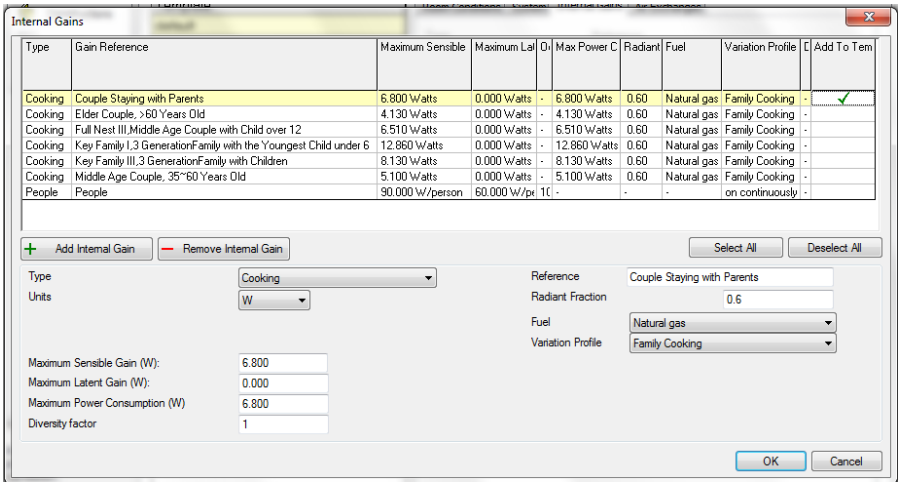


Figure 6-2: Cooking energy input sheet based on family life cycle from IES

Comparison simulation is conducted after the cooking EUI (family life cycle) database was built. Retired couple house is selected as the prototype. The simulation uses China national code, technical guide and other codes as the input date so that simulation result reflects the current simulation situation. Input data reference is listed in below table 6-3:

Table 6-3: Code applied in the energy simulation of retired couple house

Category	Heat Gain	Code / Guide
Number of residents (3.2 person per unit)	Latent heat: 38 W/person Sensible heat: 70W/person	Code of urban residential areas planning & design GB 50180-93, Edition 2002, China Architecture & Building Press, Table 3.0.3 Lu Yaoqing: Applicable Heating and Air-conditioning Design Guide, 2008, 2nd Edition, China Architecture & Building Press, p 1548, Table 20.7-3
Lighting	8W/m2	ANSI/ASHRAE/IES Standard 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings, p64, Table 9.5.1, multifamily
Home Appliances	15.5W/m2	Comnet Modeling Guideline Standard 90.1 - 2016, Appendix B: Modeling

		Data, 2-plug load default receptacle power density: multifamily
Domestic Hot Water	80 liter/person/day Inlet temp. 10C Outlet temp. 60C Efficiency=88%	Code for design of building water supply and drainage (2009 edition), GB 50015-2003, China Architecture & Building Press, Table 5.1.1-1 Design standard for energy efficiency of residential buildings, DGJ 08-205-2011, SRIBS, p14
Air conditioner	EER=2.8, Air-cool	Design standard for energy efficiency of residential buildings, DGJ 08-205-2011, SRIBS, p14
Cooking Gas	2680 MJ/p/a 6.52kW/day/unit; 34% latent heat, 66% sensible heat	Code for design of city gas engineering, GB 50028-2006, Ministry of Construction CIBSE GUIDE A, 2010

Below figure shows several simulation results of the retired couple family. The figure excludes cooling and heating energy. It shows that cooking energy takes about one fifth of household energy excluding cooling and heating in the simulation. The simulation also discloses that simulation result, which is based on building code and design guide, is almost 2 time higher than measurement in real condition. As for cooking energy, the code listed 6.52 kW/day/unit is much higher than cooking EUI listed in the Table 6-2, 4.13 kwh/day/unit. The code 6.52 kW/day/unit equals to the cooking energy used by Full Nest III family: middle-aged couple with dependent child over 12 years old. The portion of this kind of family takes the biggest part in population 12.62% as denoted in Table 6-2.

The comparison simulation reinforces the conclusion that cooking energy takes a big portion in home energy use. In-depth classification of family cooking energy is very necessary.

