Asia-Pacific
Economic Cooperation

Low Carbon Town and Physical Energy Storage

FINAL REPORT

APEC Energy Working Group

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CONTENTS

PREFACE

The APEC project - Low Carbon Town and Physical Energy Storage aims at promoting the technology combination of renewable energy and energy storage. The energy consumption of buildings will be reduced and the regional energy security in APEC regions will be enhanced.

The key objectives of the project are:

1) To develop a viability evaluation system for the efficient energy storage system. With the help of this evaluation system, the application of the renewable energy storage system can be used in different climatic zones in APEC regions to achieve Low Carbon Building.

2) To improve the communication among experts and researchers from all over the world, through the APEC Conference on Low Carbon Town and Physical Energy Storage held at Changsha during May 25th and 26th, 2013.

3) To disseminate the physical energy storage technology through the exhibition of phase change material and energy storage unit developed by Changsha Maxxom High-tech Co., Ltd..

This report presents the findings of Low Carbon Town and Physical Energy Storage Project, which was conducted Changsha Maxxom High-tech Co., Ltd. from November 2012 to August 2013.

We want to thank all the presenters and others who spent time with us for discussions. This report is inevitably inadequate; your advices and suggestions will be highly appreciated.

PART 1: APPLICABILITY ANALYSIS ON PCM-BASED FREE COOLING TECHNOLOGY FOR BUILDINGS IN APEC REGIONS

Phase change material (PCM)-based free cooling is understood as a means to store outdoors cold in a thermal energy storage unit using PCM during the night, to supply indoors cooling during the day. The evaluation of applicability of PCM-based free cooling technology is crucial to its application. In this paper, fourteen typical cities in APEC regions were selected. Based on the hourly outdoor air dry bulb temperature in the typical meteorological year, the air conditioning cooling load and the potential of PCM for cold storage in summer for the fourteen typical cities were evaluated. Then, combined with the two aspects, an applicability analysis on PCM-based free cooling technology for buildings was presented.

Applicability analysis on PCM-based free cooling technology for buildings in APEC regions

1.1. Introduction

The use of thermal energy storage (TES) system using phase change material (PCM) is an effective way to compensate the mismatches that occur between the times of energy supply and demand, and has the advantages of high energy storage density during phase change at an extremely low temperature difference or a relatively constant temperature. For those reasons, TES system using PCM has gained increasing attention [1-5]. With the constant raising of people's living standard in China, air conditioning is becoming a necessity for most families, and the energy consumption will keep rising. So, it is necessary to promote the application of TES technology using PCM for heating and cooling of buildings, using renewable energy (such as solar energy and natural cold resource). PCM-based free cooling is understood as a means to store outdoors cold in a TES unit using PCM during the night, to supply indoors cooling during the day.

The evaluation of applicability of PCM-based free cooling technology is crucial to its application. In this paper, based on the hourly outdoor air dry bulb temperature in the typical meteorological year, an applicability analysis on PCM-based free cooling technology for buildings in fourteen typical cities in APEC regions was presented. All the meteorological parameters are collected by subcontractors. The fourteen typical cities are from China, Japan and US. There are five cities in China, namely Hong Kong, Kunming, Changsha, Zhengzhou and Shenyang, locating in five different climate zones, respectively. There are three cities in Japan, Kagoshima, Tokyo and Sapporo. And the cities in US are Los Angeles, New Orleans, San Antonio, Seattle, Washington Dc and Chicago, locating in six different climate zones, respectively. Their geographical positions are shown in Table 1.1 - Table 1.3. Due to the great differences between climatic conditions among all the cities, an equal time period of the three summer months (from the beginning of June to the end of August) was selected for all the cities to make a direct comparison of the results.

Table 1.1 Selected cities in China and their geographical positions

City	Hong Kong	Kunming	Changsha	Zhengzhou	Shenyang
Latitude	22.32 °	25.02 °	28.22 °	34.72 °	41.73 °
longitude	114.17 °	102.68 °	112.92 °	113.65 °	123.45 °

Table 1.2 Selected cities in US and their geographical positions

City	Los Angeles	New Orleans	San Antonio	Seattle	Washington Dc	Chicago
Latitude	33.93 °	30.05 °	29.33 °	47.68 °	38.98 °	41.78 °
longitude	-118.40 °	-90.03 °	-98.47 °	-122.25 °	-77.47 °	-87.75 °

Table 1.3 Selected cities in Japan and their geographical positions

City	Kagoshima	Tokyo	Sapporo
Latitude	31.57 °	36.18 °	43.05 °
longitude	130.55 °	140.42 °	141.33 °

1.2. Air conditioning cooling load

Fig.1.1 - Fig.1.3 shows the monthly average temperature from June to August in the fourteen typical cities. The results show that the monthly average temperature in summer are high for Hong kong, Changsha, Zhengzhou, New Orleans, San Antonio and Kagoshima, while the values are lower for Kunming, Los Angeles, Seattle and Sapporo. For Hong Kong, Kunming, Changsha, Zhengzhou, Shenyang, Los Angeles, New Orleans, San Antonio, Seattle, Washington Dc, Chicago, Kagoshima, Tokyo and Sapporo, the average temperatures of three months in summer are 28.4, 19.9, 27.2, 26.2, 23.5, 19.4, 28.2, 28.2, 17.9, 23.4, 23.6, 26.6, 22.1 and 19.7 °C, respectively.

Cooling degree days (CDD) and cooling degree hours (CDH) can provide a simple estimate of energy consumption by cooling systems during the summer season, for the reason that both of them contain the hot degree and duration [6-8]. In this report, the air conditioning cooling load was evaluated by cooling degree days base on 26 °C (CDD26, °C·d) and cooling degree hours based on 26 °C (CDH26, °C·h).

The total numbers of CDD26 for the whole year can be calculated by:

$$CDD26 = \sum_{n=1}^{365} (T_n - 26)D \tag{1.1}$$

Where n is the number of days of the year; T_n is the daily outdoor average dry bulb air temperature, °C; D is one day, d. If T_n is lower than 26 °C, the temperature difference should be taken as 0 °C.

The total numbers of CDH26 for a day can be calculated by:

$$CDH26 = \sum_{i=1}^{24} (T_i - 26)h \tag{1.2}$$

Where i is the number of hours of the day; T_i is the hourly outdoor dry bulb air temperature, °C; h is one hour, h. If T_i is lower than 26 °C, the temperature difference should be taken as 0 °C.

Fig.1.4 shows the total numbers of CDD26 for the whole year in the fourteen typical cities. It is clear that the values of CDD26 are high for Hong Kong, New Orleans and San Antonio, especially for Hong Kong, that is up to 309 °C·d, While the values are very small for Kunming, Shenyang, Los Angeles, Seattle, Washington DC, Tokyo and Sapporo, especially for Kunming, Los Angeles and Seattle, with the value of 0.

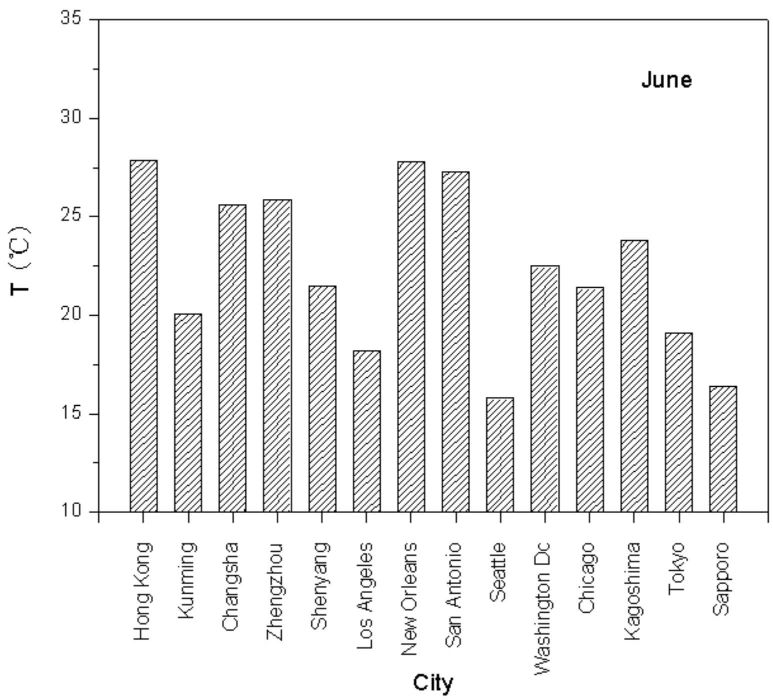

Fig.1.1 Monthly average temperature in June in fourteen typical cities

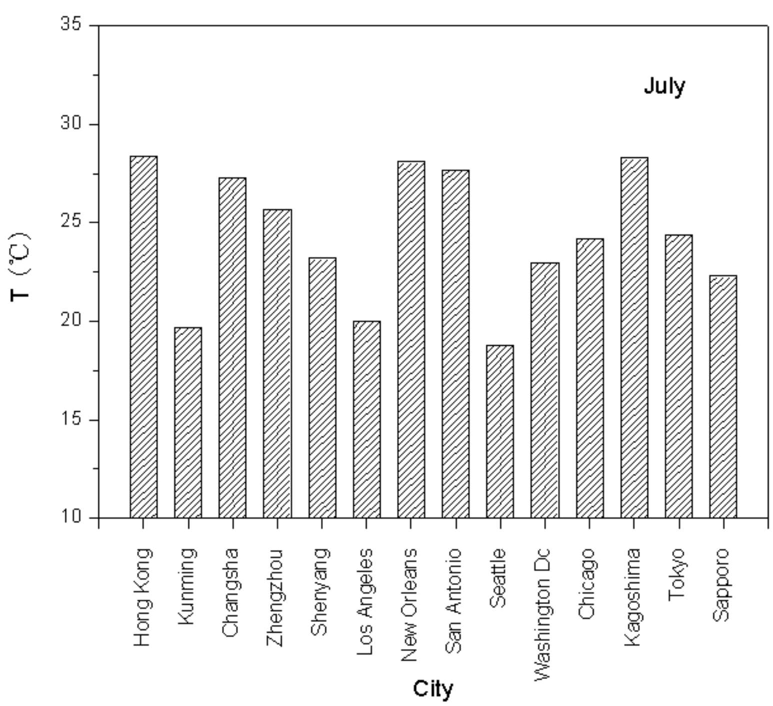

Fig.1.2 Monthly average temperature in July in fourteen typical cities

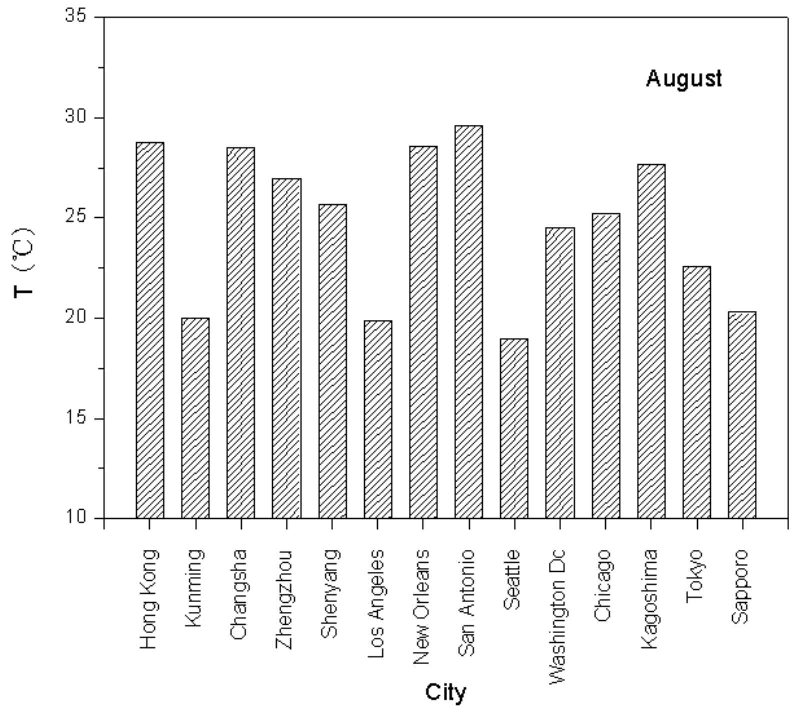

Fig.1.3 Monthly average temperature in August in fourteen typical cities

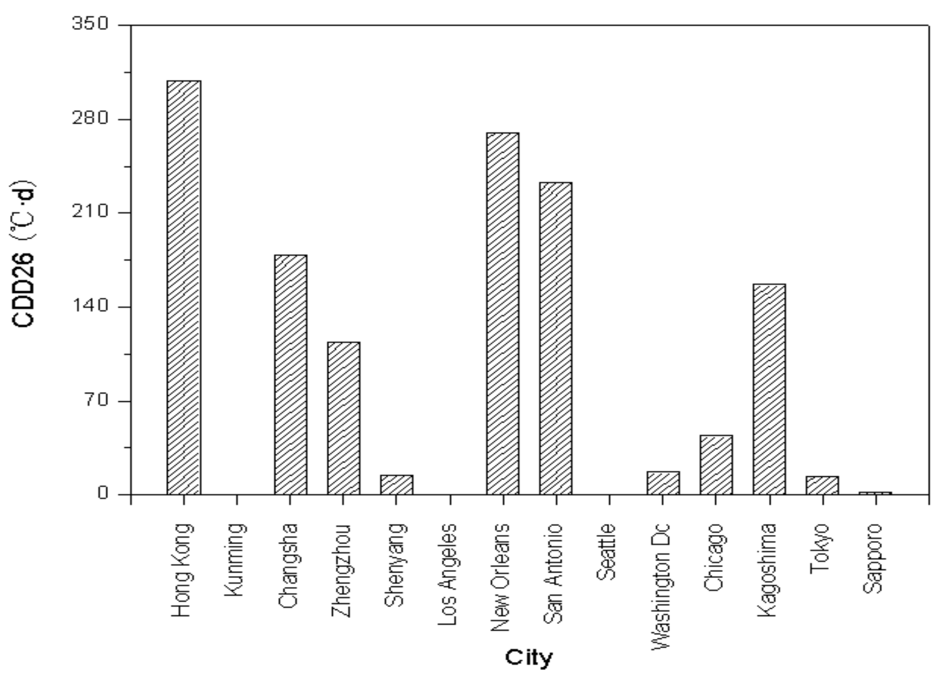

Fig.1.4 Total numbers of CDD26 for whole year in fourteen typical cities

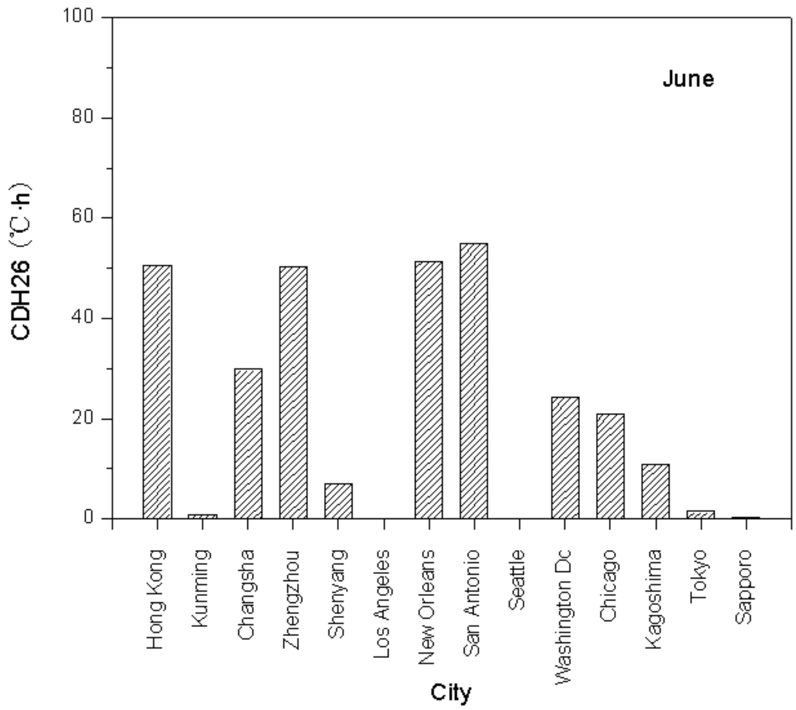

Fig.1.5 Monthly average CDH26 in June in fourteen typical cities

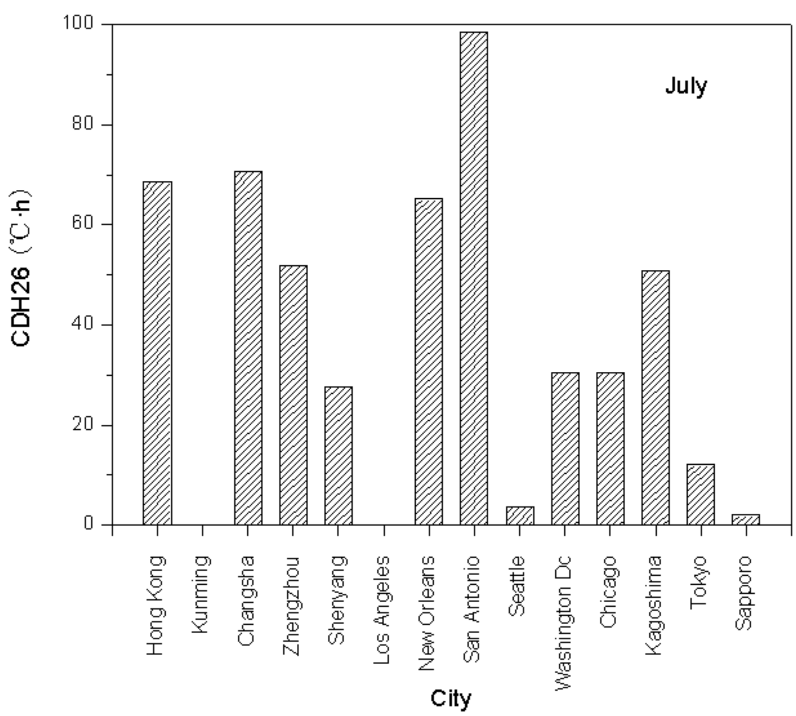

Fig.1.6 Monthly average CDH26 in July in fourteen typical cities

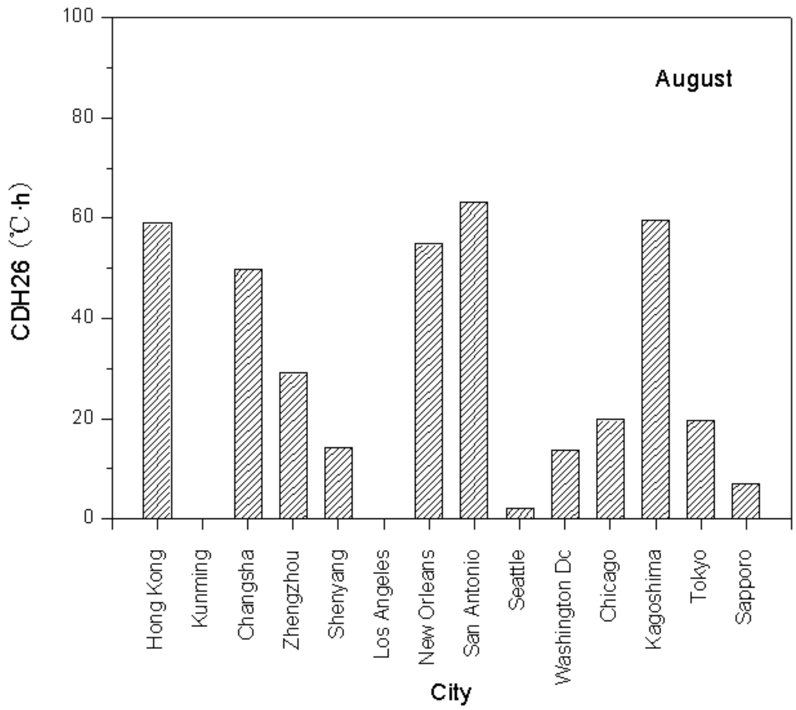

Fig.1.7 Monthly average CDH26 in August in fourteen typical cities

Fig.1.5 - Fig.1.7 shows the monthly average CDH26 from June to August in the fourteen typical cities. The results show that the monthly average CDH26 in all the three summer months are high for Hong kong, Changsha, New Orleans and San Antonio, and the corresponding values both in July and August are high for Zhengzhou and Kagoshima, while the corresponding values in all the three summer months are low or zero for Kunming, Los Angeles, Seattle and Sapporo. The average CDH26 of three months in summer are 60, 0, 50, 44, 16, 0, 57, 72, 2, 23, 24, 41, 11 and 3 ℃·h, for Hong Kong, Kunming, Changsha, Zhengzhou, Shenyang, Los Angeles, New Orleans, San Antonio, Seattle, Washington Dc, Chicago, Kagoshima, Tokyo and Sapporo, respectively.

From above analysis, the air conditioning cooling load are high for Hong Kong, Changsha, Zhengzhou, New Orleans, San Antonio and Kagoshima, while the values for Kunming, Los Angeles, Seattle and Sapporo are low.

1.3. Potential of PCM for cold storage

The monthly average diurnal temperature (diurnal temperature = daily maximum temperature - daily minimum temperature) from June to August in the fourteen typical cities is shown in Fig.1.8 - Fig.1.10. It is found that the diurnal temperature in summer is low for Hong Kong and Los Angeles, while Zhengzhou, Shenyang, San Antonio, Seattle, Washington DC and Chicago have high diurnal temperature. The average diurnal temperature of three months in summer are 3.5, 6.5, 7.2, 9.0, 9.2, 5.2, 6.9, 11.8, 8.5, 11.5, 8.9, 6.4, 7.3 and 6.7 °C, for Hong Kong, Kunming, Changsha, Zhengzhou, Shenyang, Los Angeles, New Orleans, San Antonio, Seattle, Washington Dc, Chicago, Kagoshima, Tokyo and Sapporo, respectively.