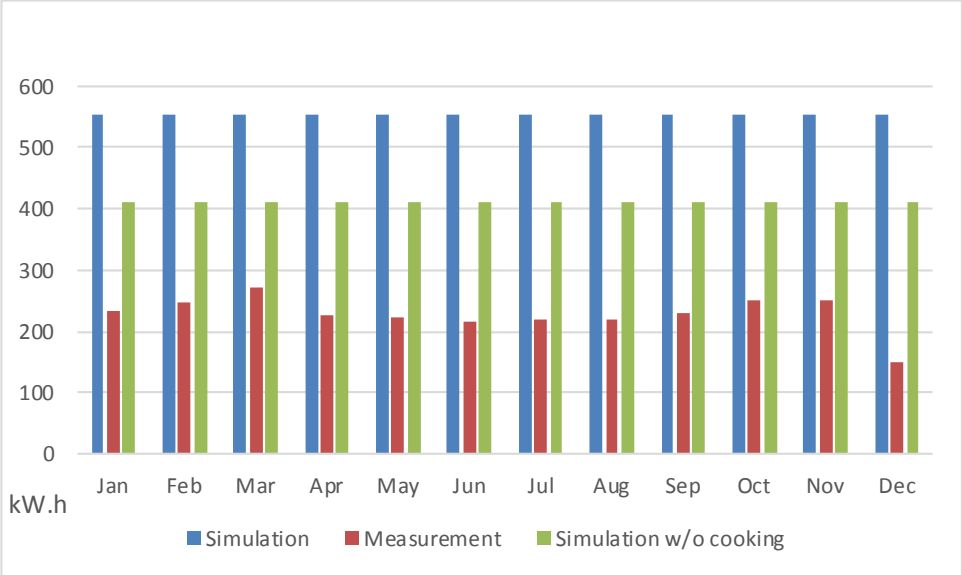


Figure 6-3: Simulation and measurement of household cooking energy

6.2 Removing Cooking Fume Fine Particles

The research discovered that small cooking fume particles ($PM_{2.5}$) have, unlike PM_{10}, a unique character. Small cooking fume particles move in the space when kitchen air flows up and down during and after a period of cooking. A traditional cooking fume exhaust fan does not perform well in removing these small particles because the light weight of the small cooking particles is affected very little by gravity. Small particles tend to float in the air for a longer period and move easily with the airflow. A high airflow rate is critical in removing small cooking fume particles.

Tracer gas testing indicates that there is not enough air ventilation in Chinese kitchen conditions. Scientists at the Lawrence Berkeley National Laboratory (Berkeley Lab) (Delp & Singer, 2012) tested and concluded that cooking exhaust hoods designed for home kitchens varied widely in their ability to capture and vent away the air pollutants generated by the gas burners on cooking stoves. According to their study of the seven representative devices they tested, the capture efficiency varied from less

than 15% to more than 98%, varying across hoods and with the airflow and burner position of each hood. The hoods were more effective at capturing pollutants from the two back burners of a stove than from the front burners. Hoods that achieved airflows recommended by the Home Ventilating Institute's HV1 standard showed capture efficiencies of about 80% or greater for back burners but only 60% or greater for the oven and 50% or more for front burners. Open hoods had higher capture efficiency than those with a grease screen and metal-covered bottoms. The hood with the highest capture efficiency, exceeding 80% for front burners, was a model with a large, open hood that covered most of the front burners, but which generated sound levels too high to allow normal conversation. The capture efficiency of hoods meeting Energy Star criteria was less than 30% for front and oven burners.

In China, Tongji University (BrandChinaWebsite, 2014) has published its research on cooking fume exhaust fan efficiency in removing fine and ultrafine cooking particles. They tested two types of exhaust hood for removing cooking fumes and monitored the fume concentration for both $PM_{2.5}$ and PM_{10}. The testing disclosed that different exhaust hoods had quite different fume removal efficiencies for cooking fumes (the E900T3 has a protruding cone filter and the T550 has an inverted cone oil filter). The inverted cone oil filter (T550) was more efficient at removing cooking fume particles. The low efficiency of the E900T3 was partially attributed to the cooking fume particles hitting the protruding cone and escaping from the hood: the higher the speed of the E900T3, the more particles escaped.

Another interesting observation was that, at low speed, the inverted cone had a lower $PM_{2.5}$ concentration than at high speed (see Figures 6-3 and 6-4). In other words, the faster the speed of the fan, the less efficient it was at removing $PM_{2.5}$. This reinforced the discovery of the current study that $PM_{2.5}$ particles bound back and escape from a hood when they are in a high-

speed air current.

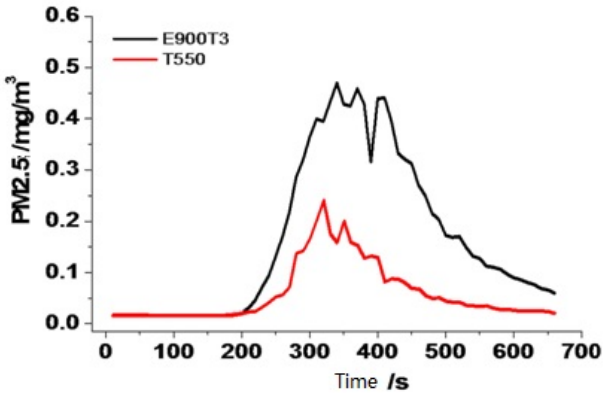


Figure 6-3:PM2.5 capture efficiency at high speed (Source: BrandChinaWebsite, 2014)

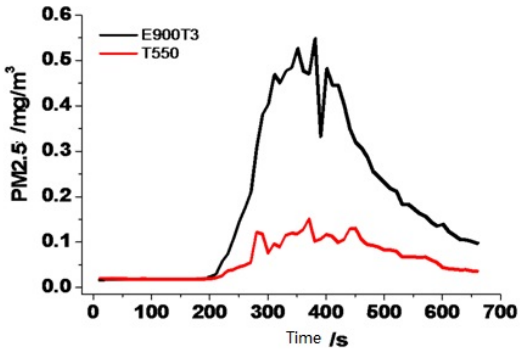


Figure 6-4:$PM_{2.5}$ capture efficiency at low speed (Source: BrandChinaWebsite, 2014)

Cooking Exhaust Fan History and Current Market Trend

Cooker hood development in China has taken place over 20 years. The earliest fans were installed on a wall (Figure 6-5) and could only extract fumes without oil filtration. The first Chinese cooking exhaust hood was manufactured in 1984 in Shanghai and, since then, this kind of product evolved into the 'traditional' Chinese-style kitchen ventilators with both fume and oil elimination, until a wide range of varieties appeared around 2000

(Yaomingjunyao, 2014).



Figure 6-5: Cooking fume exhaust fan development in China

Chinese-style cooking, such as stir frying and frying, generates more oil fumes and moisture than Western-style cooking and requires stronger ventilation forces to remove the fumes and moisture, together with deeper hoods for better exhaust gathering. However, currently, Chinese-style ventilators are only used as replacements in old homes or rented ones, with their strong noise and huge occupation deficiencies.

Western-style ventilators have less capacity in their fume and moisture removal rate but currently possess the largest market share in China. A typical Western-style extractor has a right suction side fan faced with left stove, where the strongest cooking power appears. In comparison, Western-style extractors adjusted for Chinese families have a fan at the back, which could cover larger cooking areas and be suitable for spacious open kitchens.

An inclined-style kitchen ventilator is another of the main products sold in the stores currently with a back-shelf hood. It has the same functions as Western styles, but is different in its exterior design, aiming to extract fumes nearer burner with a smaller stove-covering area. These hoods could be chosen when overhead canopies are impractical (e.g., a low ceiling height or small kitchen spaces) or not desirable. They are suitable for low cooking surface devices, such as griddles, grills, and fryers. Inclined-style kitchen ventilators have less wind flow and relatively lower wind pressure.



Figure 6-6: Domestic kitchen cooker hoods, from left to right: Chinese style, Western style and inclined style

Another typical style of ventilator is referenced from chemistry laboratory exhaust hoods with the primary function of chemical fume, vapour, gas, dust, mist and aerosol extraction (Public Works and Government Services Canada, 2013). A typical fume hood has a box-like structure with a moveable sash window. Experimental procedures are conducted within the hood, which is constantly and safely ventilated through an extract blower and ductwork. The proper hood face velocity, the speed of air induction, is important to the safe and effective operation of a fume hood, as excessive hood-face velocities can often lead to turbulence and reduce capacity to remove contaminants, while insufficient velocities will compromise hood performance. In general, a hood's velocity is suggested to be between 0.3 m/s (60 fpm) and 0.5 m/s (100 fpm).

- Current Kitchen Ventilator Design in the Chinese market

There are three focuses for cooker hood design: 1) a wind fan and turbine for controlling wind flow and wind pressure; 2) being easy to clean; and 3) exterior aesthetics.

The aim of using a cooker hood is to remove the oil but discharge the flue gas, that is screening out the spatter or part of steam, and releasing the surplus steam and submicron to the kitchen. Methodologies of cooker hood effluent extraction come from the negative pressure produced by impellers; thus, to gather exhaust fumes which then pass through an oil separation

board or nest. Finer spatter or steam particles will be thrown to the volute wall later by centrifugal force until condensing into a waste oil tank (Figure 6-7). In short, according to Yu (2014), the three main procedures are concluded as fume accumulation, fume inhalation, and fume emission (Figure 6-8).

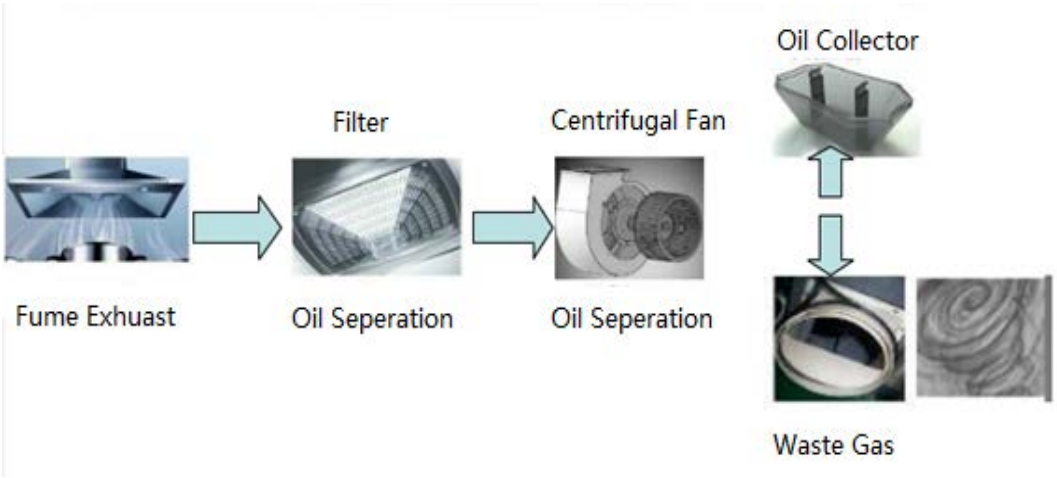


Figure 6-7: Working methodology of cooker hoods



Figure 6-8: Three main steps of cooker hoods: fume accumulation, inhalation and emission

Innovative Kitchen Ventilator Design

According to simulations of the different performances of PM_{10} and $PM_{2.5}$ particles, it was observed that $PM_{2.5}$ particles were affected by airflow in a significant way. Natural ventilation and upward and downward airflow were

all determinants of $PM_{2.5}$ concentration. The $PM_{2.5}$ particle weight is so light that it could simply be ignored. In other words, it was assumed that the $PM_{2.5}$ particle was weightless. Thus, it is more important to provide a large volume of airflow to remove particles than to provide adequate velocity to overcome gravity.