Artmann et al. [9] proposed climate cooling potential (CCP) to evaluate the potential of night ventilation. Based on the concept of CCP and CDH, cold storage degree hours (CSDH, °C·d) was developed to evaluate the potential of PCM for cold storage.

The total numbers of CSDH during the time from h_i to h_f in one day can be calculated by:

$$CSDH = \sum_{h=h_i}^{h_f} (T_m - T_i)h \quad (1.3)$$

Where *i* is the number of hours of the day; T_i is the hourly outdoor air temperature, °C; T_m is the melting temperature of PCM, °C; *h* is one hour, h. If T_m is lower than T_i, the temperature difference should be taken as 0 °C. In this report, the phase change process started at 19:00 pm and ended at 7:00 am in the next day morning. For example, to calculate the value of CSDH on the tenth day, the charging period was from 19:00 pm on the ninth day until 7:00 on the tenth.

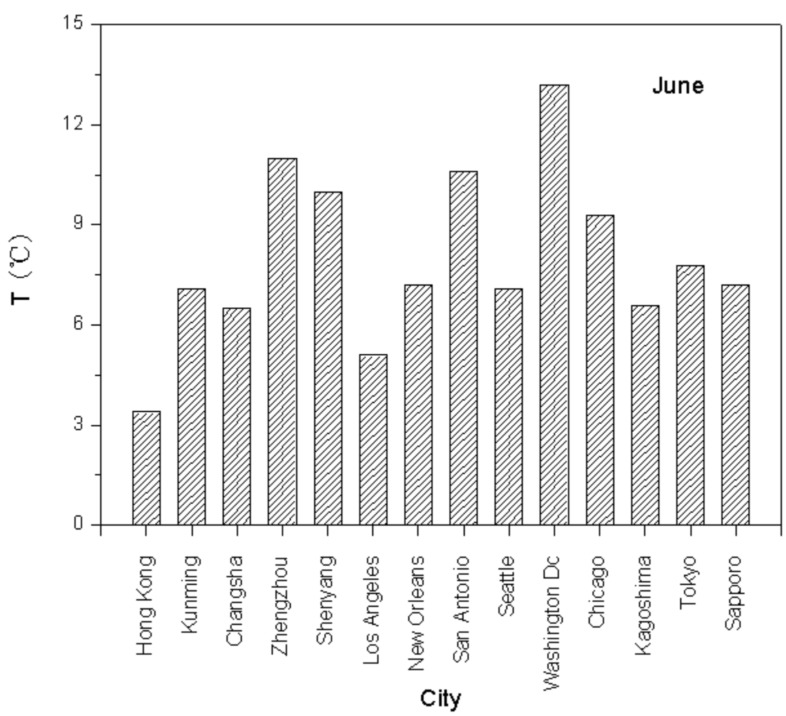

Fig.1.8 Monthly average diurnal temperature in June in fourteen typical cities

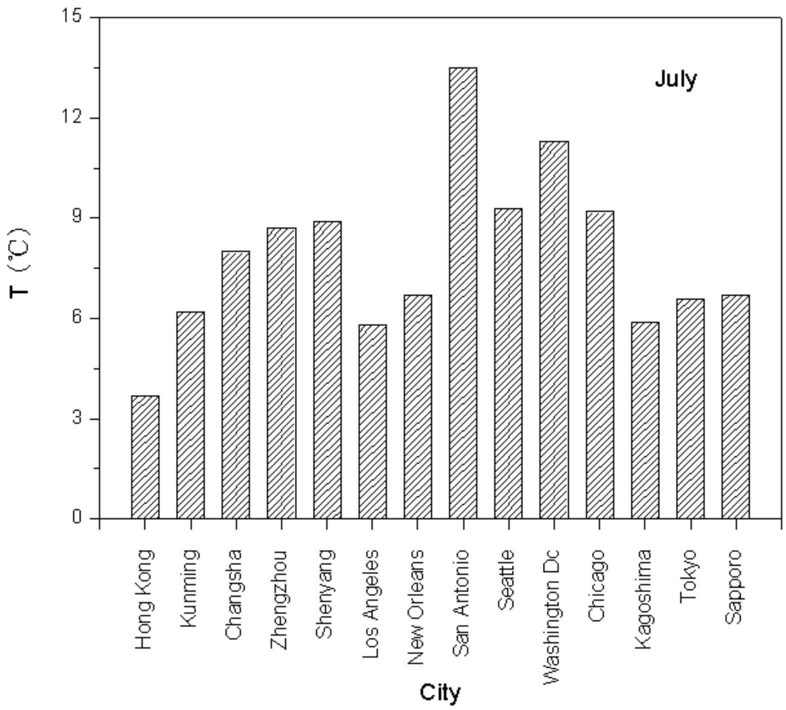

Fig.1.9 Monthly average diurnal temperature in July in fourteen typical cities

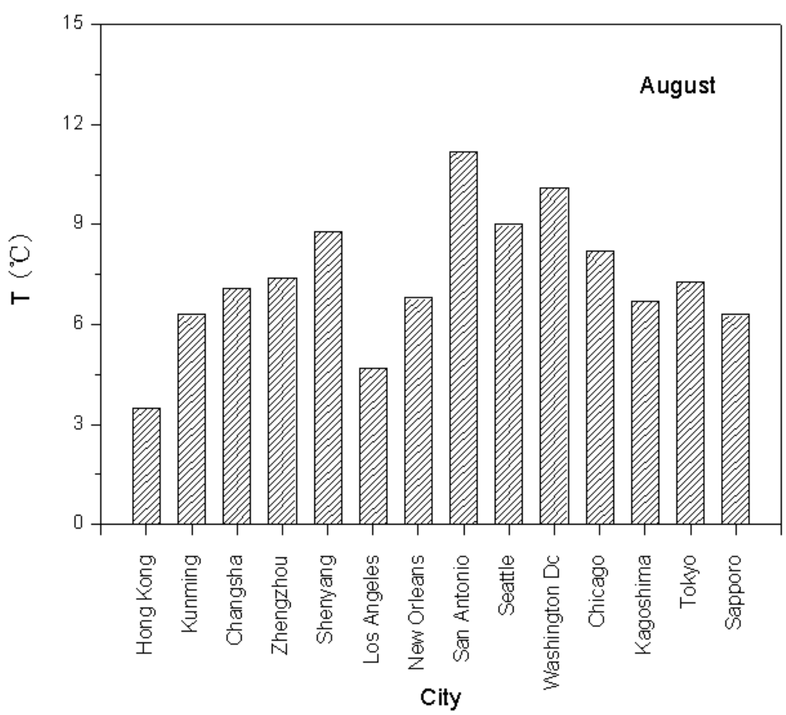

Fig.1.10 Monthly average diurnal temperature in August in fourteen typical cities

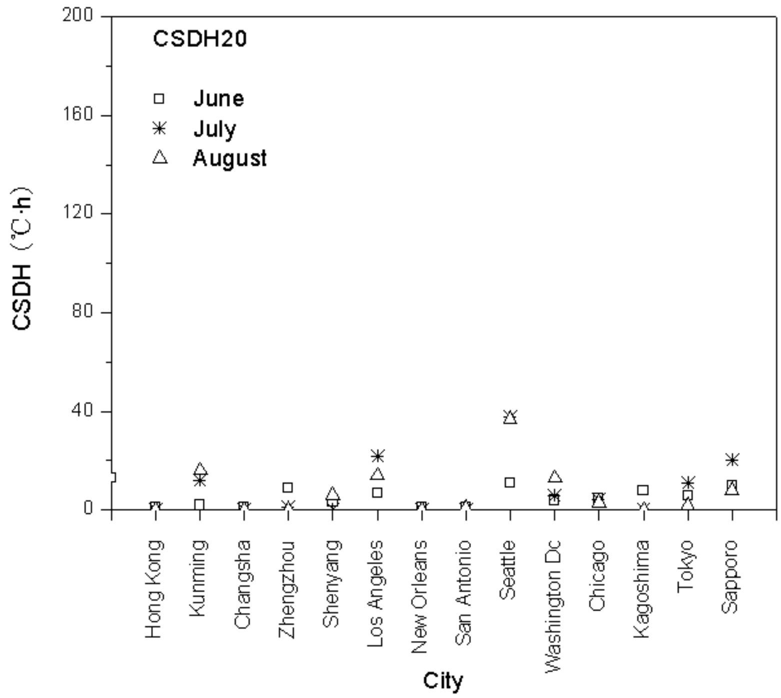

Fig.1.11 Monthly average CSDH20 from June to August in fourteen typical cities

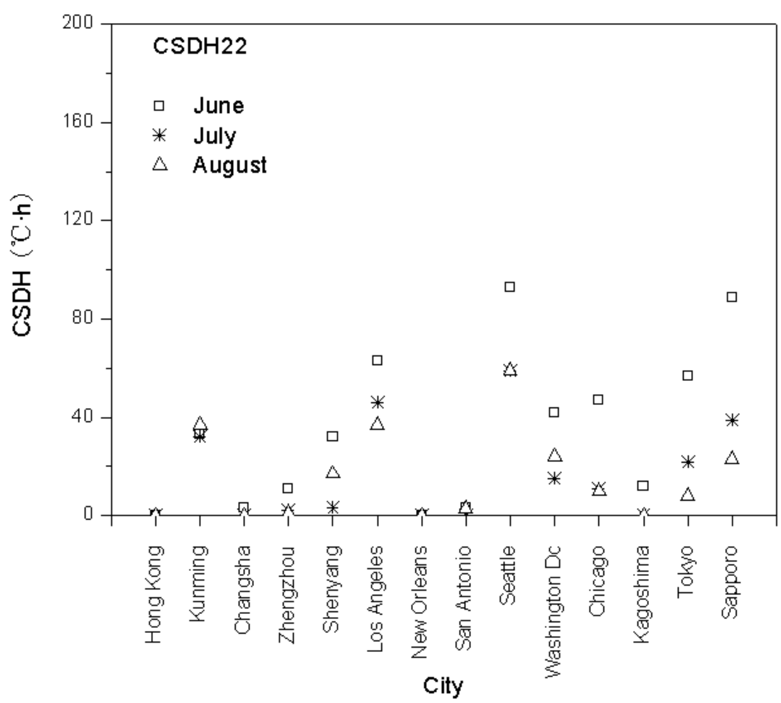

Fig.1.12 Monthly average CSDH22 from June to August in fourteen typical cities

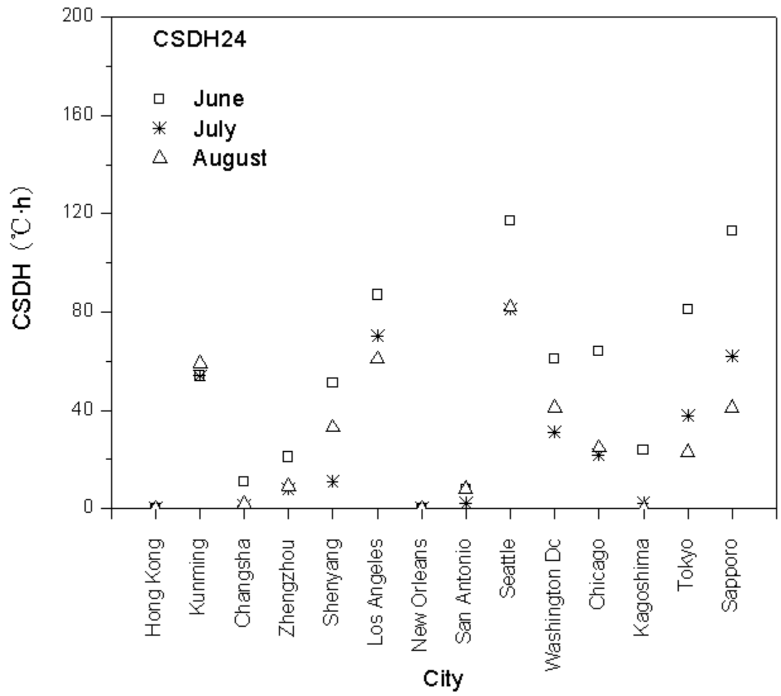

Fig.1.13 Monthly average CSDH24 from June to August in fourteen typical cities

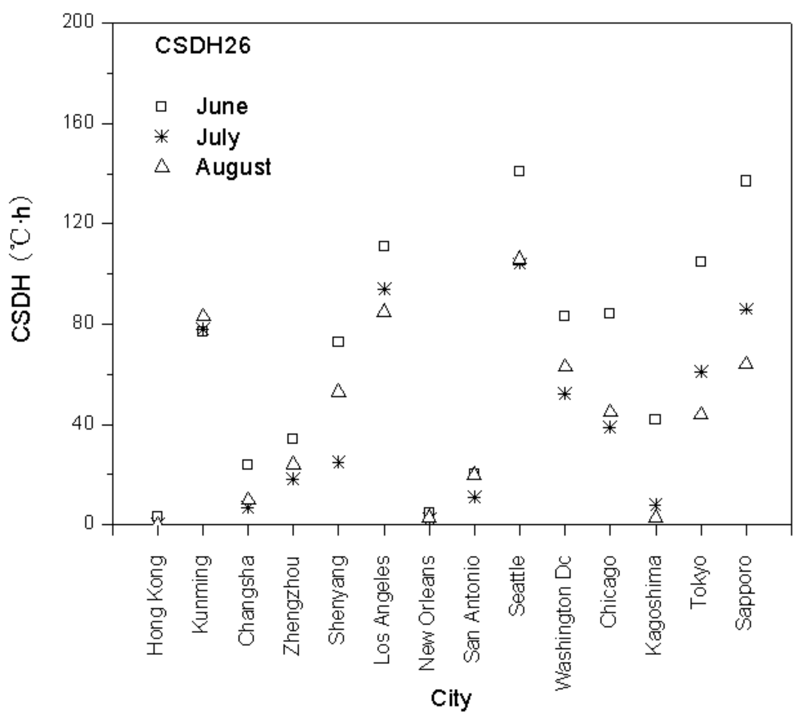

Fig.1.14 Monthly average CSDH26 from June to August in fourteen typical cities

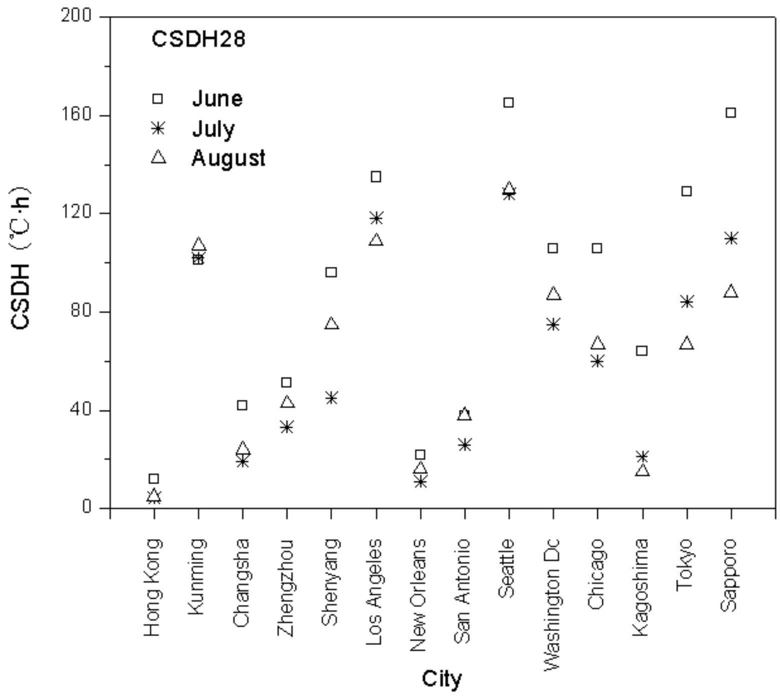

Fig.1.15 Monthly average CSDH28 from June to August in fourteen typical cities

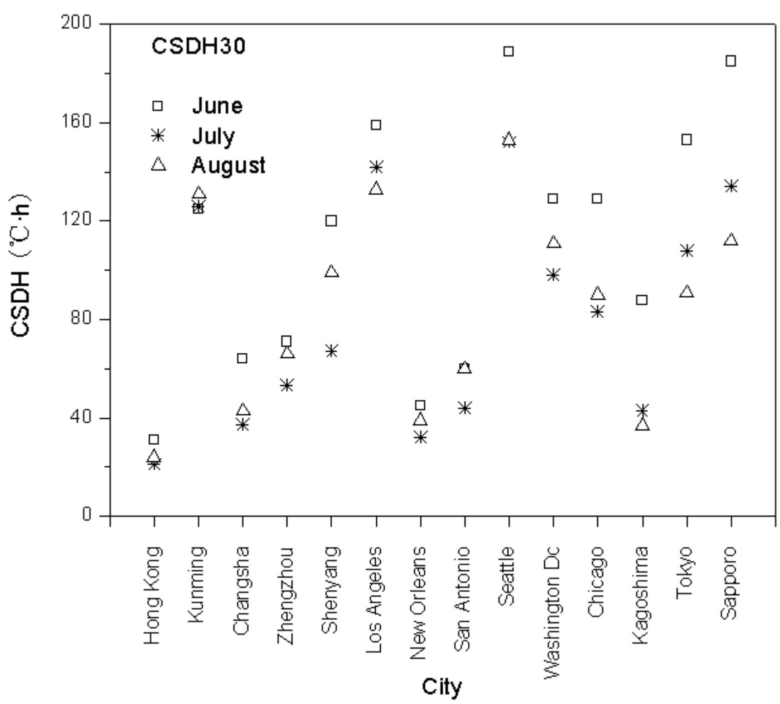

Fig.1.16 Monthly average CSDH30 from June to August in fourteen typical cities

The monthly average CSDH from June to August in the fourteen typical cities are shown in Fig.1.11 - Fig.1.16. CSDH20 to CSDH30 is the value of CSDH for melting temperature of PCM from 20 to 30 °C. The results show that the CSDH increases along with the increment of the melting temperature of PCM, that is, the potential of PCM for cold storage increases. The lowest melting temperature that the PCM can store cold in all the three summer months is 28, 20, 26, 24, 24, 20, 26, 26, 20, 20, 20, 26, 20 and 20 ℃, for Hong Kong, Kunming, Changsha, Zhengzhou, Shenyang, Los Angeles, New Orleans, San Antonio, Seattle, Washington Dc, Chicago, Kagoshima, Tokyo and Sapporo, respectively.

1.4. Applicability analysis

With the melting temperature of PCM close to the outdoor ambient temperature at night, the cold to be stored will be limited due to the low temperature difference between PCM and outdoor air. While, with the melting temperature of PCM close to the indoor design temperature during the day, the cold to be stored will improve, but the cold to supply indoors cooling during the day is reduced. So, it is important to select an appropriate melting temperature of PCM to maintain indoor thermal comfort, and the selection of PCM must base on local climatic condition and air conditioning cooling load. Numerical simulations by Arkar and Medved [10] showed that a PCM with a melting temperature between 20 and 22 ℃ is the most suitable for free cooling in the case of a continental climate. Medved and Arkar [11] found that the optimum PCM has a melting temperature that is approximately equal to the average ambient air temperature in the hottest month, and that the free cooling potential is proportional to the average daily amplitude of the ambient air's temperature swings. Butala and Stritih [12] considered that the human comfort zone in summer time is between 23 ℃ and 27 ℃. In order to achieve sufficient heat transfer, the temperature difference between the air temperature and the melting temperature of the PCM should be within the range of 3-5 ℃. So, for a summer cooling system, the melting temperature of the PCM should be from 19 to 24 °C. Mosaffa et al. [13] considered that in building applications, PCMs with a phase change temperature of 18-30 °C are preferred to meet the need for thermal comfort.

According to "Code for design of heating ventilation and air conditioning (GB50736-2012)" in China [14], the thermal comfort design temperature in summer for the region that people stay for a long time is about 24-28 °C, and the corresponding value for the region that people do not stay for a long time can increase 1-2 °C. Take into consideration about the temperature difference of 3-5 °C for heat transfer, the melting temperature of PCM for the former can be 20-24 °C, while the value of the latter can be 22-26 °C. Combined with the air conditioning cooling load and the potential of PCM for cold storage in summer, an applicability analysis on PCM-based free cooling technology for buildings was presented as follows.

In Hong Kong, due to the high ambient temperature and the low diurnal temperature, the potential of PCM for cold storage is very poor. The monthly average CSDH both in July and August are very small even when the melting temperature is 28 °C, so PCM-based free cooling technology in Hong Kong is not suitable.

In Changsha, New Orleans, San Antonio and Kagoshima, when the melting temperature is 26 ℃, the monthly average CSDH both in July and August are small for Changsha and Kagoshima, and the value in all the three summer months in New Orleans is small. When the melting temperature is 28 ℃, the monthly average CSDH from June to August in Changsha are 42, 19 and 24 °C·h respectively, the corresponding values in New Orleans are 22, 11 and 16 °C·h respectively, in San Antonio are 38, 26 and 38 °C·h respectively, and in New Orleans are 64, 21 and 15 °C·h respectively. PCM-based free cooling technology in Changsha, New Orleans, San Antonio and Kagoshima has relatively poor applicability. However, due to the high temperature and the high air conditioning cooling load, a TES system using PCM with melting temperature of 28 ℃ can be selected for cooling or precooling hot fresh air in the four cities.