The majority of kitchen ventilators in Chinese households are of an air extraction mode; that is, the air is drawn in and cleaned by the grease filters and directed outside, its retreat prevented by a non-return flap. The exhaust fan, normally of centrifugal or mixed-flow type, consumes 200~220 W to create 230~400 pascals (Pa) (Table 6-4). Most of the power is needed to generate pressure to overcome resistance in the ventilation duct, which normally discharges kitchen fumes to the rooftop, and overcome the gravity for large particles (PM_{10}).

Table 6-4: Parameters of various brands of kitchen ventilator on the Chinese market

Brand	Noise (dB)	Air flow (m^3/min)	Pressure (Pa)	Power (W)
FOTILE	48-50	15	230-270	200
ROBAM	50-70	17-20	≥ 300	200
VATTI	50-70	15-20	300-320	200
SIMENS	70	18-19	390-420	220
SACON	46-53	17-20	310-400	200-220
MIDEA	≤ 55.5	14.5-17.5	280-320	200-220

Based on this study, $PM_{2.5}$, because of its light weight, is affected more by airflow. If a way could be found to treat PM_{10} and $PM_{2.5}$ in different ways, a more energy-efficient method could be used for removing both large and small particles.

Miele has recently been selling a type of recirculation cooker hood on the Chinese market. In this system, air is drawn through the grease filters and an active charcoal filter. The cleaned air is then recirculated back indoors over a vent (see Figure 6-9) (Miele, n.d.). Working with an axial fan installed

on the wall, both cooking grease and $PM_{2.5}$ can be removed by the filter and exhaust air.



Figure 6-9: 40" DA 7000 D Aura island ventilation hood

The combination model of a recirculation and direct vent can not only remove both large and small cooking fume particles, but also save a great deal of energy. The power consumption of a kitchen recirculation cooker hood is 160 W and a direct exhaust fan is 40 W, in general. During the stirring and frying cooking procedure, both the recirculating cooker hood and axial fan on the wall are turned on, while during the boiling and steaming process, only the axial fan works.

Assuming that half the time is spent stirring and frying and the other half is for boiling and steaming, the hypothesis is that an average of two hours are spent on cooking per day according to a public survey, (Yuan, 2014) and 300 days are spent eating at home per year, which means 600 hours per year in total for kitchen ventilation system usage. For the traditional Western-style type with an average of 200 W working power, total electricity consumption is 600*200 = 120 kWh, while in the recirculation + direct vent model, total power consumption is (160+40)*600/2 + 40*600/2 = 200*300 + 40*300 = 240*300 = 72 kWh; in all, saving 48 kWh electricity per year. The power saving is 1/3 in total.

Industry analysis (Zhi Yan Consulting Group, 2015) points out that, in China, the production of kitchen exhaust hoods in 2010 was 19,272,800, while in

2014 this figure was 29,397,300. The rate of increase in 2013 was 21.5%. Assuming each exhaust hood user can save 1/3 of the power consumption, roughly 48 kWh per year, the total saving is tremendous. Figure 6-10 shows the annual production of home kitchen exhaust hoods in China from 2010 to 2014.

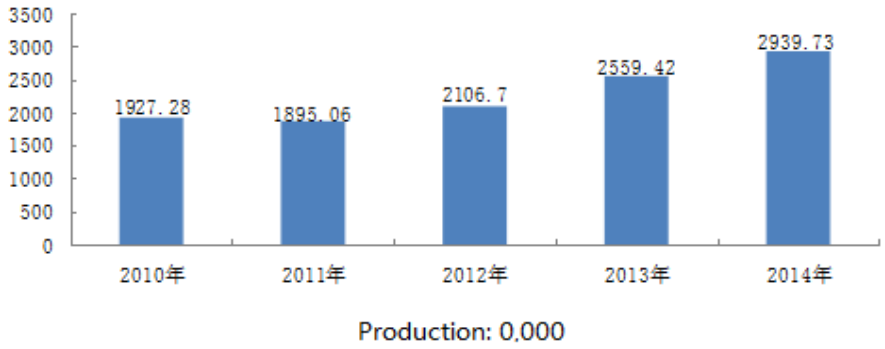


Figure 6-10: Annual production of home kitchen exhaust hoods in China, 2010-2014, (Source: Zhi Yan Consulting Group, 2015)

The tracer gas experiment found that cooking fume hood performance in real kitchen cooking conditions only provided about 1/4 of the airflow rate of that listed on the nameplate of the device. The reason for this was the existence of both suction and discharge side resistance. This resistance increased fan pressure loss and, therefore, reduced airflow rate. Resistance on the suction side included the pressure loss from the window and door. Resistance on the discharge side included the pressure loss in the discharge duct and vertical fume shaft to the rooftop. The above- mentioned recirculation and direct vent system reduces the pressure loss on the fan discharge side. This reduces fan pressure loss and increases airflow rate. In order to reduce pressure loss on the fan suction side, replacing with fresh air is recommended. Replacement fresh air can be introduced with a window and/or door open louvre. A duct without power is also recommended to bring replacement air directly to the cooking area. In this way, without an increase in power consumption, the airflow rate in the kitchen increases significantly to remove $PM_{2.5}$ more efficiently.

Chapter 7: SUMMARY AND CONCLUSION

7.1 Summary of the Thesis

This research has attempted to identify the underlying reasons for high Chinese family cooking energy consumption. Second, this research has tried to identify ways of reducing Chinese kitchen cooking fume pollution. Starting with these two purposes, the research began with an intensive literature review.

The literature review indicated that, although cooking energy takes one of the largest proportions of residential building energy consumption, previous studies in this area have not been enough. The published knowledge found indicates that urban residential buildings takes 1/4 of the national building energy consumption (excluding heating). This portion has grown continuously since 2001 in terms of energy consumption intensity (kgce/m^2). Among household energy (excluding heating), cooking, home appliances and lighting are the three largest energy end users. Although the increase in cooking energy is low, partially attributed to wide adaptation to gas cooking fuel instead of coal fuel in China, it still takes the largest household energy consumption: 31% in 2011.

Many research papers report different results based on field measurements of household energy end users, some of which show conflicting results. However, the literature review has confirmed that in China cooking energy consumes the second-largest amount of household energy after space heating. The literature review also pointed out that, although compared with Western counterparts, Chinese residential buildings consume less national energy, cooking takes a large percentage of household energy.

A further literature review showed little valuable information underpinning the reasons for high cooking energy use in Chinese households. Some

overseas research papers give hints regarding cooking energy and cooking techniques, cookware, and occupant behaviour. However, the difference in food culture traditions has led to a greater difference between Western and Chinese cooking techniques. Compared with Western countries, Chinese hot dishes require a greater number of cooking techniques. This research also considered the history of mainland China and found that, in different dynasties, cooking methods were applied in different ways, which largely depended on the level of the technology and the culture. By the Ming and Qing dynasties, most modern cooking techniques had appeared.

A literature review of a large number of research papers concluded that cooking fumes have an adverse impact on people's health. In China, a typical housewife spends about 4 hours in the kitchen every day, preparing and cooking meals. A comfortable and healthy cooking environment is critical for cooks' health. It was also found that COF emissions in Western and Chinese kitchens differed largely in mass concentration. Cooking method, cooking oil and cooking temperature all contribute to the difference. For example, deep frying gives the largest increase in the amount of concentration of $PM_{2.5,}$ followed by pan frying and stir frying. The amounts of fume particulates generated by various cooking oils is in the sequence of soybean oil > peanut oil > safflower > lard > vegetable > corn > mustard > olive > coconut. Moreover, the research points out that, in general, from 180 °C to 210 °C, every 5 °C increase in oil temperature results in a 20~50% increase in UFP number concentration.

Many other researchers have investigated the details of hood systems and their construction features in order to understand their efficiency in removing cooking fumes. However, most of the research has been based on commercial kitchen application. There is very little research on home kitchen hood efficiency. Research also points out that natural ventilation in the kitchen space has a certain amount of influence on the capture

efficiency of an exhaust system. For example, opening the door is more efficient than opening a window.

In order to find out more details of cooking energy and fume generation in real Chinese home kitchen conditions, the author used a series of research methodologies to measure and test home energy and cooking fume concentration. In the field study, a plug-in energy meter was used to record test family energy use for one year. A calorie meter was installed in the space heating system. Gas meter and water meter data were all recorded. Further, these data were classified into several categories: entertainment, hot water, cooking, cooling, heating, lighting and others. The results reconfirm that cooking energy is the second-largest home energy end user after space heating, along with other findings. These other findings include:

- The four largest energy end users in northern Chinese households are space heating, cooking, hot water and entertainment.
- Hot water, lighting and entertainment energy consumption have clear seasonal characteristics i.e., daily consumption is low in summer and high in winter. This is because of the colder weather in winter (demanding more energy to heat water) and longer nights in winter (with a longer indoor entertainment time and a greater requirement for lighting in the evening).
- Daily cooking energy consumption in a given family is almost fixed, although the difference between different families is large. This could lead to further study on the underlying reasons for the difference between families.

Further study was on trying to understand the different cooking methods and their relation with cooking energy for a Chinese family. The most popular cooking methods, boiling, steaming, frying, stir frying, baking, roasting, smoking, and their related energy consumption were measured

and ranked. It was found that boiling and steaming consumed the most energy. The underlying science points to the thermal properties of cooking media, such as water needing more energy to reach a certain degree of temperature in order to heat food. In addition, the maximum temperature of water is 100 °C before it changes to gas. As a result of these limitations, more time is needed to transfer heat from the heat source to the food. Thus, it is common for Chinese ways of cooking to need more energy than their Western counterparts, whose cooking is often done by baking and grilling.