When the melting temperature is 24 ℃, the monthly average CSDH both in July and August in Zhengzhou is small and the value in July in Shenyang is small. When the melting temperature is 26 ℃, the monthly average CSDH from June to August in Zhengzhou are 34, 18 and 24 °C·h respectively, and the corresponding values in Shenyang are 73, 25 and 53 °C·h respectively. PCM-based free cooling technology in Zhengzhou and Shenyang has good applicability. Therefore, a TES using PCM with melting temperature of 26 ℃ can be selected for the thermal comfort deign for the region that people do not stay for a long time, along with for the cooling of hot fresh air in the two cities. In addition, a TES using PCM with melting temperature of 24 ℃ can be selected for the thermal comfort deign for the region that people stay for a long time in Shenyang, due to the lower air conditioning cooling load, and the corresponding monthly average values of CSDH from June to August are 51, 11 and 33 °C·h, respectively.

In Kuming, Los Angeles, Seattle, Washington Dc, Chicago, Tokyo and Sapporo, the PCM can store cold in all the three summer months even the melting temperature is 20 ℃, the monthly average CSDH both in July and August in Chicago is small, and the value in August in Tokyo is small. When the melting temperature is 24 ℃, the monthly average CSDH from June to August in Kunming are 54, 54 and 59 °C·h respectively, the corresponding values in Los Angeles are 87, 70 and 61 °C·h respectively, in Seattle are 117, 81 and 82 °C·h respectively， in Washington Dc are 61, 31 and 41 °C·h respectively, in Chicago are 64, 22 and 25 °C·h respectively， in Tokyo are 81, 38 and 23 °C·h respectively, and in Sapporo are 113, 62 and 41 °C·h respectively. Therefore, the potential of PCM for cold storage in those regions is great. However, for Kunming, Los Angeles, Seattle and Sapporo, due to the low temperature and the low air conditioning cooling load, the thermal comfort environment can be reached by fresh air supply directly without cold storage. But, for Washington Dc, Chicago and Tokyo, a TES using PCM with melting temperature of 24 ℃ can be selected for the thermal comfort deign for the region that people stay for a long time.

1.5. Conclusions

The evaluation of applicability of PCM-based free cooling technology is crucial to its application. In this paper, combined with the air conditioning cooling load and the potential of PCM for cold storage in summer, an applicability analysis on PCM-based free cooling technology for buildings in fourteen typical cities in APEC regions was presented. The conclusions were obtained as follows.

(1) For Hong Kong, Kunming, Changsha, Zhengzhou, Shenyang, Los Angeles, New Orleans, San Antonio, Seattle, Washington Dc, Chicago, Kagoshima, Tokyo and Sapporo, the average diurnal temperature of three months in summer are 3.5, 6.5, 7.2, 9.0, 9.2, 5.2, 6.9, 11.8, 8.5, 11.5, 8.9, 6.4, 7.3 and 6.7 °C respectively, and the lowest melting temperature that the PCM can store cold in all the three summer months is 28, 20, 26, 24, 24, 20, 26, 26, 20, 20, 20, 26, 20 and 20 ℃respectively.

(2) In Hong Kong, due to the high ambient temperature and the low diurnal temperature, the potential of PCM for cold storage is very poor. The monthly average CSDH both in July and August are very small even when the melting temperature is 28 ℃ so PCM-based free cooling technology in Hong Kong is not suitable.

(3) In Changsha, New Orleans, San Antonio and Kagoshima, PCM-based free cooling technology has relatively poor applicability. However, due to the high temperature and the high air conditioning cooling load, a TES system using PCM with melting temperature of 28 ℃can be selected for cooling or precooling hot fresh air in the four cities.

(4) In Zhengzhou and Shenyang, PCM-based free cooling technology has good applicability. Therefore, a TES using PCM with melting temperature of 26 ℃can be selected for the thermal comfort deign for the region that people do not stay for a long time, along with for the cooling of hot fresh air in the two cities. In addition, a TES using PCM with melting temperature of 24 ℃can be selected for the thermal comfort deign for the region that people stay for a long time in Shenyang, due to the lower air conditioning cooling load, and the corresponding monthly average values of CSDH from June to August are 51, 11 and 33 °C·h, respectively.

(5) In Kuming, Los Angeles, Seattle, Washington Dc, Chicago, Tokyo and Sapporo, the potential of PCM for cold storage in those regions is great. However, for Kunming, Los Angeles, Seattle and Sapporo, due to the low temperature and the low air conditioning cooling load, the thermal comfort environment can be reached by fresh air supply directly without cold storage. But, for Washington Dc, Chicago and Tokyo, a TES using PCM with melting temperature of 24 ℃can be selected for the thermal comfort deign for the region that people stay for a long time.

1.6. Reference

[1] Sharma A, Tyagi V.V., Chen C.R., et al. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 2009, 13(2):318-345.

[2] Raj V.A.A., Velraj R. Review on free cooling of buildings using phase change materials. Renewable and Sustainable Energy Reviews, 2010, 14(9):2819-2829.

[3] Osterman E, Tyagi V.V., Butala V, et al. Review of PCM based cooling technologies for buildings. Energy and Buildings, 2012, 49:37-49.

[4] Al-Abidi A.A., Bin Mat S, Sopian K, et al. Review of thermal energy storage for air conditioning systems. Renewable and Sustainable Energy Reviews, 2012, 16(8):5802-5819.

[5] Waqas A, Ud Din Z. Phase change material (PCM) storage for free cooling of buildings—A review. Renewable and Sustainable Energy Reviews, 2013, 18:607-625.

[6] Satman A, Yalcinkaya N. Heating and cooling degree-hours for Turkey. Energy, 1999, 24(10):p.833-840.

[7] Fu X, Zhang H, Huang G. Discussion of climatic regions of building energy efficiency in China. Heating Ventilating & Air Conditioning, 2008, 38(2):44-47. [In Chinese]

[8] Lv S， Kazuo E， Norio I. Distribution characteristics of heat load and correlation with meteorological elements in China. Sichuan Building Science, 2010, 36(2):248-251. [In Chinese]

[9] Artmann N, Manz H, Heiselberg P. Climatic potential for passive cooling of buildings by night-time ventilation in Europe. Applied Energy, 2007, 84(2): 187-201.

[10] Arkar C, Medved S. Free cooling of a building using PCM heat storage integrated into the ventilation system. Solar Energy, 2007, 81(9):1078-1087.

[11] Medved S, Arkar C. Correlation between the local climate and the free-cooling potential of latent heat storage. Energy and Buildings, 2008, 40(4):429-437.

[12] Butala V, Stritih U. Experimental investigation of PCM cold storage. Energy and Buildings, 2009, 41(3):354-359.

14] Mosaffa A.H., Infante Ferreira C.A., Talati F, et al. Thermal performance of a multiple PCM thermal storage unit for free cooling. Energy Conversion and Management, 2013, 67:1-7.

[15] National Standard of the People's Republic of China. Code for design of heating ventilation and air conditioning (GB50736-2012). Beijing: China Architecture & Building Press, 2012. [In Chinese].

PART 2: PHASE CHANGE MATERIAL FOR PCM-BASED FREE COOLING TECHNOLOGY FOR BUILDINGS

This part of report presents a review of the phase change materials (PCMs) for PCM-based free cooling technology for buildings. The classification and properties of PCMs, thermal energy storage technology and its application in buildings are stated. Based on all the contents above, the method to select PCMs for buildings is discussed. Finally, a summary of candidate PCMs with melting temperature between 20 and 26 °Cis presented.

2.1. Summary of phase change material

The main forms of physical energy storage are sensible heat storage and latent heat storage. The latter form has attracted particular attention because of the large amount of heat absorption/release during the phase change processes with small temperature intervals. Phase change material is the essential part for latent heat storage. PCMs use chemical bonds to store and release the energy. They are categorized as organic materials and inorganic materials, as shown in Fig.2.1.

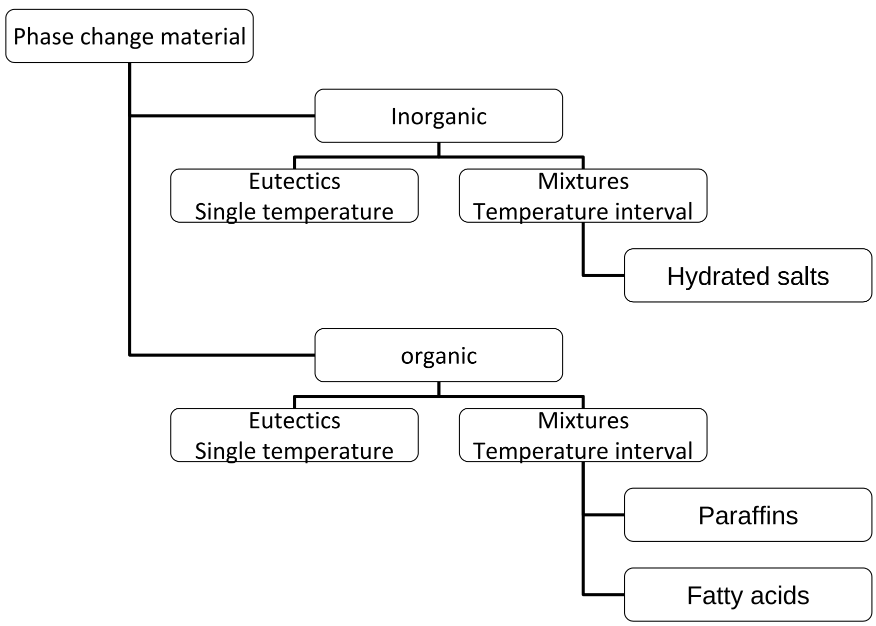

Fig.2.1 Classification of phase change materials [1]

Both organic and inorganic materials could be classified as eutectic temperature and multiple temperature materials. Inorganic material has higher thermal conductivity, higher energy storage density and no flammability. However, super cooling and phase segregation happen during phase transition [2, 3]. Organic material has little super cooling and segregation during transition; while, the thermal conductivity is lower. And it has higher volume changes during transition and flammability. The main properties of inorganic and organic PCMs are present in Table 2.1.

At present, the application of PCMS for HVAC in buildings is mainly about two methods. The first one is incorporating PCMs in building envelope. And the other one is integrating PCM into the ventilation system. This report mainly concerns about the latter method, using PCMs with night natural source.

Table 2.1 Classification and properties of PCMs [4]

Classification	Inorganic	Organic
Category	Crystalline hydrate, molten salt, metal or alloy	High aliphatic hydrocarbon, acid/esters or salts, alcohols, aromatic hydrocarbons, aromatic ketone, lactam, freon, multi-carbonated category, polymers
Advantages	Higher energy storage density, higher thermal conductivity, non-flammable, inexpensive	Physical and chemical stability, good thermal behaviour, adjustable transition zone
Disadvantages	Subcooling, phase segregation, corrosive	Low thermal conductivity, low density, low melting point, highly volatile, flammable, volume change
Methods for improvement	Mixed with nucleating and thickening agents, thin layer arranged horizontally, mechanical stir	High thermal conductivity additives, fire-retardant additives

Hasnain et al. [5] compared the typical data of sensible heat storage and phase change materials used in thermal storage, as shown in Table 2.2. The energy storage density of PCMs is much bigger than that of sensible heat storage materials. The value of inorganic is ten times more than the value of water.

Table 2.2 Comparison of various heat storage media (stored energy=10^6 kJ=300 kWh; ΔT=15 K) [5]

	Heat storage material			
	Sensible heat storage materials		Phase change materials	
Property	Rock	Water	Organic	Inorganic
Latent heat of fusion (kJ/kg)	*	*	190	230
Specific heat (kJ/kg)	1.0	4.2	2.0	2.0
Density (kg/m^3)	2240	1000	800	1600
Storage mass for storing 106 kJ (kg)	67000	16000	5300	4350
Relative mass **	15	4	1.25	1.0
Storage volume for storing 106 kJ (m^3)	30	16	6.6	2.7
Relative volume **	11	6	2.5	1.0

* Latent heat of fusion is not used for sensible heat storage material.

** Relative mass and volume are based on latent heat storage in inorganic phase change materials

2.2. Selection methods of PCM for PCM-based free cooling technology for buildings

2.1 Thermophysical properties

According to Ref [6], the desirable thermophysical parameters of PCM for thermal storage system are as follows:

I. Melting temperature is in the desired operating temperature range.
II. It should have high latent heat of fusion per unit volume.
III. In addition, it should have high specific heat to provide extra sensible heat.
IV. High thermal conductivity for both solid and liquid phases is needed.
V. Small volume change during phase change process and small vapour pressure at operating temperature are requested.

Cool storage technology for air conditioning systems gradually developed and flourished with the development of cool storage materials [7]. Stritih and Butala[8] considered that the human comfort zone in summertime is 23-27 ℃ In order to achieve sufficient heat transfer, the temperature difference between the air temperature and the melting temperature of the PCM should be within the range of 3-5 ℃ This means that for a summer cooling system, the melting temperature of the PCM should be from 19 ℃to 24 ℃ A latent heat storage unit incorporating heat pipes embedded in phase change material (PCM) is developed and tested for a novel application in low energy cooling of buildings by Turnpenny et al.[9]. They found that when the difference between air and PCM temperature was 5 °C, the heat transfer rate was approximately 40 W over a melt period of 19 h. Numerical simulations by Arkar and Medved [10] showed that a PCM with a melting temperature between 20 and 22 °C is the most suitable for free cooling in the case of a continental climate.

From above analysis, the PCM should be selected according to the different climatic and air conditioning cooling load conditions. According to "Code for design of heating ventilation and air conditioning (GB50736-2012)" in China [12], the thermal comfort design temperature in summer for the region that people stay for a long time is about 24-28 ℃, and the corresponding value for the region that people do not stay for a long time can increase 1-2 ℃ Take into consideration about the temperature difference of 3-5 °C for heat transfer, the melting temperature of PCM for the former can be 20-24 °C, while the value of the latter can be 22-26 °C. So the melting temperature of PCM to be consider in this paper is 20-26 ℃ The candidates PCMs have been studied by researchers are shown in Section 2.3.

2.2 Other properties.

A good PCM not only should have desirable thermophysical properties, but also desirable kinetic and chemical properties, along with economics. The other characteristics required for a good PCM are as follows[6]:

(1) Nucleation and crystal growth.

High nucleation rate to avoid subcooling of the liquid phase during solidification, assuring that melting and solidification process occurs at the same temperature.

High rate of crystal growth promises the system could meet the demand for heat recovery from storage system.

(2) Stable chemical properties.

Complete reversible freeze/melt cycle.
No degradation after a large number of freeze/melt cycles.
No corrosiveness to the construction/encapsulation materials.
Non-toxic, non-flammable and non-explosive.

(3) Economics.

Abundant.
Available.
Cost effective.
Easy recycling and treatment.
Good environmental performance based on Live Cycle Assessment (LCA).

2.3. Candidate PCMs for PCM-based free cooling technology for buildings

3.1. Inorganic phase change material

The thermophysical properties of inorganic PCMs investigated in the literature are listed in Table 2.3 - Table 2.5.

Table 2.3 Thermophysical properties of inorganic eutectic materials

Material	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)	References
50% $CaCl_2$ + 50% $MgCl_2 + 6H_2O$	25	95	–	–	[1]
66.6% $CaCl_2 \cdot 6H_2O$ + 33.3% $MgCl_2 \cdot 6H_2O$	25	127	–	–	[3]

Table 2.4 Thermophysical properties of inorganic (salt hydrate) materials

Material	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)	References
$FeBr_3 \cdot 6H_2O$	21	105	–	–	[1]
$Mn(NO_3) \cdot 6H_2O$	25.5	125.9	–	1738	[1]

Table 2.5 Thermophysical properties of inorganic mixture materials

Material	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)	References
55–65% $LiNO_3 \cdot 3H_2O$ + 35–45% $Ni(NO_3)_2$	24.2	230	–	–	[1]
45% $Ca(NO3)_2 \cdot 6H_2O$ + 55% $Zn(NO3)_2 \cdot 6H_2O$	25	130	–	1930	[1]
66.6% $CaCl_2 \cdot 6H_2O$ + 33.3% $MgCl_2 \cdot 6H_2O$	25	127	–	1590	[1]

3.2. Organic phase change material

The thermophysical properties of organic PCMs investigated in the literature are listed in Table 2.6 - Table 2.9.

Table 2.6 Thermophysical properties of paraffin materials

Material	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)	References
Paraffin C_{16}–C_{18}	20–22	152	–	–	[12]
Paraffin C17	21.7	213	–	–	[1]
Paraffin C13–C24	22–24	189	–	–	[3]

Table 2.7 Thermophysical properties of fatty acid mixture materials

Material	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)	References
Capric acid + lauric acid	21	143	–	–	[3]
26.5% myristic acid + 73.5% capric acid	21.4	152	–	–	[1]
75.2% capric acid + 24.8% palmitic acid	22.1	153	–	–	[1]
34% myristic acid + 66% capric acid	24	147.7	–	–	[1]

Table 2.8 Thermophysical properties of organic eutectic materials

Material	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)	References
34% $C_{14}H_{28}O_2$ + 66% $C_{10}H_20O_2$	24	147.7	–	–	[1]

3.3. Commercial product material

The thermophysical properties of commercial products are listed in Table 2.9 - Table 2.10.

Table 2.9 Thermophysical properties of commercial salt hydrate products [1]

Material	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
E23	23	155	0.43	EPS Ltd.
Climsel C 23	23	148	–	Climator
Climsel C 24	24	108	1.48	Climator
TH 24	24	45.5	0.8	TEAP

Table 2.10 Thermophysical properties of commercial paraffin products [1]

Material	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
RT 20	22	172	0.88	Rubitherm GmbH
RT 26	25	131	0.88	Rubitherm GmbH
RT 25	26	232	-	Rubitherm GmbH

2.4. Conclusions

(1) A desirable PCMs should have desirable thermophysical properties such as large latent heat and high thermal conductivity, along with being inexpensive, non-flammable and durable.

(2) The melting temperature of PCMs suitable for PCM-based free cooling technology for buildings is 20 - 26 ℃

(3) Inorganic material has higher thermal conductivity, higher energy storage density and no flammability, along with being inexpensive, and is more promising for real applications. However, further research is need to solve the problem such as super cooling and phase segregation.

2.5. Reference

[1] Cabeza L F, Castell A, Barreneche C, et al. Materials used as PCM in thermal energy storage in buildings: A review. Renewable and Sustainable Energy Reviews, 2011, 15(3):1675-1695.

[2] Zhang Y, Zhou G, Lin K, et al. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. Building and Environment, 2007, 42(6):2197-2209.

[3] Tyagi V V, Buddhi D. PCM thermal storage in buildings: A state of art. Renewable and Sustainable Energy Reviews, 2007, 11(6):1146-1166.

[4] WANG X, ZHANG Y, Wei X, et al. Review on thermal performance of phase change energy storage building envelope. Chinese Science Bulletin, 2009, 54(06):920-928.

[5] Hasnain S M. Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. Energy Conversion and Management, 1998, 39(11):1127-1138.

[6] Oró E, de Gracia A, Castell A, et al. Review on phase change materials (PCMs) for cold thermal energy storage applications. Applied Energy, 2012, 99(0):513-533.

[7] Y.H. Bi, T.W. Guo, T.Y. Zhu. Influences of additives on the gas hydrate cool storage process in a new gas hydrate cool storage system. Energy Conversion and Management 47(11) (2006) 2974-2982.

[8] Stritih U, Butala V. Energy saving in building with PCM cold storage. International Journal of Energy Resea, 2007, 31(15):1532-1544.

[9] Turnpenny J R, Etheridge D W, Reay D A. Novel ventilation cooling system for reducing air conditioning in buildings. Part I: testing and theoretical modelling. Applied Thermal Engineering, 2000, 20(11):1019-1037.

[10] Arkar C, Medved S. Free cooling of a building using PCM heat storage integrated into the ventilation system. Solar Energy, 2007, 81(9):1078-1087.

[11] GB50736-2012. National Standard of the People’s Republic of China: Code for design of heating ventilation and air conditioning (In Chinese).

[12] Zalba B, Marín J M, Cabeza L F, et al. Free-cooling of buildings with phase change materials. International Journal of Refrigeration, 2004, 27(8):839-849.

PART 3: ENERGY AND ECONOMIC ANALYSIS OF PHASE CHANGE MATERIAL FOR COOLING IN BUILDINGS

Latent heat energy storage systems have received increasing attention because of the large amount of heat absorption/release during the phase change processes. The heat transfer performance during phase change process is analyzed with moving heat-source method in this report. The important factors, such as Fo, Ste, and parameters of phase change material, have been addressed respectively. Combined with the analysis of meteorological parameters in China, United States and Japan, the energy and economic savings are evaluated. Energy saving ratio and economic recovery period are developed to assess the application of phase change material in buildings. As last, the selection of phase change material for different local climate is analyzed, using economic recovery period as index. It is suggested that phase transition temperature should be equal to or higher than mean outdoor temperature, making the investment worthy.

ENERGY AND ECONOMIC ANALYSIS OF PHASE CHANGE MATERIAL FOR COOLING IN BUILDINGS

3.1. Introduction

Building energy consumption has continued to increase, reaching 28% of China's total energy consumption in 2000, which is close to the level of about 30% in developed countries [1, 2]. Only air conditioning electricity consumption is about 20% of total electricity consumption [3] in summer in 2006. According to the review of US Department of Energy [4] the energy consumption of the buildings constitutes more than 30% of US total energy consumption of the country and the amount of energy consumption of the heating, ventilation, and air-conditioning (HVAC) systems is about 40% of total energy consumption of the buildings. Most air conditioning and refrigeration systems are sized to meet the maximum level of demand, which occurs only a few hours per year, and thus spend their operational life working at reduced capacity and low efficiency, resulting in huge energy consumption [5].

Latent heat energy storage systems have received increasing attention for cooling in buildings in the literature because of the large amount of heat absorption/release during the phase change processes, with only small temperature variations. Since Phase change materials (PCMs) as thermal energy storage systems in buildings can store cool energy by using night time cheap electricity or free one from nature environment, and use it with a time delay for space cooling in summer. Therefore, they can be used for peak cooling load shifting/reduction [6]. A down-size of HVAC equipment is also possible [7]. Better power generation management can be achieved if some of the peak load could be shifted to the off peak load period, which can be achieved by thermal storage of heat or coolness. The shift of electricity usage from peak periods to off peak periods will provide significant economic benefit [8]. Furthermore, the energy stored during melting can be recovered during freezing, with significant energetic opportunities. Among the available techniques suitable for storing thermal energy, use of the solid-liquid phase change material has attracted considerable attention. Cool storage technology for air conditioning systems gradually developed and flourished with the development of cool storage materials [9].

John et al. [10] have designed a novel ventilation night time cooling system (a novel combination of PCM and heat pipes) as an alternative to air conditioning. The system offers substantial benefits in terms of reducing or eliminating the need for air conditioning and thereby significantly reducing CO_2 emissions and saving energy in buildings [8]. S. Takeda [11] proposed a ventilation system utilizing thermal energy storage used to reduce ventilation load and examined it in eight representative cities in Japan. Medved and Arkar [12] selected six cities in Europe to investigate the correlation between the climatic condition and the free cooling potential of using PCMs in buildings. The results showed that the optimal PCM should have a melting temperature that approximately equals to the average ambient air temperature plus 2 K and the free cooling potential is proportional to the average daily variation range of the ambient air temperature. The results obtained from these studies have demonstrated that the proper use of PCMs in buildings can help reduce energy consumption and CO_2 emissions, and improve indoor thermal comfort for occupants due to the relatively small temperature variations. However, the phase change processes are transient and the rates of heat transfer are not uniform. It is difficult to assess the processes to predict the energy conversation potential and economic feasibility.

In this work, moving heat-source method was used to evaluate the location of solid-liquid interface and heat flux during phase change process. The heat transfer process was verified compared with another researcher's work. The calculation results agree well with evaluation results in reference [15]. Thirteen cities that cover a wide range of different climatic conditions were selected. The energy savings and electricity savings of the application of phase change material in building were investigated numerically for a time period of three summer months from 1st June to 31st August. Meteorological parameters were obtained from energyplus database. Energy saving ratio (ESR) and economic recovery period (ERP) were developed to assess this application. Then the selection of phase change material for buildings in different climatic zones was obtained to conduct the design of buildings with PCMs.

3.2. Mathematical model

Moving heat-source method was first proposed by Lightfoot [13] to solve the one-dimensional transient phase change problem. He assumed there was a moving heat-source on the solid-liquid interface. So the equations of phase change problem could be substituted by equations of transient heat conduction with moving heat-source. Then the solid-liquid interface could be evaluated, so is the temperature distribution.

The generic problem to be analyzed is schematically shown in Fig.3.1, where the storage unit consists of two parallel plates. The PCM fills up the space between the plates. To maintain the generality, the equivalent generic mathematical problem was posed in Fig.3.2. The plate 1 holds at different constant temperatures to charge or discharge energy with intensity $Q(t)$. The plate 2 is insulated from the surroundings. The problem depicted in Fig.3.2 belongs to classic "Stefan Problem". Despite widespread applications of these types of problems, they have no general solutions [14]. In order to simplify the calculation, the following assumptions are introduced in this analysis:

The phase change is one-dimensional and conduction dominated.

Material properties of the solid and liquid phases are different, but are assumed to remain constant within each phase.

It is assumed the PCM changed phase at a single temperature rather than a temperature range.

The fluid in the liquid PCM is ignored.

Based on the above assumptions, the governing equations for the "Stefan Problem" are as follows:

$$\lambda \frac{\partial^2 T(x,t)}{\partial x^2} + (-1)^n \rho L \frac{dx(t)}{dt} \delta[x - x(t)] = \rho c \frac{\partial T(x,t)}{\partial t} \qquad 0 < x < x_{\max,} t > 0 \tag{3.1}$$

Where λ is the heat conductivity of PCM (W/m/℃); ρ is the density (kg/m^3); L is the enthalpy of fusion (kJ/kg); C is the specific heat of PCM (kJ/kg/℃); $\delta[x - x(t)]$ is the Dirac Function, taking the following values:

$$\delta[x - x(t)] = \begin{cases} 1 & x = x(t) \\ 0 & x \neq x(t) \end{cases} \tag{3.2}$$

$$n = \begin{cases} 0 & T_i < T_m \\ 1 & T_i > T_m \end{cases} \tag{3.3}$$

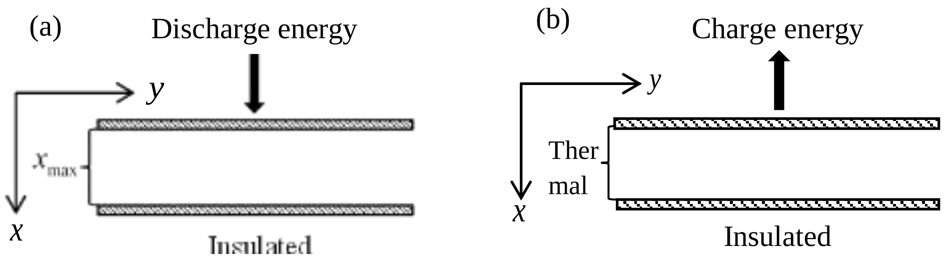

Fig.3.1 A schematic diagram of the generic problem

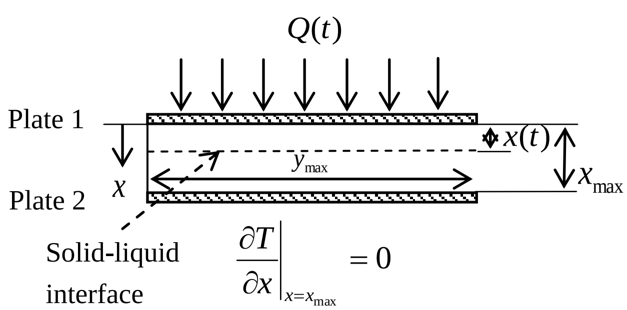

Fig.3.2 Mathematical model for generic problem

The corresponding initial and boundary conditions are as follows:

$$T(x,t) = T_m \qquad 0 < x < x_{max}, t = 0 \tag{3.4}$$

$$T(x,t) = T_i \qquad x = 0, t > 0 \tag{3.5}$$

$$x(t) = 0 \qquad x = 0, t = 0 \tag{3.6}$$

$$\frac{\partial T(x,t)}{\partial x} = 0 \qquad x = x_{max}, t > 0 \tag{3.7}$$

$$T(x,t) = T_m \qquad x = x(t), t > 0 \tag{3.8}$$

Where T_m is the phase transition temperature (°C); T_i is the temperature of plate 1 (°C).

Heat transfer rate will be exactly same along the x axis for the reason that the fluid in liquid PCM was ignored. So the heat transfer rate through horizontal planes could be calculated by Eq. (3.9).

$$q = \frac{T_i - T_m}{x(t)/k} \tag{3.9}$$

In order to simplify the results, all the variables have been transferred to dimensionless forms.

$$Ste = \frac{c(T_i - T_m)}{L} \quad X = \frac{x}{x_{\max}} \quad Fo = \frac{at}{x_{\max}^2}$$

In order to compare our calculation results with others, the parameters of phase change material used in the calculation is same with them in reference [15], as shown in Table 3.1.

Table 3.1 Parameters of phase change material in calculation

Melting point (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m/k)		Specific heat (kJ/kg/k)		Density (kg/m^3)		Kinematic viscosity (m^2/s×10^6)	
		liquid	solid	liquid	solid	liquid	solid	liquid	solid
27.4	243.5	0.152	0.358	2.18	2.15	775	778	5.03	5.72

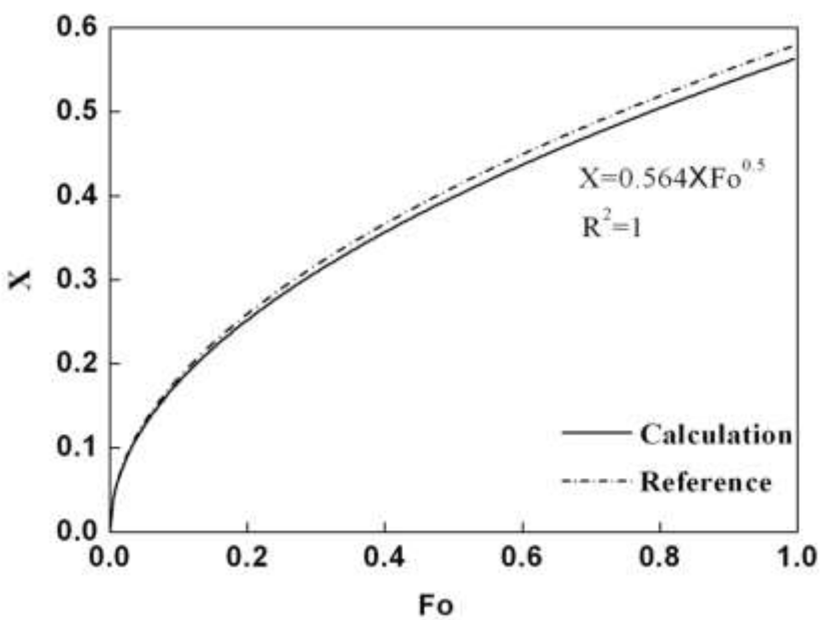

Fig.3.3 Solid-liquid interface position vs. time ((IStewI=0.2) for freezing process

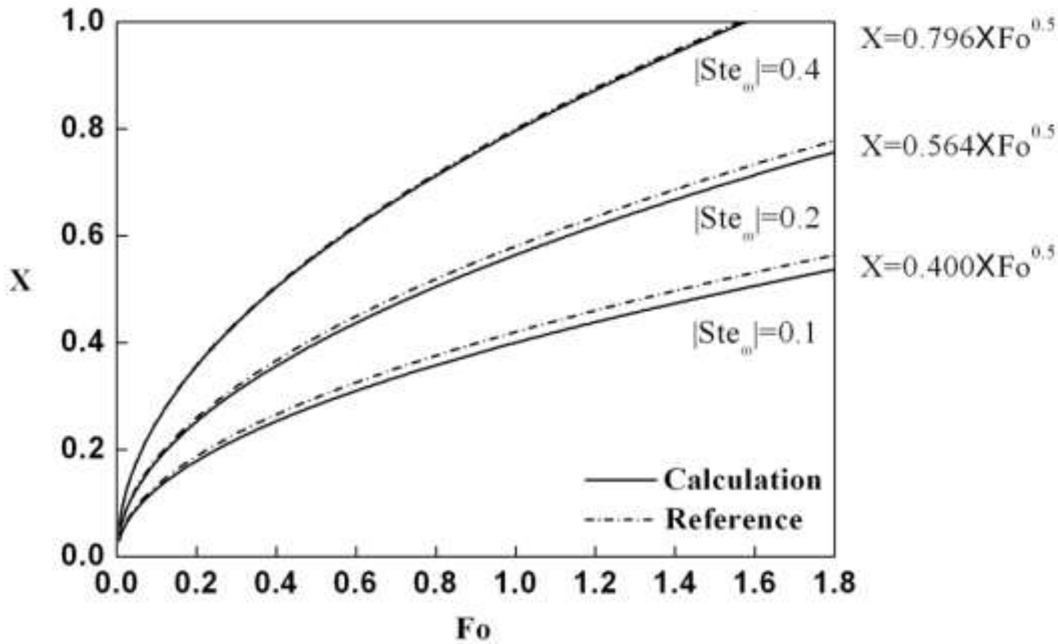

Fig.3.4 Solid-liquid interface position vs. time for freezing process

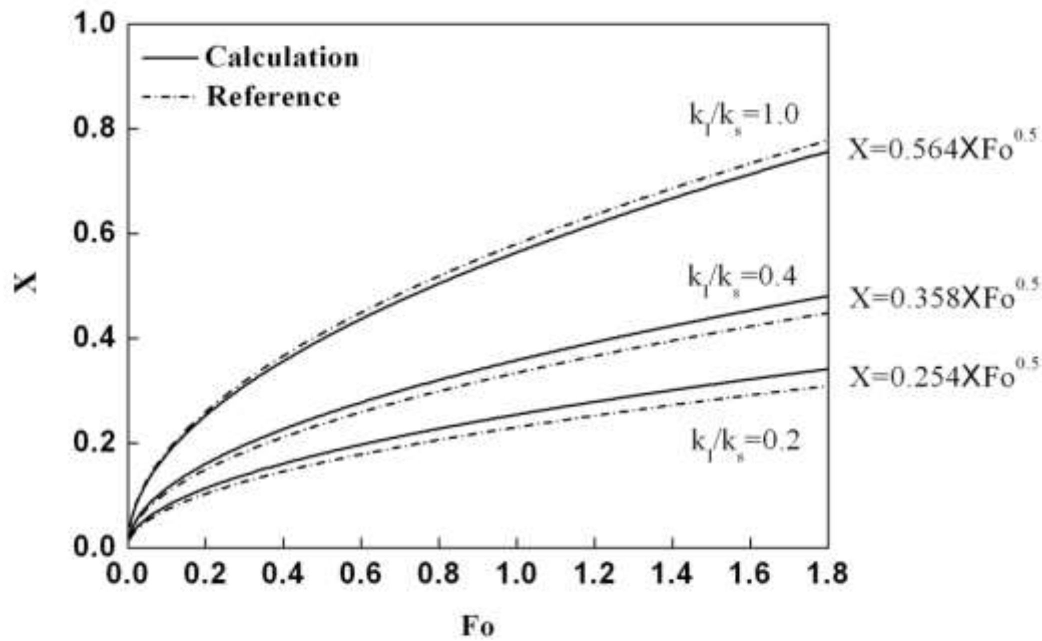

Fig.3.5 Solid-liquid interface position vs. time for melting process ((IStewI=0.2)

As shown in Fig.3.3 - Fig.3.5, the position of solid-liquid interface is determined by time, boundary condition and properties of PCM. It increased as exponent with the increase of dimensionless time. The result from calculation agreed well with the result from reference [15]. The position of solid-liquid interface moved faster at the beginning of heat transfer. Along with the increase of time, the movement of interface slowed down. This phenomenon coincided with the rule of Stephen Problem. The largest error in Fig.3.3 was 2.76% between our calculation and Reference.

Fig.3.4 shows the variation of solid-liquid interface along with time under different boundary conditions. Like in Fig.3.3, the movement of solid-liquid interface was an exponent of time. The movement of interface was 41% faster when we increased Ste value from 0.1 to 0.2. And it was 99% faster when we increased Ste value from 0.1 to 0.4. And the results we obtained were similar with the results in reference [15].

The movement of solid-liquid interface is not exactly same because of the different parameters in solid and liquid phases. We assume that PCM has same thermal diffusivity but different thermal conductivity. The results in Fig.3.5 were obtained. When the thermal conductivity of liquid phase was same with that in solid phase, the movement of interface was exactly same. While with the decrease of thermal conductivity, the movement of interface slowed down. When thermal conductivity of liquid phase was 40% of that of solid phase, the movement was reduced by 36.5%. While thermal conductivity of liquid was 20% of that of solid phase, the movement was reduced by 55%.

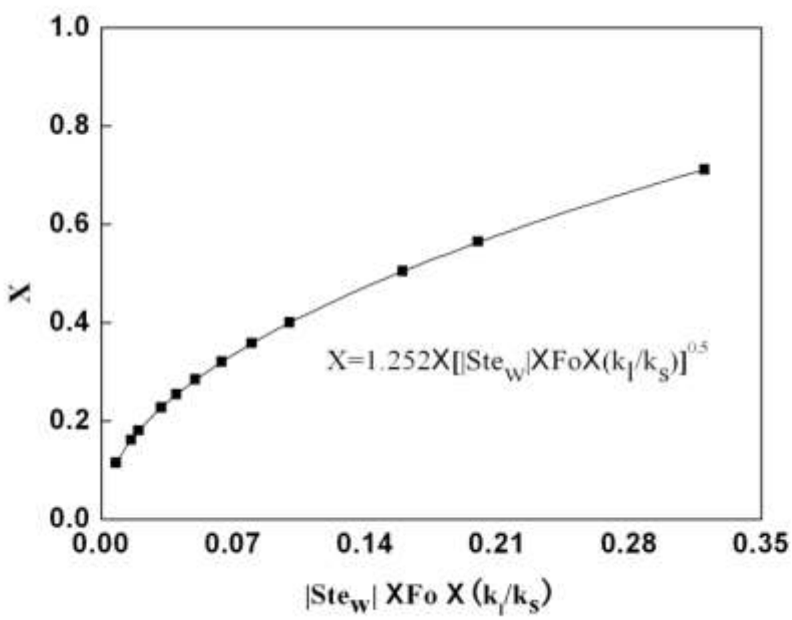

Fig.3.6 Solid-liquid interface vs. all variables

According to our calculation, the relationship between solid-liquid interface position and all related variables is shown in Fig.3.6. As shown in the figure, the interface position was an exponent of variables. This dimensionless relationship is significant for the design of energy exchanger with phase change material.

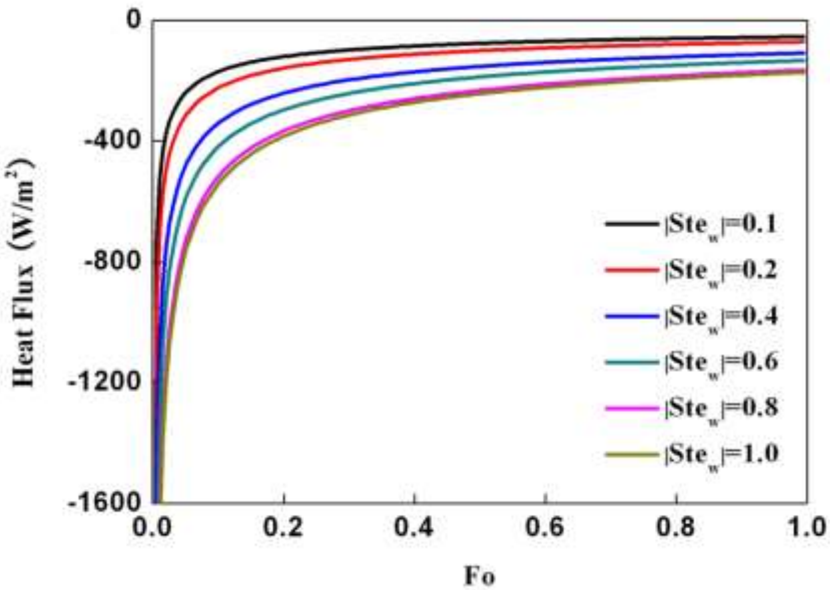

Fig.3.7 Heat transfer rate vs. time for freezing process

Fig.3.7 shows how the heat flux varies along with time under different boundary conditions during freezing process, which is calculated by Eq. (3.9). We can see that the heat flux changed as a part of hyperbola. The relationship between heat flux and time for each line has been fittinged, as shown in Eq. (3.10).

$$q_f = a + \frac{b}{Fo} \tag{3.10}$$

Where q_f is the heat flux (W/m^2), a and b are constant, as shown in Table 2.

Table 3.2 Constants in Eq. (3.10) and corresponding R2

ǀStewǀ	a	b	R2
0.1	-54.01	-14.48	0.99
0.2	-71.20	-19.09	0.99
0.4	-108.51	-29.09	0.99
0.6	-133.29	-35.74	0.99
0.8	-164.83	-44.20	0.99
1.0	-172.76	-46.32	0.99

With the increase of time, heat flux approached to be a horizontal. We can see that at the beginning of heat transfer, a larger heat flux could be obtained due to small heat resistance. With the moving of solid-liquid interface, heat resistance increased dramatically. When Fo is larger than 0.5, all the heat fluxes under different boundary conditions almost maintained at constants. Although the heat transfer process is complex due to the moving solid-liquid interface, the heat flux approaches at a constant after a certain time.

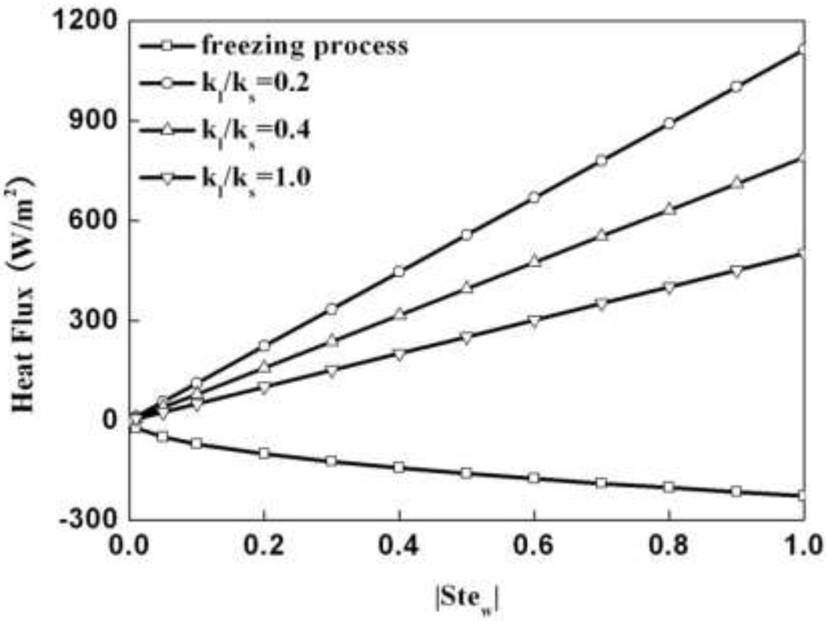

Fig.3.8 Heat transfer rate vs. boundary temperatures for melting process (Fo=0.5)

The heat flux during melting process compared with freezing process is shown in Fig.3.8. We can see that heat flux during melting process displayed a linear relationship with boundary conditions. That is to say at a certain time, increasing temperature difference can improve heat transfer efficiently for melting process. The relationship for each line during melting process is in Eq. (3.11).

$$q_m = c \times |Ste_w| \tag{3.11}$$

Where q is the heat flux (W/m^2); c is constant, as shown in Table 3.3.