Another aspect of the work in this research was occupants' cooking habits. The records found that a young couple and their family stir fried their food 65% in total. In second and third places were boiling (12%) and steaming (9%). The elderly couple who took part most often boiled their food (43%), then used stir frying (26%) and steaming (22%). It is easy to conclude that reducing the cooking frequency of steaming and boiling is a key to reducing family cooking energy.

An RFID technique was used to track occupants' behaviour in the test house. It was found that the retired couple spent a large portion of their time cooking (28% of their non-sleeping time). As a result of the large amount of daily time spent on cooking in a Chinese family, educating occupants on energy-efficient cooking practice is an important approach.

The most important finding in the research is the discovery of the relationship between home cooking energy and family life cycle. A strong relation was observed between these two factors. This was confirmed by the measurement of the test families as well as the survey of 70 random selected families. The relation is, therefore, denoted as the CookEUI (cooking energy use intensity) of the different family life cycles. Following the data analysis and survey, it was also found that the cooking energy for a certain family life cycle was constant, i.e., locked in an FLC stage until the stage changed. Finally, a database was built into the IES energy simulation

using figures found in the research. This represents significant progress in home energy study. Before discovering cooking EUI, cooking energy in most pieces of energy simulation software was treated as a process load with a constant figure.

Another focus of this research was kitchen air pollution, particularly $PM_{2.5}$. Previous research has indicated the adverse impact of kitchen fume $PM_{2.5}$ on people's health. However, very little research has been conducted on how to remove $PM_{2.5}$ effectively from Chinese kitchen conditions.

In this research, the measurements of kitchen $PM_{2.5}$ and PM_{10} were carried out in real home kitchen cooking conditions. The relation between $PM_{2.5}$ and PM_{10} emissions and different Chinese cooking methods was measured. It was found that deep frying and stir frying discharged the most $PM_{2.5}$, while boiling emitted the least. A typical $PM_{2.5}$ discharging pattern in Chinese cooking was observed. The pattern showed a sharp increase in $PM_{2.5}$ concentration in the beginning at breath level with a drop afterwards because of the using up of cooking oil or the rising of water steam to a higher level. A small sub-surge was observed after the first selection because the downward flow of cold air brought high-level $PM_{2.5}$ down to breath level.

The research also established that, in Chinese families, breakfast cooking releases less $PM_{2.5}$ than lunch and supper because it uses more water-based cooking methods. Indoor $PM_{2.5}$ concentration is influenced by outdoor $PM_{2.5}$ in a more significant way than PM_{10}. This means that natural ventilation, even a small leakage from the kitchen windows and door or a short open-window period, reduces $PM_{2.5}$ sharply but does not affect PM_{10} very much. During the testing, it was observed that a water-washing-type air cleaner was less effective than mechanical ventilation at reducing $PM_{2.5}$ concentration, even though it is indeed useful in reducing $PM_{2.5}$ concentration. Measurements found that airflow in the kitchen affected

$PM_{2.5}$ much more significantly than PM_{10}. The gravity of $PM_{2.5}$ has little impact on its airborne character.

CFD simulation denoted that it is more important to provide a large volume of airflow to remove particles than to provide adequate velocity to overcome gravity in order to remove $PM_{2.5}$. Several rounds of CFD simulation were conducted to check the airborne patterns of $PM_{2.5}$ and PM_{10} when frying eggs for breakfast with mechanical ventilation on or off. The simulation indicated more PM_{10} sank compared with $PM_{2.5}$. This suggests that $PM_{2.5}$ is much less affected by gravity. Its distribution pattern is close to air movement/velocity and, especially when the cooking fume hood is on, the distribution of the particulates is coherent with the direction of the vectors. This means the particulates from the stove are being transported by the air movement towards the exhaust fan.

In order to verify the airflow of a kitchen cooking hood, tracer gas was used in the research. Unlike the blower door method, tracer gas can be used to check the mechanical ventilation air change in a room. It also has the advantage of not changing building physical structure or introducing other controlled/uncontrolled factors to the testing space, such as adding a blower in the blower door method. The disadvantage of using tracer gas is that it is time-consuming. In the test, in order to check kitchen airtightness, it took about 6 hours for the CO_2 concentration to reach a constant level. The test had to be carried out in the evening so that there was no outside influence during the testing.

A hard learning experience was that since CO_2 exists in the air, there was a baseline CO_2 concentration in the test. This is different from using other tracer gases such as CH_4. As a result of the existence of baseline CO_2, the regression formula is also different. If the wrong formula is applied, the result can be a 20% difference in air change rate.

A very interesting finding observed when using tracer gas to measure kitchen cooking hood efficiency was the large difference between the airflow rate listed on the kitchen fume hood nameplate and the airflow rate measured in real kitchen conditions. On the nameplate of the cooking hood, airflow was rated as 800 m^3/h at medium speed, while in the tracer gas testing the flow rate was a maximum of 175 m^3/h when all the kitchen windows and the door were open. This finding reinforces the experiment conclusion by the Lawrence Berkeley National Laboratory for the seven representative devices they tested, whereby, according to Chen (2012), the capture efficiency varied from less than 15% to more than 98%.