Table 3.3 Constant in Eq. (3.11)

kl/ks	c	R2
0.2	1114	0.99
0.4	790	0.99
1.0	502	0.99

The heat flux during freezing process is not as simple as in melting process. It increased much faster in the beginning as an exponential function. This phenomenon could be explained by that with the raise of temperature difference, the solid-liquid interface moved faster resulting in a larger thermal resistance which reduced the heat transfer. We can see that with the rise of boundary temperature, heat flux increased. However, when boundary dimensionless temperature increased from 0.8 to 1.0, the heat flux did not change a lot. This is because of that higher boundary temperature,I Ste_wI, resulted in a faster movement of interface, which induces a larger heat resistance. So, increasing boundary temperature is not always effective to improve the heat transfer. The relationship between heat flux and boundary condition for freezing process is shown in Eq. (3.12) with R^2 of 1.

$$q_f = -328 + 134e^{-\frac{|Ste_w|+0.053}{0.045}} + 293e^{-\frac{|Ste_w|+0.053}{1.007}} \tag{3.12}$$

3.3. Meteorological parameters in 13 cities

To determine the correlation between the climate conditions and the energy saving potential, five cities in China, five cities in United States and three cities in Japan located in different climate zones were selected. Detail information of the selected cities in period of three summer months from 1st June to 31st August can be found in Table 3.4. Hourly values of the ambient air temperatures were derived from energyplus database.

3.4. Analysis of energy saving

Alfonso et al. [16] used life cycle assessment methodology to evaluate if energy savings by phase change material were large enough to balance the environmental impact caused by manufacture and installation of phase change material, concluding that the use of phase change material can reduce the overall energy consumption and the environmental impacts. The specific energy savings were calculated in this report. The energy savings with using phase change material were divided into energy savings by natural cold energy and electricity savings by air conditioning system.

4.1 Energy savings by natural cold energy

When night outdoor air is cold enough that it can provide the cold energy that is demanded during day time, phase change material could be charged by cold energy from outdoor environment. The energy savings, $Q_{s/n}$, by natural cold energy could be calculated by following equation.

$$Q_{s/n} = \sum_{i=1}^{92} \min\left(m_{PCM} \times L, \sum_{j=20}^{24} q_{ij} \times \tau_{ij} + \sum_{j=0}^{7} q_{i+1,j} \times \tau_{i+1,j} \right) \tag{3.13}$$

Where q_{ij} is energy charging rate at time j in day i (W); $q_{i+1,j}$ is energy charging rate at time j in day i+1 (W), which can be calculated by Eq. (3.10); τ_{ij} is time j in day i (hr); and $\tau_{i+1,j}$ is time j in day i+1 (hr); m_{PCM} is the amount of phase change material (kg), which is determined by the largest daily energy savings. The amount of phase change material should be large enough to contain all the cold energy in daily night.

Table 3.4 Main climate characteristic of the selected cities in summer (°C)

Country	City	Location	Climate zone	Daily mean T	Daily diurnal T	Range
China	Shenyang	41^o 44\`N 123o53\`E	Severe cold	23.45	9.19	9.6 to 34.1
	Zhengzhou	34^o 46\`N $113^o$ 39\`E	Cold	26.20	9.01	14.7 to 37.2
	Changsha	28^o 11\`N $112^o$ 58\`E	Hot summer and cold winter	27.16	7.2	19.2 to 38.2
	Kunming	25^o 04\`N $102^o$ 41\`E	Mild	19.93	6.49	13.4 to 28.8
	Hong Kong	22^o 30\`N $114^o$ 17\`E	Hot summer and warm winter	28.41	3.53	23.1 to 32.8
United states	Seattle	47^o 61\`N $122^o$ 33\`E	Marine	17.88	8.48	10 to 32
	Chicago	41^o 85\`N $87^o$ 65\`E	Cold and very cold	23.62	8.91	9 to 40
	Washington DC	38^o 89\`N $77^o$ 03\`E	Mixed-humid	23.36	11.49	8.9 to 37.2
	Los Angeles	34^o 05\`N $118^o$ 24\`E	Hot-dry and mixed dry	19.38	5.2	14.4 to 26.7
	New Orleans	29^o 97\`N $90^o$ 06\`E	Hot and humid	28.18	6.9	22 to 40
Japan	Sapporo	43^o 07\`N $141^o$ 35\`E	Frigid	19.7	6.74	9.3 to 33.5
	Tokyo	35^o 68\`N $139^o$ 77\`E	Temperate	22.06	7.27	12 to 34
	Kagoshima	31^o 58\`N $130^o$ 55\`E	Subtropical	26.61	6.37	15.5 to 35.6

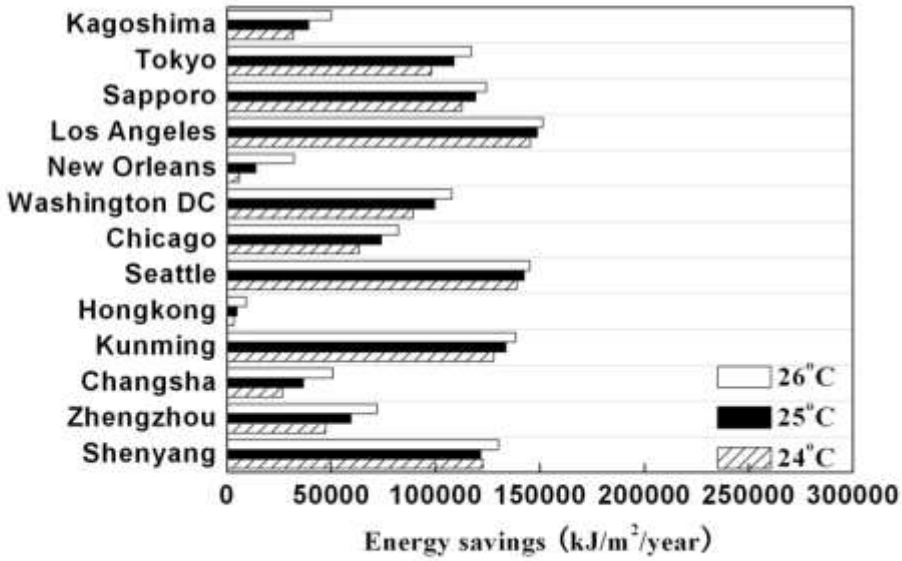

Fig.3.9 Energy savings with 10mm thick PCM board by natural cold resource

The energy savings with 10mm thick PCM board is shown in Fig.3.9. It is obvious that with higher phase transition temperature, more energy savings could be obtained except the city of Shenyang in China. We can see that the energy savings with 24 °C PCM were a little larger than it with 25 °C PCM in Shenyang. The amount of phase change material was designed to contain the maximal cold energy in daily night; so the amount of phase change material was more for 25 °C PCM than it for 24 °C. However, the total energy savings did not make a big difference. Consequently, the energy savings by per square meter for 25 °C was smaller than it for 24 °C. Increasing phase transition temperature from 24 to 26 °C could enlarge cold energy savings in Zhengzhou, Changsha, Hong Kong, China, New Orleans, and Kagoshima; while it did not make sense for other cities.

4.2 Electricity savings by air conditioning system

When night outdoor environment is not cold enough, the phase change material should be charged by cold energy that is generated by air conditioning system during night. Part of cooling load in daytime could be shifted to night-time, resulting in reducing HVAC equipment and smoothing its operation. In this condition, there is no energy savings but electricity savings. The electricity savings are obtained by higher efficient operation of air conditioning system. According Rankine circulation, coefficient of performance (COP) of air conditioning system is determined by Eq. (3.14). The decrease of condensing temperature will increase COP, which means that it will cost less electricity to generate same amount of cold energy. And the energy savings, $Q_{s/a}$, can be evaluated by Eq. (3.15).

$$COP = \frac{T_e}{T_c - T_e} \tag{3.14}$$

Where T_e is evaporating temperature, 278 K was adopted; T_c is condensing temperature (K).

$$Q_{s/a} = m_{PCM} \times L \times \sum_{i=1}^{92} \left(\frac{1}{COP_i^d} - \frac{1}{COP_i^n} \right) \times \delta\left(T^d - T^n\right) \tag{3.15}$$

$$\delta\left(T^d - T^n\right) = \begin{cases} 1 & T^d > T^n \\ 0 & T^d < T^n \end{cases} \tag{3.16}$$

Where COP_i^d is the coefficient of performance in day i, mean day temperature was used as condensing temperature; COP_i^n is the coefficient of performance in night i, mean night temperature was used as condensing temperature; T^d is the mean day temperature (K); T^n is the mean night temperature (K).

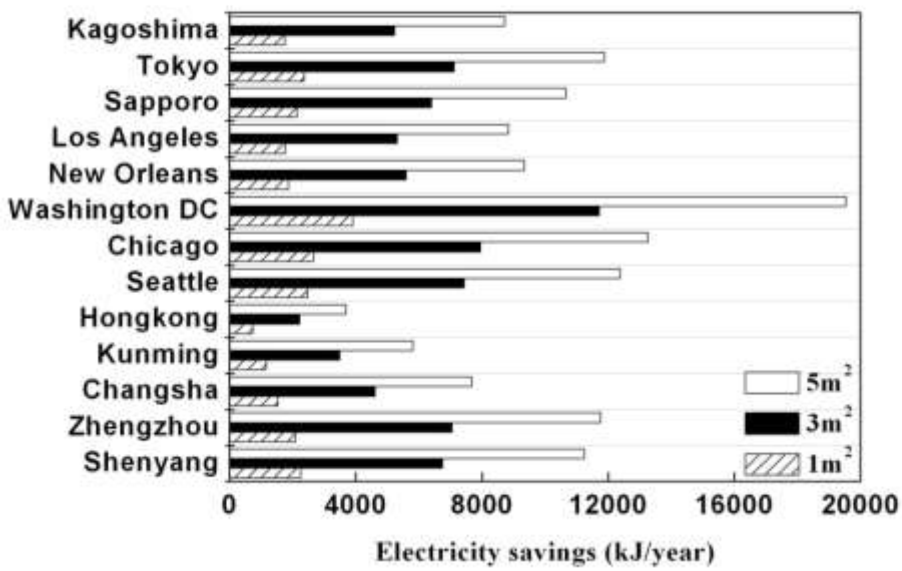

Fig.3.10 Energy saving with 10mm thick PCM board by air conditioning system

Fig. 3.10 shows how electricity savings vary, which are determined by the outdoor air temperature in daytime and night time. Daytime is defined the time period from 8:00am to 8:00pm in one day. The larger the amount of PCM, the more electricity savings could be got. Daily electricity savings is determined by daily diurnal temperature, which can be found in Table 3.4. The energy savings reach the maximum in Washington DC, suggesting that the diurnal temperature in Washington DC is larger than it in other cities.

4.3 Electricity saving ratio

The electricity saving ratio (ESR) is defined as following:

$$ESR = \frac{Q_{AC} - Q_{PCM}}{Q_{AC}} \times 100\% \qquad (3.17)$$

Where Q_{PCM} is the electricity consumption for cooling with phase change material (kJ), Q_{AC} is the electricity consumption for cooling by air conditioning system.

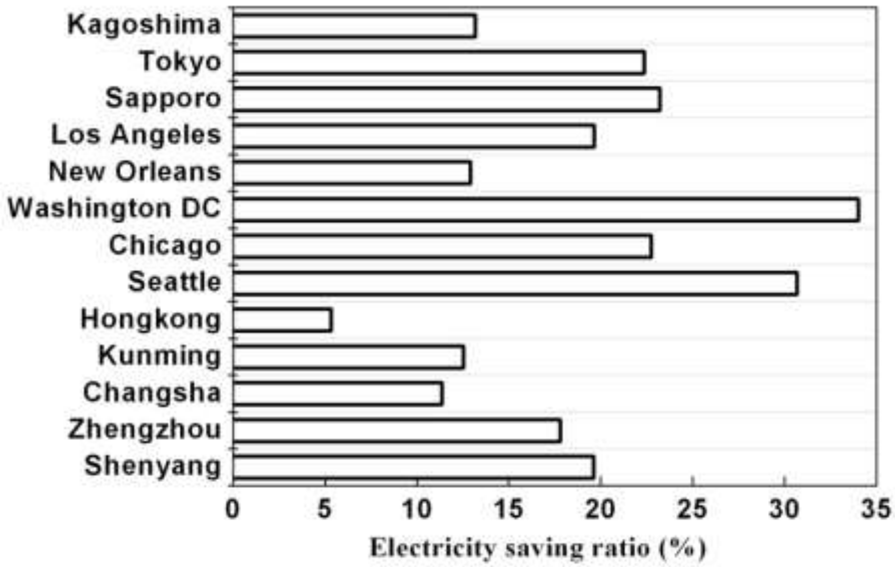

Fig.3.11 Electricity saving ratio with 10mm thick PCM board for different locations

There is no electricity consumption when PCM is charged by natural cold energy, so the electricity savings ratio by natural cold energy is 100%. For the electricity savings by air conditioning system, mean daily temperature was used as condensing temperature for air conditioning without PCM. Electricity saving ratio is shown in Fig.3.11. The application of PCM with air conditioning system can bring good electricity saving potential. Electricity saving ratios in Washington DC, Seattle, Chicago, Sapporo and Tokyo were all bigger than 20%. For other cities except for Hong Kong, China, all the energy saving ratio was bigger than 10%.

3.5. Analysis of economic savings

Different electricity tariffs during the night period and day period are applied in many cities in China. The electricity tariff in the night-time is about 1/3 to 1/2 of that in the daytime. Thus the shifting the electrical consumption from the daytime to night-time provides significant economic benefit. Also, the reduction of the peak electricity consumption contributes to the stability of the electricity supply grid [17]. So the application of phase change material brings a huge economic advantage. Similarly, the economic savings are also divided into two forms.

5.1 Economic savings by natural cold energy

Economic savings by natural energy is the economic savings that is cost by air conditioning system to generate the same amount of cold energy in Eq. (3.13). So it is defined as Eq. (3.16).

$$C_{s/n} = \frac{Q_{s/n}}{COP} \times P \tag{3.18}$$

Where $C_{s/n}$ is economic savings by natural cold energy (Cents), P is the electricity price, 10 Cents/kWh was used in US, 14 Cents/kWh was used in Japan, and 16 Cents/kWh was used in China; COP is coefficient of performance for air conditioning system, 4.2 was used in this report.

5.2 Economic savings by air conditioning system

Different electricity tariffs during daytime and night-time were took into consideration in this calculation. We assumed the electricity price is night-time is half of it in daytime. The economic savings by air conditioning system is defined as Eq. (3.19).

$$C_{s/a} = m_{PCM} \times L \times \sum_{i=1}^{92} \left(\frac{P^d}{COP_i^d} - \frac{P^n}{COP_i^n} \right) \times \delta\left(T^d - T^n\right) \tag{3.19}$$

Where $C_{s/a}$ is economic savings by air conditioning system (Cents), P^d is the electricity price in daytime, P^n is the electricity price in night-time, which is half of the price in daytime; the Dirac Function is same as in Eq. (3.16).

5.3 Economic recovery period

Economic recovery period (ERP) is an important index to measure if the investment is worthy or not. Usually, if the period is shorter than 5 years, it is considered that the investment is worthy. The economic recovery period is defined as $ERP_{s/n}$ by natural cold energy and $ERP_{s/a}$ by air conditioning system.

$$ERP_{s/n} = \frac{C_{PCM}}{C_{s/n}} \tag{3.20}$$

$$ERP_{s/a} = \frac{C_{PCM}}{C_{s/a}} \tag{3.21}$$

Where C_{PCM} is the economy cost by purchasing and installing phase change material, $2/kg was used in this report.

We can see that in Fig.3.12, the investment in Hong Kong, China, was not worthy at all; the other city was New Orleans. Compared with the mean daily temperature in Table 3.4, economic recovery period increased when temperature increased. Higher mean daily temperature means that there is less cold energy in air and less energy savings could be obtained; so economic recovery period is longer. Increasing phase transition temperature did not help a lot for shortening economic recovery period for the reason that more PCM will be needed to contain more energy. In verse, it had a side effect in Hong Kong, China, when phase transition temperature was changed from 24 to 25 °C. In order to contain all the cold energy that can be used in daytime, more PCM was added. However, the energy savings are not large enough to balance the cost of additional PCM.

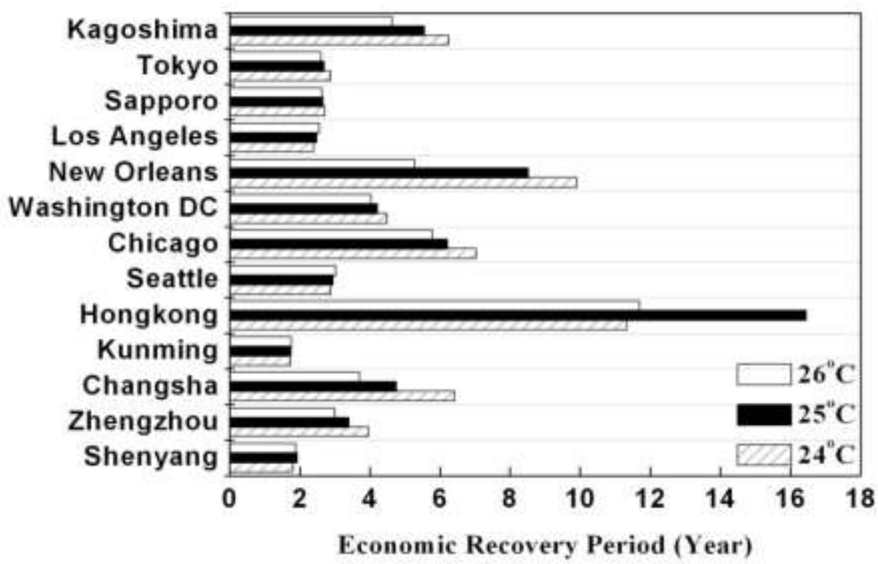

Fig.3.12 Economic recovery period for different locations by natural cold energy

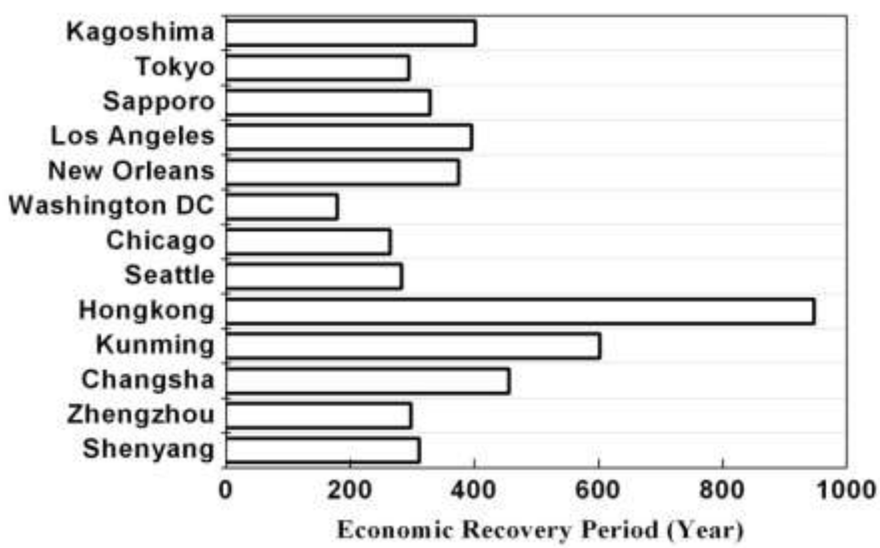

Fig.3.13 Economic recovery period for different locations by air conditioner

The economic recovery period by air conditioner was too long, as shown in Fig.3.13. Compared with Fig.3.10, the electricity savings was less than 4000 kJ/m^2/year, which is 1.11kWh/m^2/year. So the investment for PCM only cooled by air conditioning system is not worthy at all.

3.6. The selection of phase change material for buildings

Theoretical analysis of latent heat storage systems has shown that, in a system with working fluid passing at different temperatures during the melting and freezing cycles, the optimum phase change temperature is the geometric mean of the two working fluid temperatures [18]. It is also showed that the optimal diurnal heat storage can be achieved when the PCM has a phase change temperature of 1- 3^{o}C above the average room temperature [19]. For the phase change material used in buildings for cooling, the optimum phase transition temperature is determined by outdoor temperature and indoor temperature. Phase transition temperature has to be lower than indoor temperature.

Fig.3.14 - Fig.3.16 show that the economic recovery period varies with different phase transition temperatures in China, US and Japan. The mean outdoor air temperatures among three months are 23.45, 26.2, 27.61, 19.33 and 28.41°C in Shenyang, Zhengzhou, Changsha, Kunming, and Hong Kong, China, respectively, which can be found in Table 3.4. It was obvious that the economic recovery period decreased with the rise of phase transition temperature when it was higher than mean outdoor air temperature; while it did not decrease much. The lower of phase transition temperature, the longer it would take to recover the investigation. This phenomenon can be explained that the lower phase transition temperature, the smaller daily energy savings; so longer time it will take.

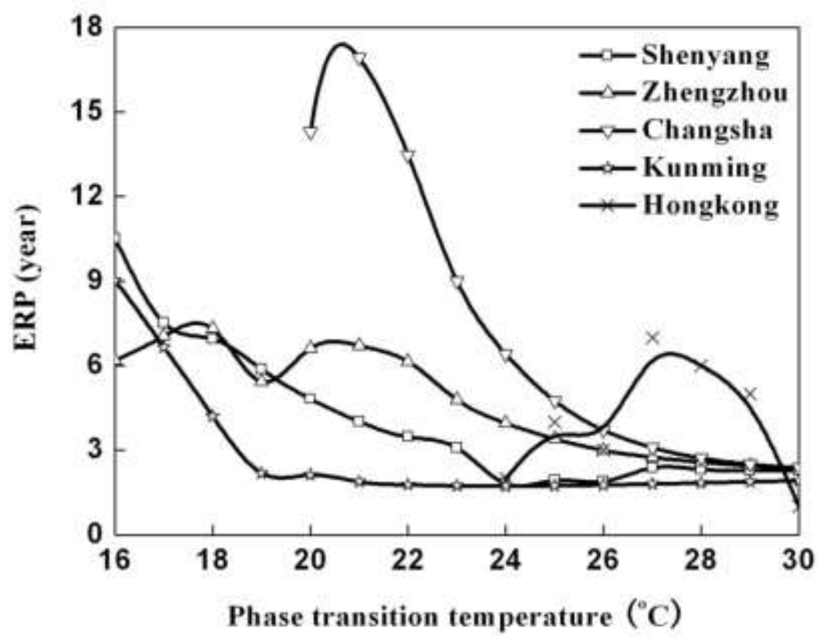

Fig.3.14 Economic recovery period with different phase transition temperatures in China

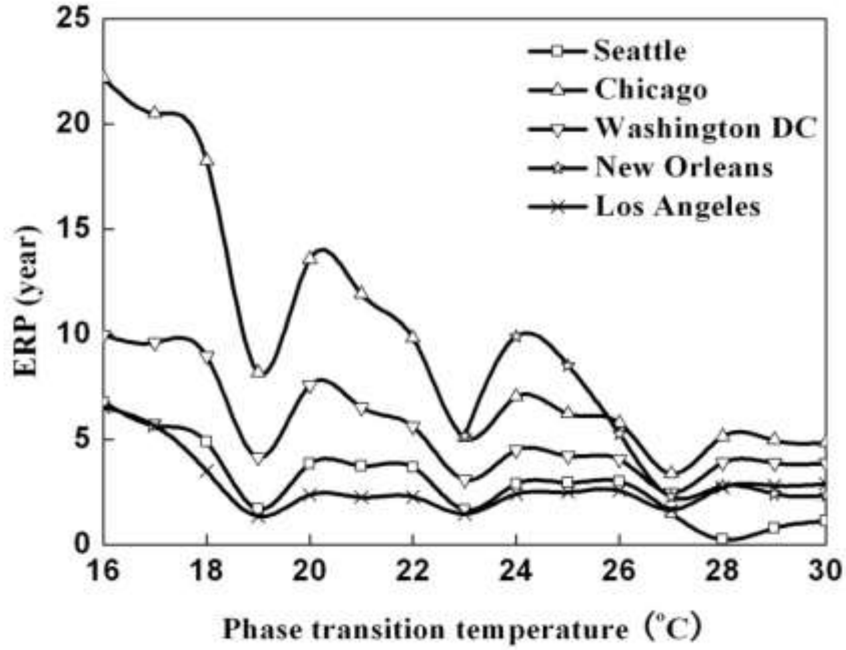

Fig.3.15 Economic recovery period with different phase transition temperatures in US

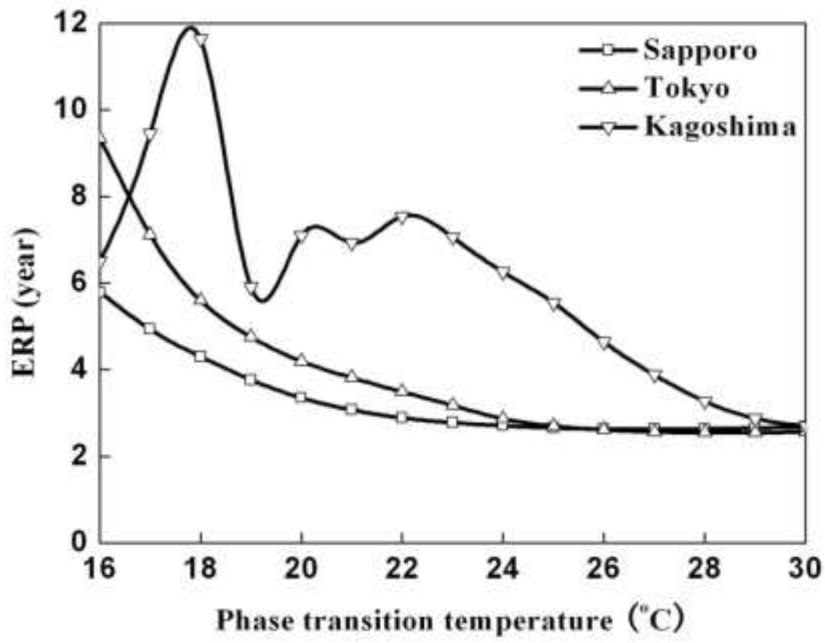

Fig.3.16 Economic recovery period with different phase transition temperatures in Japan

The economic recovery period by using phase change material in us varied more than it in China. We can find the same law that is used in China. When phase transition temperature was higher than mean outdoor air temperature, economic recovery period maintained at a lower value. There were small waves in Fig.3.15; while the tendency of ERP was getting smaller.

The economic recovery period in Japan was clear. It decreased along with the rise of phase transition temperature in Sapporo and Tokyo and maintained at a stable value when phase transition temperature is higher than mean outdoor air temperature. However, it changed a lot in Kagoshima, where the mean outdoor temperature is 26.61 °C. The fluctuation at lower phase transition temperature is because that outdoor temperature which is lower than 19 °C only occurs in several days; while more phase change material should be provided for only these days' cold energy. So the economic recovery period is longer, indicating the investment is not worthy.

3.7. Conclusion

The application of phase change material with natural cold energy and air conditioning system for cooling in building was analysed in this report. Energy saving ratio and economic recovery period were developed to assess the application from aspect of energy and investment. The following conclusions could be drawn.

(1) The solid-liquid interface position is determined by boundary condition, Ste, time, Fo, and material properties. It is an exponential function of all these parameters. The heat flux increases with boundary dimensionless temperature during phase transition process.

(2) The energy savings by natural cold energy increases with the rise of phase transition temperature and the amount of phase change material, and the energy saving ratio is 100%. There is no energy savings but electricity savings when phase change material is charged by air conditioner. The biggest electricity saving ratio happens in Washington DC, 34.01% and the smallest electricity saving ratio occurs in Hong Kong, China, 5.04%.

(3) The optimal economic recovery period by natural cold energy can be obtained when phase transition temperature is equal to or a little bit higher than mean outdoor air temperature. Hong Kong, China and New Orleans is not recommended to use phase change material for energy savings.

(4) The application of PCM with air conditioning system does not benefit at all, even though electricity saving ratio of about 20% could be obtained. The cost of PCM is much higher than the cost of electricity it saves.

3.8. Appendix 1

Eq.(1)-Eq.(8) could be split into the following forms:

Part I

$$\lambda \frac{\partial T_1^2(x,t)}{\partial x^2} = \rho c \frac{\partial T_1(x,t)}{\partial t} \qquad 0 < x < x_{max}, t > 0$$

$$T_1(x,t) = T_i \qquad x = 0, t > 0$$

$$T_1(x,t) = T_m \qquad 0 < x < x_{\max}, t = 0$$

Part II

$$\lambda \frac{\partial^2 T_2(x,t)}{\partial x^2} + \rho L \frac{dx(t)}{dt} \delta[x - x(t)] = \rho c \frac{\partial T_2(x,t)}{\partial t} \qquad 0 < x < x_{\max,} t > 0$$

$$T_2(x,t) = 0 \qquad x = 0, t > 0$$

$$T_2(x,t) = 0 \qquad 0 < x < x_{\max}, t = 0$$

The solution for part I is:

$$T_1(x,t) = T_i - C_1 \times \sum_{n=1}^{\infty} \frac{1}{N_n} \times e^{-\frac{aN_n^2 \pi^2}{4x_{\max}^2} t} \sin\left(\frac{N_n \pi}{2x_{\max}} x \right)$$

Where C_1 is a constant, which can be obtained by the following equation.

$$C_1 = \frac{4(T_i - T_m)}{\pi}$$

$$N_n = 2n - 1$$

The solution for part II is:

$$T_2(x,t) = C_2 \times \sum_{n=1}^{\infty} \frac{(-1)^n - 1}{n} \times \sin\left(\frac{n\pi}{x_{\max}} x \right) \int_0^t \frac{dx(\tau)}{d\tau} e^{-\frac{an^2 \pi^2 (t-\tau)}{x_{\max}^2}} d\tau$$

Where C_2 is a constant, which can be obtained by the following equation.

$$C_2 = -\frac{2L}{\pi c}$$

Where $x(t)$ could be resolved by Eq. (3.8).

Due to the energy conservation theory, $x(t)$ should be an equation about time, $\sqrt{t}$. We assume $x(t)$ is as following:

$$x(t) = 2c\sqrt{\alpha t}$$

3.9. Reference

[1] Wang Z, Bai Z,Yu H. Regulatory standards related to building energy conservation and indoor-air-quality during rapid urbanization in China, Energy and Buildings, 2004, 36(12): 1299-1308.

[2] Luis PL, Ortiz J, Pout C. A review on buildings energy consumption information, Energy and Buildings, 2008, 40(3): 394-398.

[3] Lu W. Potential energy saving and environment impacts of energy efficiency standards for vapor compression central air conditioning units in China. Energy Policy, 2007, 35(3): 1709-1717.

[4] DOE, Department of Energy. Annual energy review. <http://www. eia. doe. gov.>

[5] Cristopia energy system. <www.cristopia.com.>

[6] De Saulles T. Free cooling systems: design and application guidance. Bracknell, England: Building Services Research and Information Association; 1996.

[7] Zhu Na, Ma Zhenjun, Wang Shengwei. Dynamic characteristics and energy performance of buildings using phase change material: A review. Energy Conversion and Management, 2009, 50: 3169-3181.

[8] Mohammed M. Farid, Amar M. Khudhair, Siddique Ali K. Razack. A review on phase change energy storage: materials and applications, Energy Conversion and Management, 2004, 45: 1597-1615.

[9] Bi YH, Guo TW, Zhu TY. Influences of additives on the gas hydrate cool storage process in a new gas hydrate cool storage system. Energy Conversion and Management, 2006, 47(11): 2974-2982.

[10] John T, David E, David R. A novel ventilation system for reducing air conditioning in building: Testing and theoretical modeling. Application Thermal England, 2000, 20: 1019-1037.

[11] Takeda S, Nagano, K, Mochida T. Development of a ventilation system utilizing thermal energy storage for granules containing phase change material, Solar Energy, 2004, 77: 329-338.

[12] Medved S, Arkar C. Correlation between the local climate and the free cooling potential of latent heat storage, Energy Build, 2008, 40(4): 429-437.

[13] Lightfoot NMH. The effect of latent heat on the solidification of steel ingot, Third Rep. of the Committee on Heterogeneity of Steel Ingots, The Journal of the Iron Steel Institute ,1929, 1: 364.

[14] Chakraborty S, Dutta P. Analytical solutions for heat transfer during cyclic melting and freezing of a phase change material used in electronic or electrical packaging, Journal of Electronic Packaging, 2003, 125(1): 126-133.

[15] Hasan M, Mujumdar AS, Weber ME, Cyclic melting and freezing, Chemical Engineering Science, 1991, 46 (7) : 1573-1587.

[16] Aranda-uson A, Ferreira G, Lopez-Sabiron AM, et al. Phase change material applications in buildings: An environmental assessment for some Spanish climate severities, Science of the Total Envrionment, 2013, 444: 16-25.

[17] Wang Xichun, Niu Jianlei. Performance of cooled-ceiling operating with MPCM slurry. Energy Conversion and Management, 2009, 50(3):583-591.

[18] Aceves-Saborio S, Nakamura H, Reistad GM, Optimum efficiencies and phase change temperature in latent heat storage systems, Transactions of the ASME-Journal of Energy Resources Technology, 1994, 116(1): 79-96.

[19] Peippo K, Kauranen P, Lund PD. A multicomponent PCM wall optimized for passive solar heating, Energy Build, 1991, 17(4): 259-270.

PART 4: EXPERIMENTAL RESEARCH FOR PHASE TRANSITION PROCESS UNDER DIFFERENT BOUNDARY CONDITIONS

This report represents an experiment setup for phase transition process of phase change material. A cubic box with frame inside was designed and fabricated. And an environment simulator was used to generate temperature that is used as boundary conditions. A portable air conditioner was connected with the simulator and eight bulbs were used as heat source. DSC test was run to measure the fusion of heat and phase transition temperature of phase change material and calibration experiment was conducted before test. Three sets of experiments were carried out both for freezing and melting processes. All the reading of thermal couples and heat flux meters were collected every ten seconds. The experimental data was used to verify the calculation results in part I. They agree well with each other so that this research could help the design of buildings with phase change material.

Experimental research for phase transition process under different boundary conditions

4.1. Introduction

Inaba [1] conducted an experimental research about the latent heat release system. The heat loss based on the temperature difference between emulsion and atmospheric temperature is measured at the preparatory experiment by using cold water as the test fluid. Hasan et al. [2] investigated numerically and experimentally the conduction controlled periodic melting and freezing of a plane slab due to a thermal boundary condition cycling above and below the melting point. This investigation was extended by Voller et al.[3] taking into account the fluid motion in the liquid phase. Bontemp et al. [4] studied the application of three phase change materials whose melting temperatures are 21 °C, 25 °C and 27.5 °C in an outdoor test cell in real climate conditions. There are many experimental researches about heat transfer during phase change process. However, most of the researches are about special heat exchangers.

This report presents an experiment about general heat transfer process. Phase change material used in this experiment was called RT27 with phase transition temperature between 26 and 28 °C. DSC test was conducted to measure the phase transition temperature and fusion of heat of this material. A cubic box was made to store phase change material by aluminium plate and it was insulated by R30 and R90. Thermal couples were fixed inside of PCM, PCM box surface and insulation surface. And six heat flux meters were attached at the insulation surface. Three sets of experiments both for melting and freezing processes were carried out to measure the heat transfer. And the experimental data was compared with calculation results in part I of this report.

4.2. Properties test of phase change material

The phase change material used in the test is octadecane paraffin, which was sold under the trade name RT27 by Rubitherm GmbH, Berlin, Germany. The details of phase change material are shown in Table 4.1 [5].

Table 4.1 Manufacturer properties data of selected PCM (Rubitherm GmbH and PCM Energy P. Ltd.)

Type	Approximate melting point (°C)	Approximate solidification point (°C)	Latent heat of fusion (kJ/kg)	Density (kg/m^3)		Conductivity (W/m/°C)
				solid	liquid	
RT27	28	26	147	870	750	0.2

To investigate the properties of the PCM, Differential Scanning Calorimeter (DSC) tests were performed, as shown in Fig.4.2. The DSC is instrumental in helping obtain phase change related properties, such as melting point, solidification point, and latent heat of fusion. Before testing, the testing cell was cleaned according to the recommendations outlined in the User's Manual. Baseline and cell constant calibrations were run. To prevent the PCM sample from contacting the air, aluminium hermetic pans were used to contain the samples. The weight of samples for this test is 13.2 mg. All the DSC tests were run at 5 °C/min heating or cooling rates. Dry N_2 gas was connected to the purge gas and vacuum gas ports of the machine at a rate of 50 ml/min.

Fig.4.2 DSC experimental setup

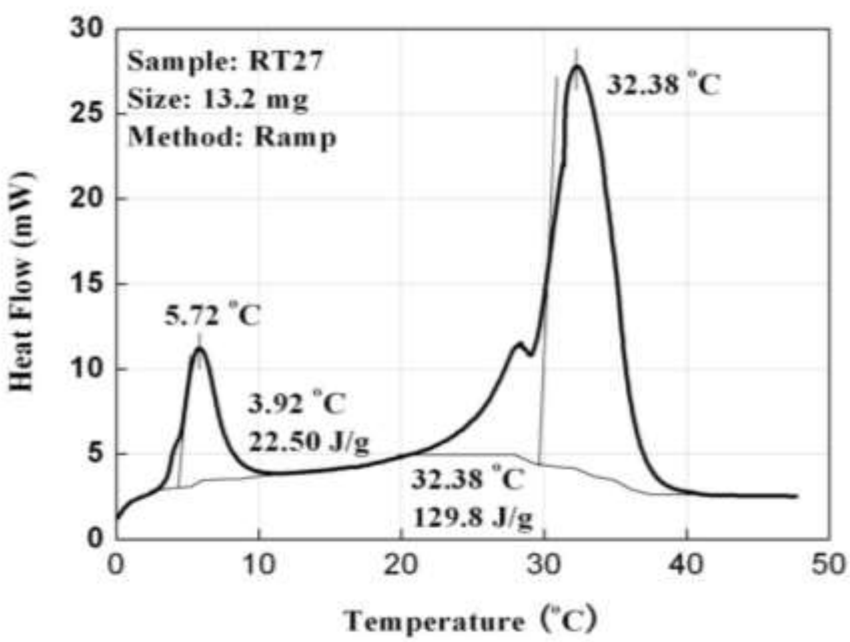

Fig.4.3 DSC test for RT27 during melting process

Fig.4.3 is the DSC test result for RT27 during melting process. The peak heat flow occurs when the material is melting. We can see that there were two peaks during this melting process for RT27. The first one happened when ambient temperature was 5.72 °C and its corresponding heat of fusion was 22.50 J/g. The second one happened when ambient temperature was 32.38 °C and its corresponding heat of fusion was 129.8 J/g. So the total heat of fusion was 152.3 J/g. The melting point is higher than the data that is given in Table 4.1. This difference might come from the change in the composition of paraffin after oxidation [1].

Fig.4.4 shows the freezing process of RT27. The freezing process is simple that only one peak occurred. It started melting when ambient temperature was 26.58 °C and reached the peak when ambient temperature was 22.55 °C and its corresponding heat of fusion was 116.0 J/g. Compared with the result in Fig.4.3, there was a temperature difference between melting and freezing process. The freezing process occurred at the temperature which was 5.8 °C lower than melting process. This phenomenon is called “super cooling”, the process of lowering the temperature of a liquid below its freezing point without it becoming a solid.

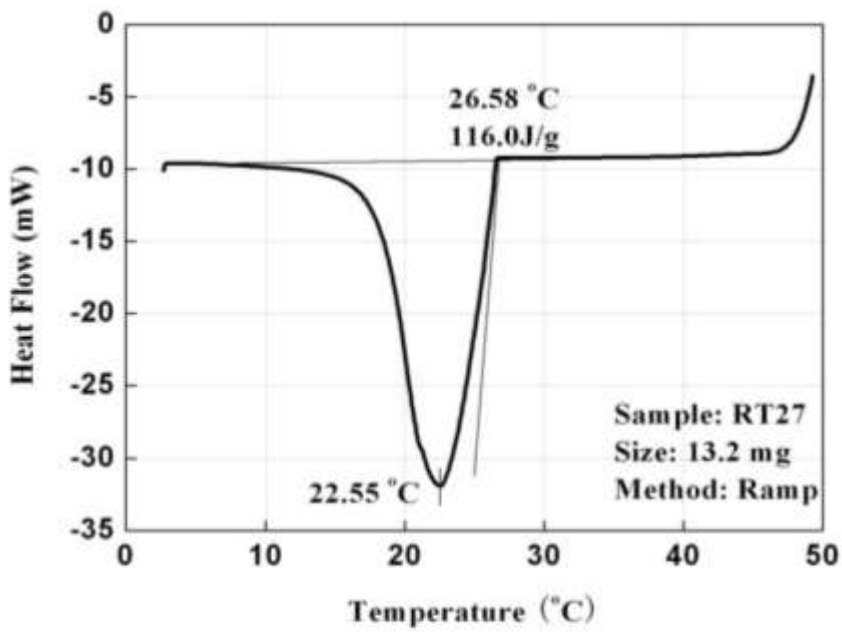

Fig.4.4 DSC test for RT27 during freezing process

4.3. Performance test of phase change material

3.1 Experimental setup

The environmental simulator (46in×46in×46in) used in this research is shown in Fig.4.5. The simulator was located in an air-conditioned room, in which the indoor room air temperature was kept at 24 °C. Inside the simulator, eight 200W light bulbs were used as the heat source to heat up temperature. And they were all connected to dimmers to create different boundary conditions for phase change process. A hole was cut at the top of the simulator for the connection of air conditioner. A portable air conditioner was connected with the simulator to cool down temperature. Two fans were installed inside the simulator to stir the air and reduce stratification effects.

Fig.4.5 Environment simulator

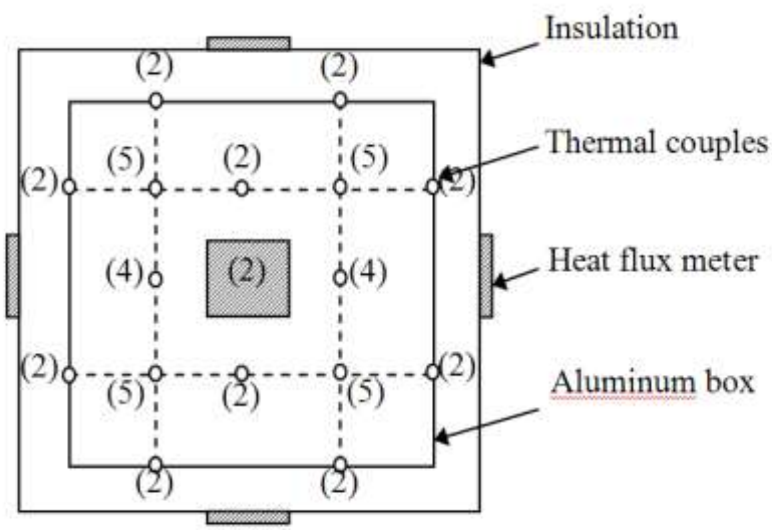

Fig.4.6 Thermal couple and heat flux meter locations

A cubic box (8in×8in×8in) with a cubic frame inside was made to store the phase change material. The inside frame was used to install and fix thermal couples to avoid movement during phase change process. Twenty-eight type T thermal couples were installed inside the box to measure PCM temperatures, and sixteen type T thermal couples were used to measure box surface temperatures, and ten type T thermal couples were used to measure insulation surface temperature, and five type T thermal couples were used to measure the inside air temperatures. Thermocouples were shielded with aluminium tape to eliminate the effects of radiation on the temperature measurement. The location of thermal couples is shown in Fig.4.6. The figures in brackets stand for the number of thermal couples or heat flux meters. Five outside surfaces were insulated with R30 and R19 insulations to prevent heat transfer with environment, leaving one surface exposed in environment. Six heat flux meters were attached to insulation outside surface to monitor heat flux across each surface. A data logger and a computer collected the data at an interval of 10 seconds.