Identifying the airborne moving characteristics of $PM_{2.5}$ can be used to help redesign ventilation systems for Chinese home kitchens. The traditional way of enhancing cooking fume removal efficiency is to increase the fan discharge pressure head. This leads to increased energy consumption. It also has less effect on removing $PM_{2.5}$ particles, since, unlike PM_{10}, $PM_{2.5}$ is affected by airflow rate more significantly than air velocity. The proposed new ventilation system is intended to treat $PM_{2.5}$ and PM_{10} separately. PM_{10} will be removed by the filter in recirculation devices and $PM_{2.5}$ will be exhausted by a direct venting fan with replacement air. In this way, less energy is used and the system is more efficient at removing kitchen $PM_{2.5}$.

7.2 Originality of the Research and the Contribution to Knowledge

The originality of this research and its contribution to knowledge are twofold. Firstly, although it is reported in several previous pieces of research that Chinese cooking uses more energy than its Western counterpart, very little of the research has probed into the details, not to mention attempting to find the cause of this phenomenon. The present research, by measurement and survey, investigated cooking methods, culture preferences and occupant behaviour and their relation to Chinese cooking energy. The most important

finding is that there is an internal relation between Chinese cooking energy and Chinese family life cycle. The underlying reason, i.e., the cooking energy lock-in effect, was discovered and decoded. Cooking energy use intensity (CookEUI) was used to measure the energy consumption of families in different stages of the family life cycle. A database was then built for energy modelling software (IES) to forecast home energy consumption accurately, cooking energy in particular, rather than treating cooking energy as a process load.

Secondly, by measurement and CFD simulation, it was found that $PM_{2.5}$ in kitchens behaves very differently from larger particles such as PM_{10}. Unlike PM_{10}, $PM_{2.5}$ is influenced significantly by airflow in the kitchen. Increasing airflow rate is the key to removing $PM_{2.5}$ efficiently. In real kitchen conditions, there is also a large difference between the airflow rate listed on the nameplate and the real performance of a fan. This is because the factory testing condition has very less pressure loss of the equipment while in kitchen, because of building envelope airtightness and long distance of discharging air duct, pressure loss is high. However, current research on home kitchen ventilation hoods focuses on increased fan power to generate higher pressure to overcome the resistance of the ventilation duct. The home ventilation system suggested in this research treats PM_{10} and $PM_{2.5}$ separately: PM_{10} is removed by a filter and/or a centrifugal grease separator through recirculation, whereas $PM_{2.5}$ is removed by a direct venting fan. In this way, significant energy saving can be achieved. Considering that the number of home kitchen fume hoods sold each year in China is close to 29 million, the total energy saving would be highly significant nationwide.

7.3 Suggestions for Further Work

In this research, the largest contribution to understanding Chinese home cooking energy is how the family life cycle relates to cooking energy use

intensity. It was found that home energy use intensity was strongly related to Yu and Liu's (2007) proposed Chinese family life cycle. In Yu and Liu's life cycle, a Chinese family can experience 10 stages, as shown below:

- Young couple (13.56%)
- Middle-aged couple (4.73%)
- Elderly couple (1.27%)
- Couple living with parents (5.68%)
- Full nest I, young couple with dependent child, dependent child under 6 (18.61%)
- Full nest II, young couple with dependent child, dependent child over 6 (12.62%)
- Full nest III, middle-aged couple with dependent child over 12 (22.71%)
- Key family I, three-generation family, with the youngest dependent child under 6 (12.62%)
- Key family II, three-generation family, with the youngest dependent child over 6 (3.47%)
- Key family III, three-generation family, with dependent child (4.73%)

The research found a strong relation between cooking EUI and six stages of the family life cycle and calculated an EUI number through a survey, summarized in Table 7-1. The EUIs for the other four stages remain undefined. Three of these undefined stages are directly related to young couples because of the uncertainty regarding their cooking and eating-at-home behaviour. The undefined key family II EUI is because of insufficient data to conclude an EUI figure from the survey.

Table 7-1: Cooking energy consumption by stage of family life cycle (Yu & Liu, 2007)

Stage of family life cycle	Cooking energy kWh/day
Young couple, < 35 years old (13.56%)	Various
Middle-aged couple, 35~60 years old (4.73%)	5.1
Elderly couple, > 60 (1.27%)	4.13
Couple living with parents (5.68%)	6.8
Full nest I, young couple with dependent child, dependent child under 6 (18.61%)	Various
Full nest II, young couple with dependent child, dependent child over 6 (12.62%)	Various
Full nest III; middle-aged couple with dependent child, over 12 (22.71%)	6.51
Key family I, 3-generation family, with the youngest dependent child under 6 (12.62%)	12.86
Key family II, 3-generation family, with the youngest dependent child over 6 (3.47%)	N.A.
Key family III, 3-generation family, with dependent child (4.73%)	8.13

The survey, which was carried out in a Beijing residential quarter, covered about 70 randomly selected families. As indicated in Chapter 3: Field Study, Beijing is an immigration city which accommodates various cultures nationwide, including cooking culture. The study undertaken in this research and the discoveries regarding the cooking of Beijing citizens represent nationwide behaviour. However, the existence of local culture may influence the representativeness of the EUI.

Based on the above notes from the research, future studies on Chinese home cooking energy are suggested to focus on the following areas.