Fig.4.7 shows the PCM box hung inside of environment simulator. As shown in the figure, PCM box was hung in the centre of simulator during the experiment. All the thermal couples and heat fluxes were connected to terminal strips, which connect to a data logger.

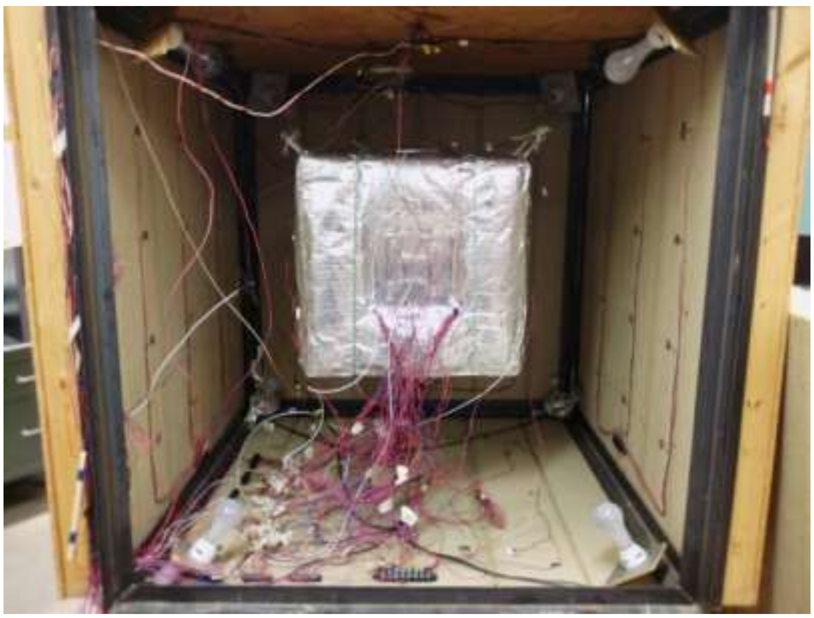

Fig.4.7 PCM box inside environment simulator

3.2 Calibration experiment

The bottom insulation was taken away, leaving the bottom surface as heat transfer interface. In order to find out if the insulation is good enough to prevent the heat loss, calibration experiment was conducted. The PCM box was hung in the centre of simulator. The inside temperature was heated up and held at 36.5 °C for 19 hrs. The PCM box and insulation surface temperature were measured, so were the heat fluxes through six faces. The results are shown in Fig.4.8-Fig.4.10.

Fig.4.8 shows the PCM box surface and environment temperatures. All these temperatures of six surfaces held at about 29 °C as a constant, suggesting that the insulation is good enough to prevent the heat transfer through insulations.

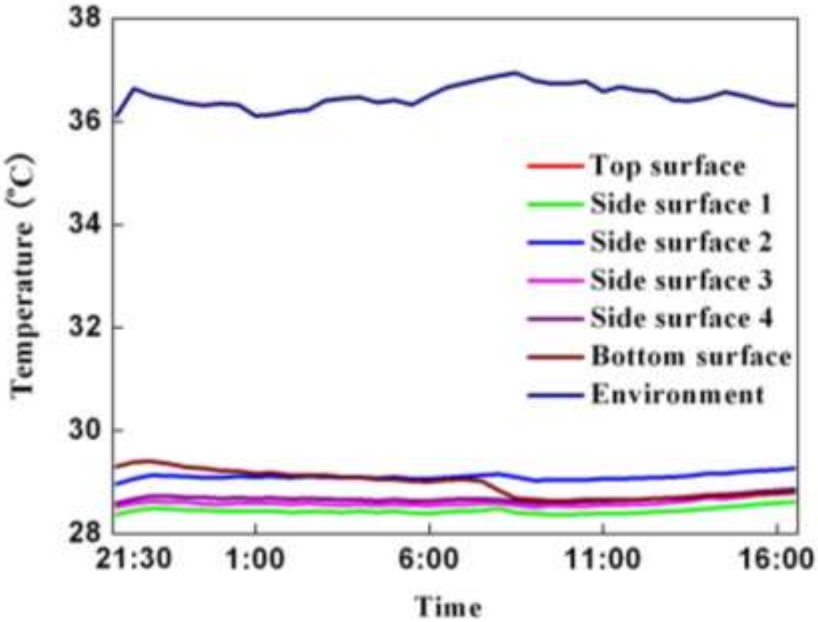

Fig.4.8 PCM box surface and environment temperatures during calibration

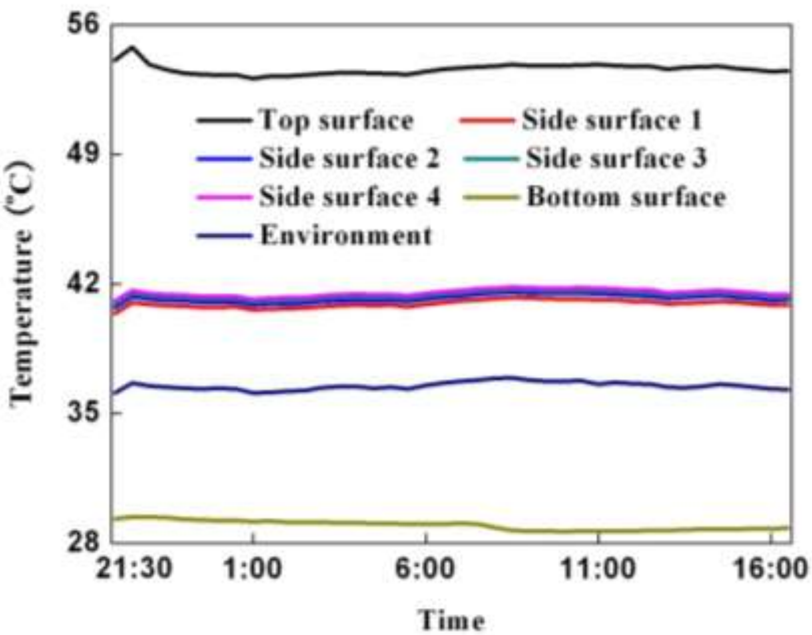

Fig.4.9 Insulation surface and environment temperatures during calibration

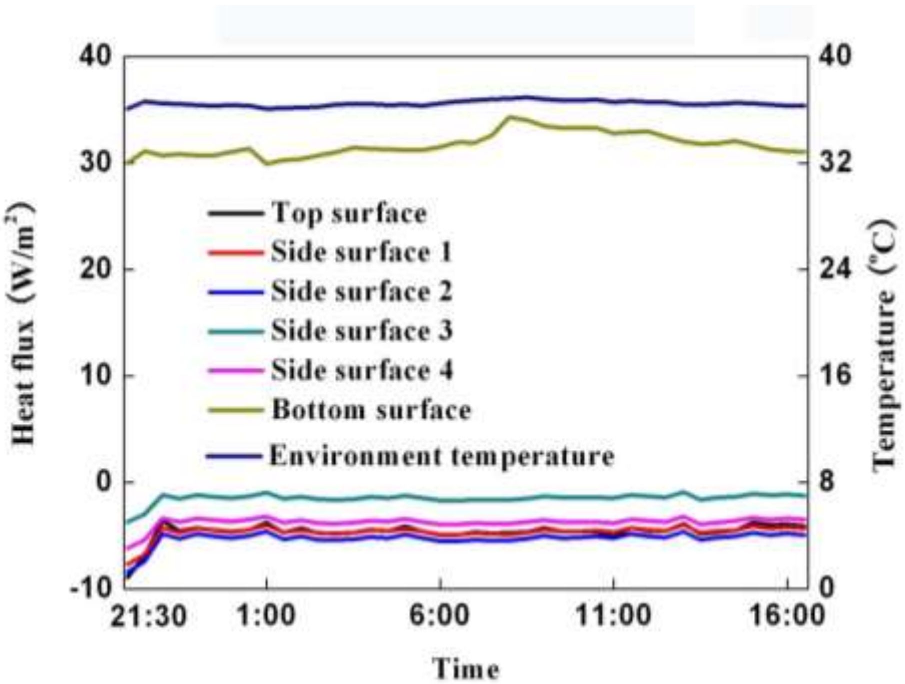

Fig.4.10 Heat fluxes during calibration

Fig.4.9 shows the insulation surface and environment temperatures. Insulation surfaces were aluminium foil which can reflect the heat back to environment from where they are coming from. And it works in both hot and cold environment by reflecting high temperature rays to the direction of source. All the insulation temperatures were higher than environment temperature because of radiation. The top insulation surface temperature was much higher than environment temperature because of temperature gradient. Comparing the results in Fig.4.7 and Fig.4.8, even though the insulation surface temperatures were much higher than the PCM box surface temperatures, the box surface temperatures stayed well at a constant, indicating the insulations were good enough.

Fig.4.10 shows the variation of heat fluxes through six faces. All the heat fluxes except for bottom were negative for insulation faces, indicating that there is no heat coming into the box. And the values kept stable within the stable environment temperature, suggesting that no heat coming in once again. Bottom face was used for heat transfer; so the heat came in with heat flux of 32 W/m^2.

3.3 Performance experiment

Heat transfer through one direction was tested for current research. Bottom and one of the side surfaces were used as heat transfer interface respectively. Three sets of experiments both for freezing and melting were carried on. All the data were collected every ten seconds. If the temperatures of PCM change dramatically, then we assume that all the PCM get melted or solidified.

3.3.1 Heat transfer through bottom face

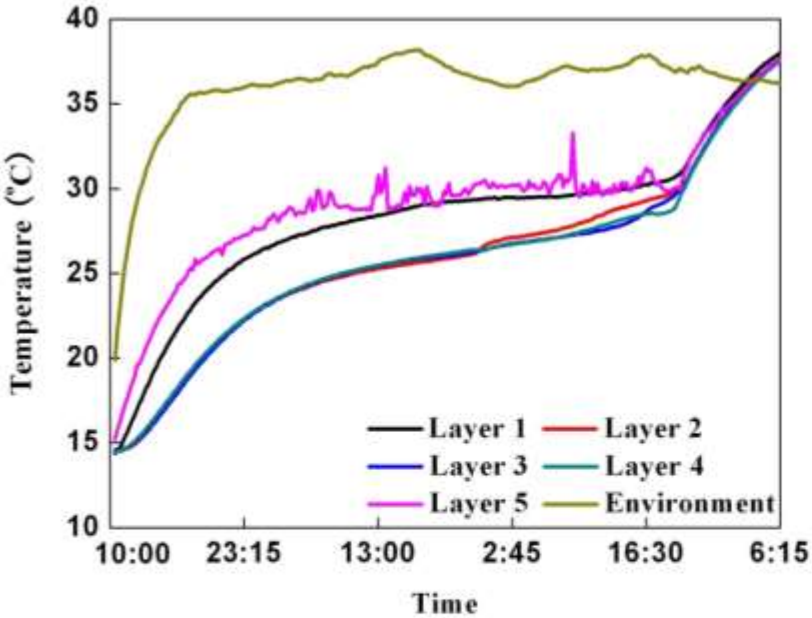

Fig.4.11 PCM and environment temperatures with heat transfer through bottom face during melting process (lStewl=0.178, Fo=2.662)

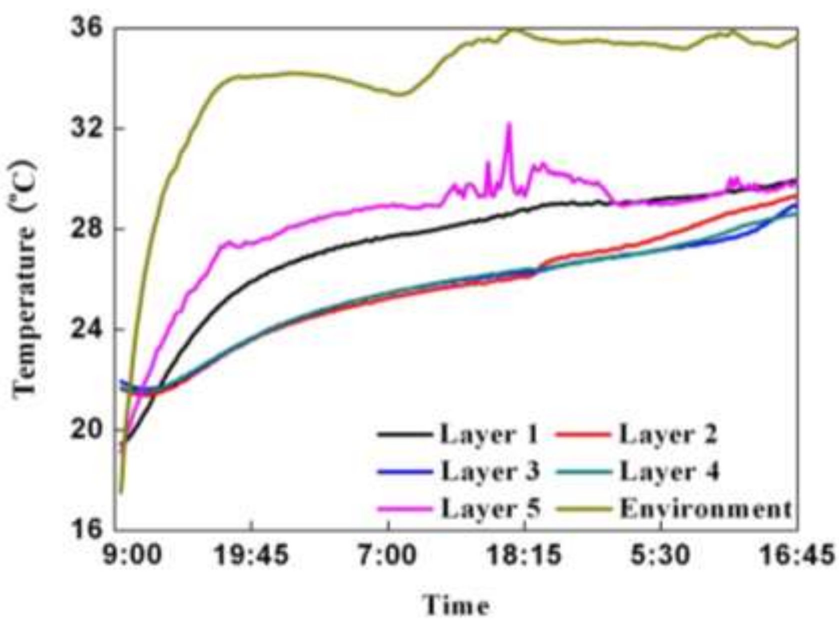

Fig.4.12 PCM and environment temperatures with heat transfer through bottom face during melting process (lStewl=0.139, Fo=2.616)

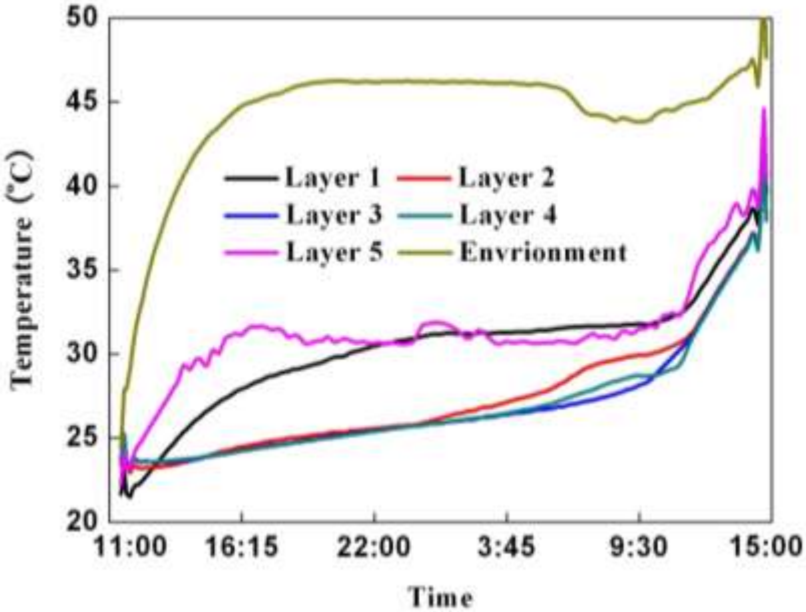

Fig.4.13 PCM and environment temperatures with heat transfer through bottom face during melting process (|Stew|=0.340, Fo=1.170)

Fig.4.11 - Fig.4.13 shows the variation of PCM temperatures during melting processes under different boundary conditions through bottom face. The temperature of PCM was divided into three layers as shown in Fig.4.6, layer 2 to layer 4 from top to bottom. Bottom face (layer 5) was used as heat transfer interface, so the temperature of layer five was higher than it of other layers. The temperature of layer 1 is the top surface temperature. It was clear that a melting process happened. As first, temperature of PCM increased fast as PCM did not start melting when the temperature was lower than 26 °C. Then it maintained at about 26 °C. After all the PCM got melted, the temperature increased dramatically.

From theoretical analysis, the temperature from layer 2 to layer 3 should get higher and higher for the heat coming in through bottom surface. However, we cannot tell apart the temperature difference among layer 2, layer3 and layer 4. This is for the reason that liquid PCM went up for its density is smaller than solid PCM. The movement of liquid PCM made the temperature distribution inside PCM uniform. And we can see that temperature in layer 2 was higher than other two layers at the end of melting process, indicating that liquid PCM did go up.

Fig.4.14 - Fig.4.16 shows the variation of PCM temperatures during freezing processes under different boundary conditions through bottom face. Same as melting process, the temperature of different layers did not change a lot. Temperature in layer 4 was a little lower than it in layer 2 and layer 3 for the reason that thermal heat got out through bottom surface.

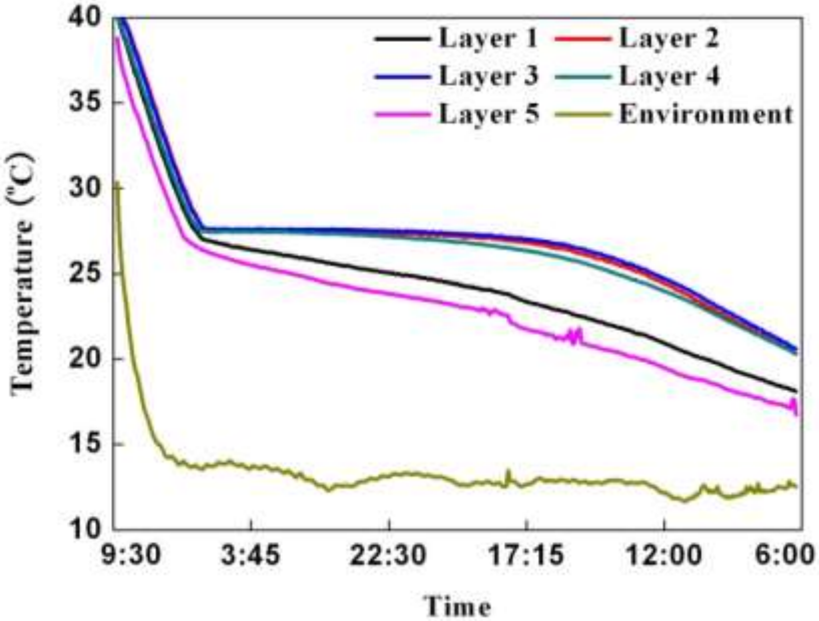

Fig.4.14 PCM and environment temperatures with heat transfer through bottom face during freezing process (|Stew|=0.267, Fo=2.847)

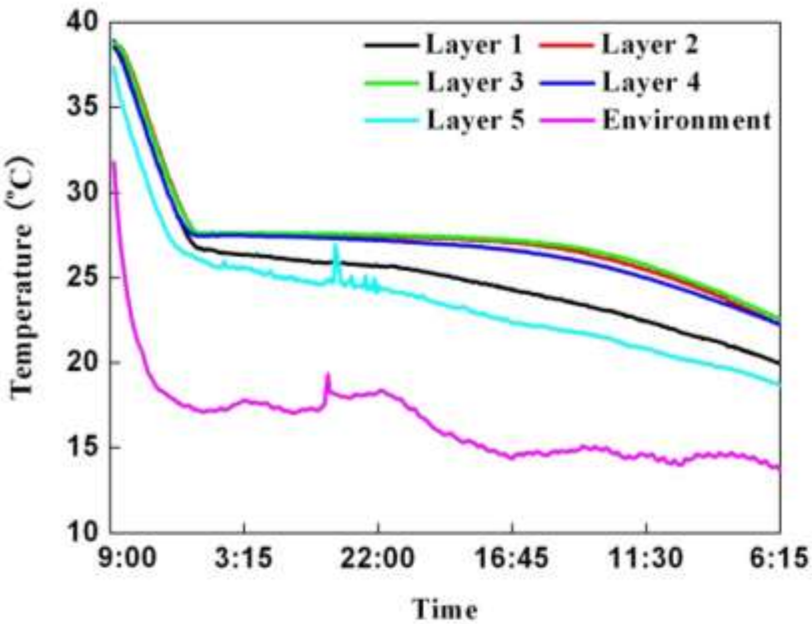

Fig.4.15 PCM and environment temperatures with heat transfer through bottom face during freezing process (|Stew|=0.20, Fo=3.14)

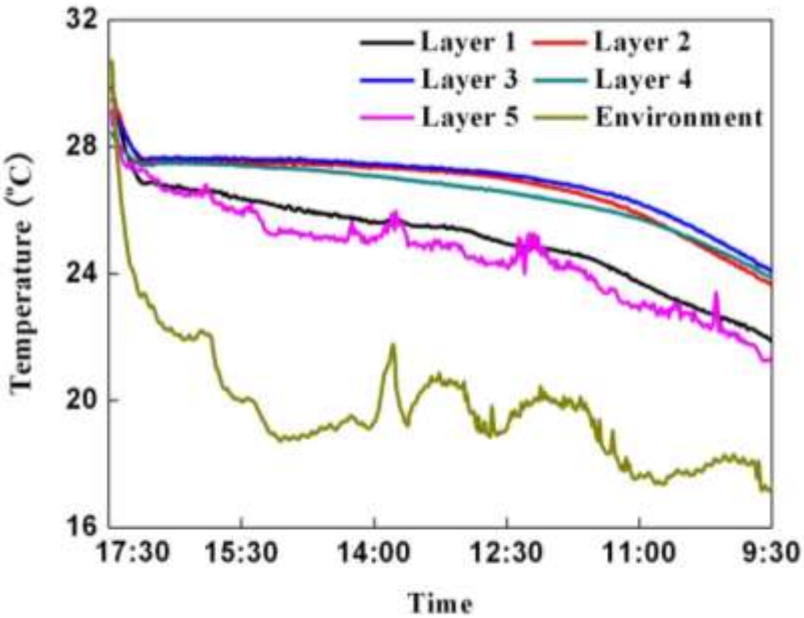

Fig.4.16 PCM and environment temperatures with heat transfer through bottom face during freezing process (|Stew|=0.14, Fo=4.61)