1. Separate home cooking and eating behaviour studies should be carried out among young couples. Since young couples cover three different family life cycle stages - young couple without children, young couple with young children, and young couple with grown-up children - each of them represents a sub-group. The underlying reasons for eating out or eating at home need to be classified. This will help to understand the inconsistency in home cooking energy results found in the survey

conducted in this research.

2. An example of key family II, a three-generation family, with the youngest dependent child over 6 (3.47%), was rarely found in the survey. Although in Yu and Liu's (2007) research this stage represents 3.47% of Chinese families, the percentage needs to be reviewed, as nine years have passed since the research was published. The changing housing conditions, demographics and economic development may reduce the chance for three generations to live together under one roof. If further research demonstrates that there is a significant reduction of families in this stage of the family life cycle, the EUI will not be studied.

3. The conclusion for EUI was based on research in a Beijing residential quarter. Adjusting for cultural differences is unavoidable because it was found that the EUI lock-in effect had a cultural component. For example, parents' cooking menu affected children's taste preferences and had a further effect on children's cooking behaviour. The responses agreeing with this kind of influence represented 29% of the answers to the online cooking behaviour survey. One task for future research is to understand the degree to which cooking behaviour is different for different family life cycles. Once this difference is identified, EUI adjustment will be easier and have a clearer direction. This kind of research may need more time and a larger scale of survey and measurement.

Another significant contribution of this research is the proposal of a way to treat PM_{10} and $PM_{2.5}$ separately when removing home kitchen cooking fumes. A recirculation system is proposed to remove large cooking grease particles and a direct venting system is proposed for removing small cooking particles and water vapour/moisture. Both systems can work separately in order to save energy. Further, replacement air needs to be introduced to the kitchen to enhance the airflow rate of the fan. Since the discovery in this research was made by CFD modelling, future study should

focus on product development, project implementation, and field measurement of system efficiency.

1. The trend in research in the current Chinese market on kitchen exhaust hoods is to increase fan power in order to generate higher pressure. This pressure is used to overcome vertical cooking fume duct resistance and gravity, as well as to increase airflow velocity in order to raise larger cooking particles to the rooftop vent opening. The pressure loss is higher in the vertical cooking fume shaft than is used to overcome gravity. The proposed system, however, is made of two separate devices: a grease filter and a direct venting fan. The key task of the grease filter is to separate grease from the cooking fumes. Recirculation devices currently on the market mainly use a filter to remove grease. A dedicated centrifugal grease separator should be designed and added by using centrifugal force to separate grease further, as shown in Figure 7-1.

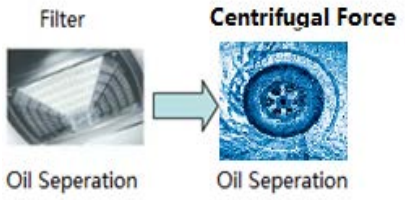


Figure 7-1: Two stages of oil separation in the proposed recirculation device

2. Replacing air is important in a kitchen ventilation system. As observed in the tracer gas experiment carried out in real kitchen conditions, the actual airflow rate performance of a fume hood is about 1/4 of that listed on the nameplate of the device. This coincides with an experiment at the Lawrence Berkeley National Laboratory. According to Chen (2012), of the seven representative cooking fume hoods tested at the laboratory, the capture efficiency varied from less than 15% to more than 98%.

3. A pilot project should be built using the new system to test its actual

performance. The first batch of pilot projects is suggested to be conducted in one-storey or low-rise residential buildings. These projects are suggested to be located in different provinces in China, since different cultures apply different ways of cooking, e.g., using different cooking oils and cooking methods.

4. Measurements taken in actual cooking conditions in the pilot projects on $PM_{2.5}$ removal efficiency need to continue. A comparison study using a traditional Chinese cooking ventilation hood system is suggested. Thus, both cooking fume removal efficiency and energy consumption can be concluded. Any small energy saving observed and measured is important, since the collective energy saving in all home cooking fume removal devices will be significant, as shown in Figure 6-10.

The discovery of cooking energy use intensity and the redesigning of home kitchen ventilation systems will dramatically change Chinese kitchen technologies. It is intended that the findings in this research will draw the attention of industry players in the right direction and catalyse innovation. This research is particularly useful in proposing a new home kitchen ventilation system. However, BAH's (Booz, Allen & Hamilton, 1982) new product process indicates that new product development does not automatically appear in the marketplace. Instead, development is the result of labour-intensive, expensive and bureaucratic efforts. One such process comprises seven sequential stages: new product strategy development, idea generation, screening and evaluation, business analysis, development, testing, and commercialization. The purpose of this research was to identify existing problems in the Chinese cooking environment. Ideas for a solution were generated from problems found in the experiment; these were not tested by any market analysis. Thus, the author's suggestion of developing a prototype of a new kitchen ventilation system/ device is rushed and impractical.

However, the author still puts forward the idea of developing a new kitchen fume exhaust system because, according to Schumpeter, the supply of new technologies is more important than the adaptation to existing patterns of demand. Furthermore, only product innovations can lead to the creation of new industries. Product innovation are thus more significant than process innovations, which can only lead to the increased efficiency of existing industries (Coombs, Saviotti, & Walsh, 1987).

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