3.3.2 Heat transfer through side face

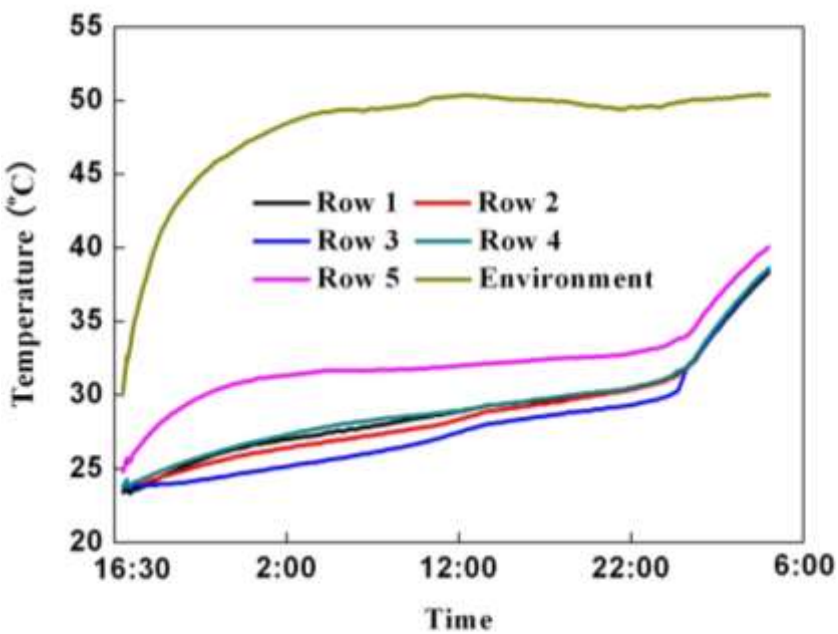

Fig.4.17 PCM and environment temperatures with heat transfer through side face during melting process (|Stew|=0.413, Fo=1.493)

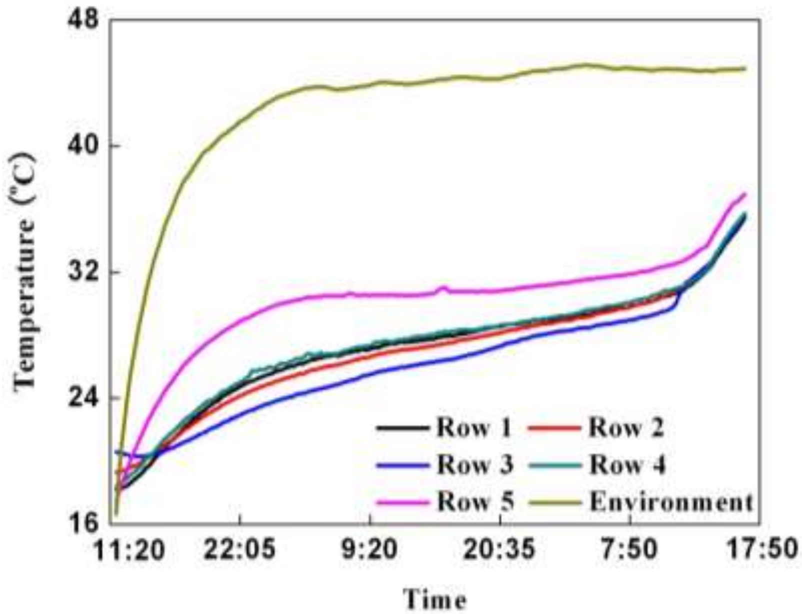

Fig.4.18 PCM and environment temperatures with heat transfer through side face during melting process (|Stew|=0.32, Fo=2.031)

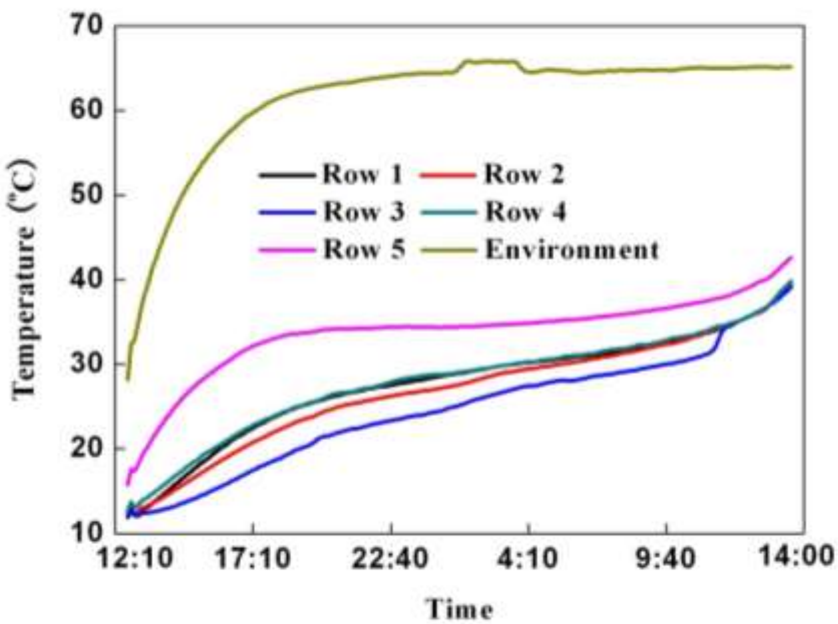

Fig.4.19 PCM and environment temperatures with heat transfer through side face during melting process (|Stew|=0.69, Fo=0.939)

In order to find out the impact on temperature distribution of movement of liquid PCM, side face was used as heat transfer interface. The temperature distribution during melting process was shown in

Fig.4.17-Fig.4.19. The temperature was divided into five rows and row 5 measured the heat transfer interface temperature. And Row 1 measured the other box surface temperature.

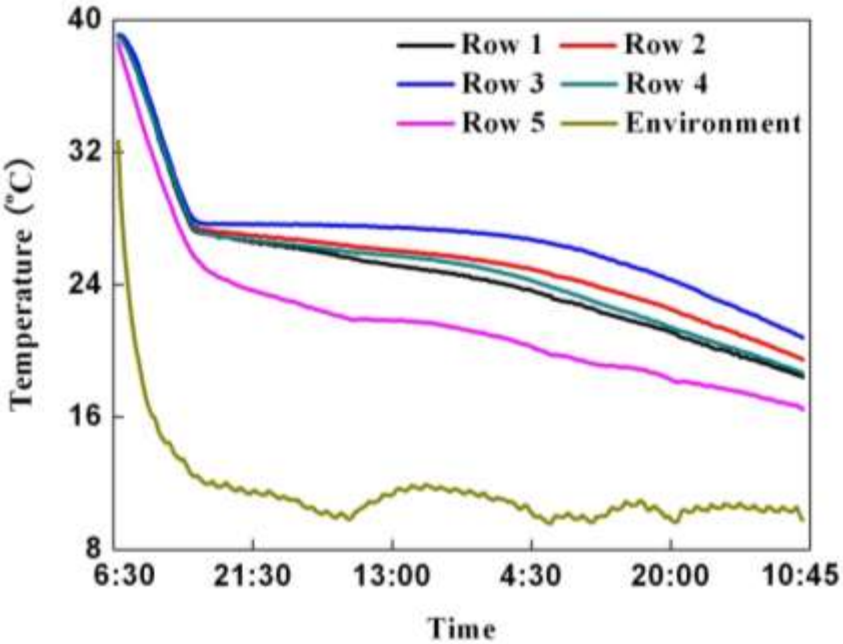

Fig.4.20 PCM and environment temperatures with heat transfer through side face during freezing process (|Stew|=0.306, Fo=2.678)

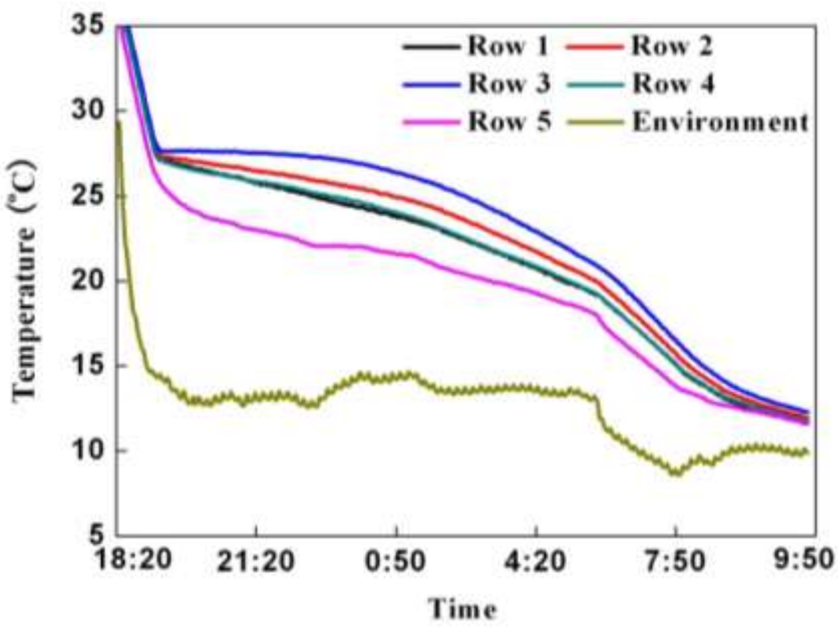

Fig.4.21 PCM and environment temperatures with heat transfer through side face during freezing process (|Stew|=0.26, Fo=5.52)

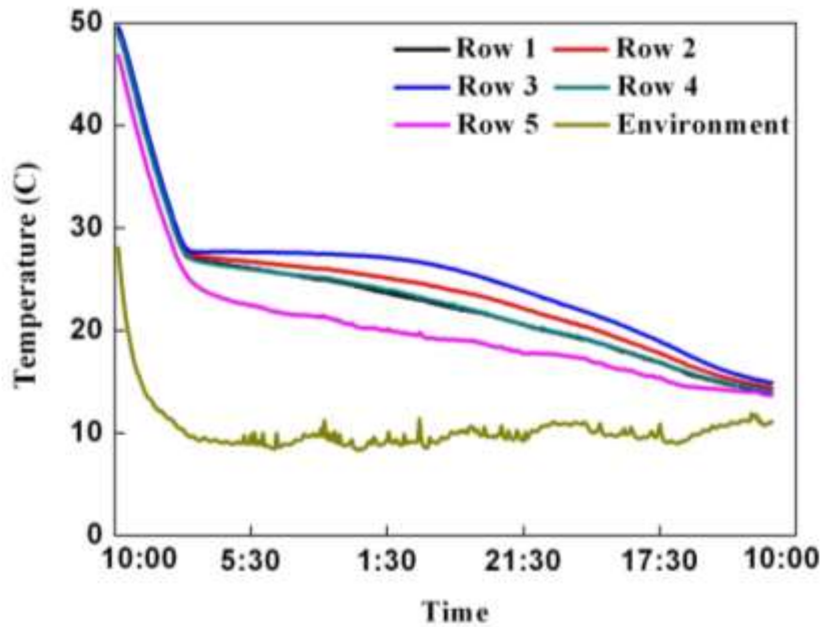

Fig.4.22 PCM and environment temperatures with heat transfer through side face during freezing process (|Stew|=0.33, Fo=3.98)

Even the insulation was good enough; the temperature of aluminium box was getting higher. When the heat transfer interface was heated up, the heat transferred to other surfaces by conduction, inducing temperature of other surfaces go up. We can see that temperature in row 2 was higher than it in row 3 for the reason that heat came in through Row 1. The PCM temperature different between two adjacent rows was about 1 °C rather 0.

Fig.4.20 - Fig.4.22 shows the variation of PCM temperatures during freezing processes under different boundary conditions through side face. Like the temperature distribution in melting process, the temperature in different rows changed about 1 °C. And the temperature was getting lower through row 4, row 2 and row 3.

4.4. Results and Discussion

4.1 Temperature comparison between simulator with and without PCM

We can see clearly that the variation of environment temperature inside simulator with and without PCM in Fig.4.23. Phase change material helps a lot to remove the energy peak. For the high peaks, indoor temperature with PCM was 10, 8 and 11°C lower than that without PCM. The higher environment temperature resulted in a larger temperature difference for simulator with and without PCM. This can be understood by the reason that larger temperature difference between environment and PCM generated a larger drive to improve heat transfer. PCM absorbed heat from environment faster; so environment temperature was reduced more. And indoor temperature with PCM was about

3 °C higher than that without PCM for low peaks. The temperature difference is not clear as the environment temperature did not change as much as it in melting process.

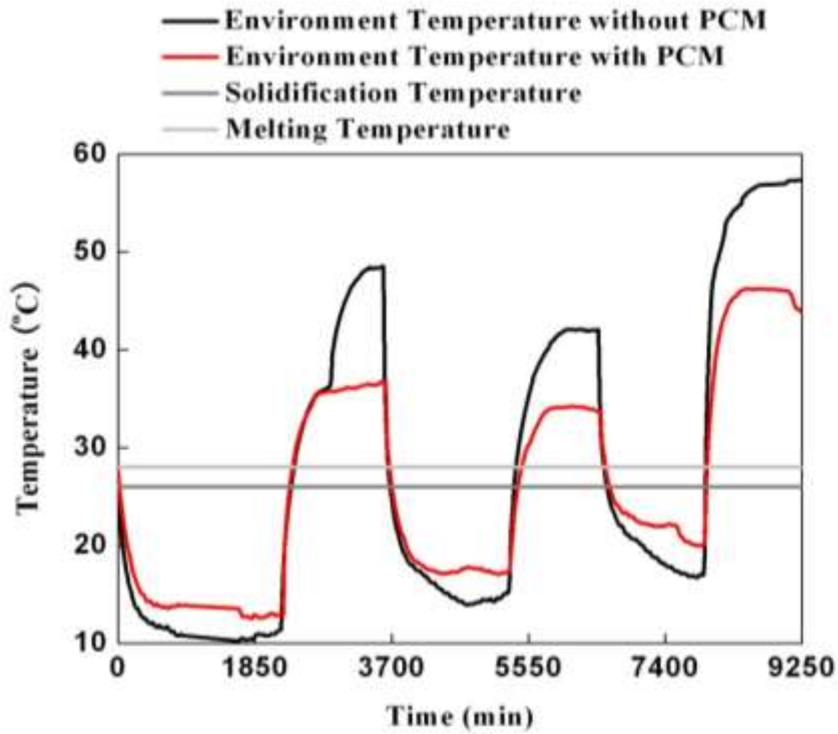

Fig.4.23 Comparison about environment temperature for simulator with and without PCM

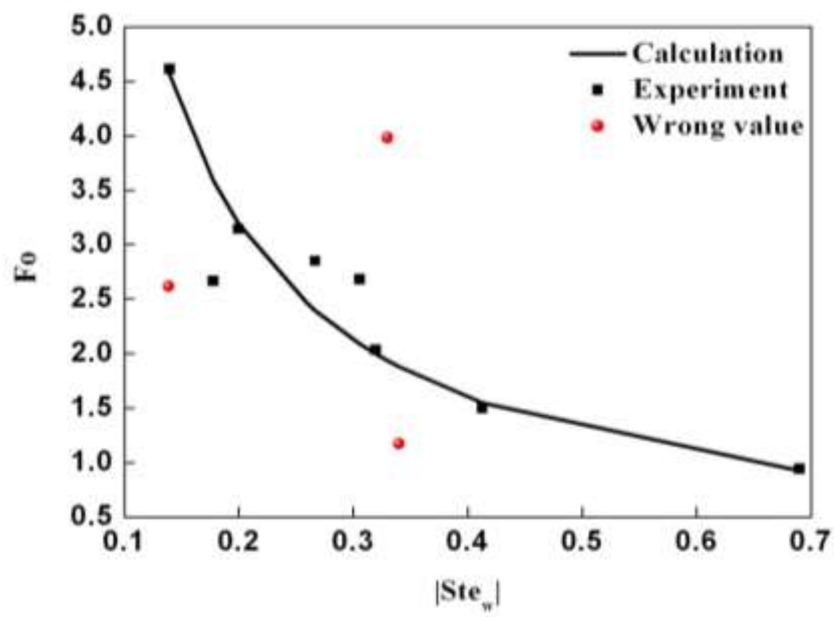

Fig. 4.24 Comparison about dimensionless time under different boundary conditions

4.2 Solid-liquid interface position comparison between experiment and calculation

Fig.4.24 shows how the dimensionless time for all PCM finishing melting or freezing variation in calculation and experiment. The calculation value can be found in Part I of this report. Three values in experiment should be skipped as show in red dot because the difference between red dots and calculation was larger than 30%. While for the other experiment data, it agrees well with the calculation.

4.5. Conclusion

An experiment test was developed in this report for general phase change process. The experimental data was compared with calculation results and they agree well with each other. The following conclusion could be made.

(1) Aged phase change material has a higher phase transition temperature than new phase change material.

(2) The movement of liquid PCM impacted the heat transfer process more when heat comes through horizontal surface than when heat comes through vertical surface.

(3) The bigger difference between environment temperature and PCM temperature is, the more environment temperature is reduced.

4.6. Reference

[1] Inaba H. Cold heat-release characteristics of phase-change emulsion by air-emulsion direct-contact heat exchanger method, International Journal of Heat and Mass Transfer, 1996, 39(9): 1797-1803.

[2] Hasan M, Mujumdar AS, Weber ME. Cyclic melting and freezing, Chemical Engineering Science, 1991, 46(7): 1573-1587.

[3] Voller VR, Felix P, Swaminathan CR, Cyclic phase change with fluid flow, International Journal of Numerical Methods for Heat & Fluid Flow, 1996, 6(4): 57–64.

[4] Bontemps Andre, Ahmad Maha, Johannes Kevin, et al. Experimental and modeling study of twin cells with latent heat storage walls, Energy and Buildings, 2011, 43(9): 2456-2461.

[5] Fang Yuan. A comprehensive study of phase change materials (PCMs) for building walls applications. Kansas, University of Kansas, 2009.

PART 5: APEC CONFERENCE ON LOW CARBON TOWN AND PHYSICAL ENERGY STORAGE

At the 9th APEC Energy Ministers Meeting (EMM9), ministers pointed out the importance of developing renewable energy, which focused on the theme "Low Carbon Paths to Energy Security". A two-day APEC conference was co-organized by Hunan University, the Hong Kong Polytechnic University, University of Kansas and Changsha Maxxom High-tech Co., Ltd. to provide a platform for experts and researchers to communicate with each other about their views and technologies to low carbon town. Scholars from 11 economics attended this conference and more than 120 papers were received from all over the world. All the papers are about how to reduce the energy consumption of building, how to build the low carbon town.

APEC conference on low carbon town and physical energy storage

5.1. Introduction

APEC is the important economic cooperation mechanism in Asia-Pacific region. And the energy working group (EWG) is a significant platform for APEC economics to communicate and cooperate with each other about energy technologies and energy polices. At the 9th APEC Energy Ministers Meeting (EMM9), ministers pointed out the importance of developing renewable energy, which focused on the theme "Low Carbon Paths to Energy Security". They observed that the "Introduction of low-carbon technologies in city planning to boost energy efficiency and reduce fossil energy use is vital to manage the rapidly growing energy consumption in urban areas of APEC". With the rapid development of developing economies, the energy consumption grows up dramatically and the electricity demand is more and more unmatched. While abundant renewable energy, such as solar energy, natural cold resource and waste heat, exists in these economics. So, how to make use of the existing renewable energy to reduce the energy consumption in urban areas of APEC is the main aim of the project.

A project titled research on the application of physical energy storage technology with renewable energy in low carbon town was approved by APEC Energy Working Group in 2013. As we know, all over the world society's foremost challenges this century are global warming, sustainability and security of energy supply. These issues are altogether linked with global stability, economic prosperity, and quality of life. The energy storage technology is more effective for intermittent renewable energy (solar energy, natural cold resource, etc) than present technologies. With the applied integration between renewable energy and energy storage, the energy consumption of buildings will be reduced by 20% and the regional energy security in APEC regions will be enhanced.

In order to improve the communication among experts and researchers from all over the world, a conference was co-organized by Hunan University, the Hong Kong Polytechnic University, University of Kansas and Changsha Maxxom High-tech Co., Ltd. in Hunan Province during May 25th and 26th, 2013. Experts from 11 economics took part in the conference, including senior officer from U.S. Department of Energy, the project director from APEC Secretariat, officer from Chinese Department of Energy and so on. And several different kinds of units with physical energy storage technology and phase change materials developed by Changsha Maxxom High-tech Co., Ltd. were exhibited.

5.2. Conference theme

To encourage all the experts communicate about their research view, ten different kinds of themes were proposed to distinguish the different technologies to reduce energy consumption, as following:

E1. Policy, codes and guidelines for low carbon towns;

Experts from someAPECeconomies attended the conference, including Canada; China; Hong Kong, China; Japan; Singapore; Chinese Taipei; Thailand; United States and non-APEC economies (France and

United Kingdom). Various energy conservation technologies and policies were applied in different economic regions due to their different climate and geographical traits. Based on their discussion and exchange, new technologies can be introduced in all regions and the economies in APEC regions can be improved.

E2. Implementation and assessment of sustainable technologies for low carbon towns;

Diverse new technologies and skills were developed recently to reduce energy consumption of buildings. While how to apply all the technologies and how to assess the technologies whether work in APEC regions is a big issue.

E3. Energy conservation and energy efficiency for low carbon towns;

In 2010, leaders of APEC pointed out that both economic growth and environmental sustainability should be advanced in a holistic manner, and progress toward a green economy should be accelerated by promoting trade and investment in environmental goods and services, developing this sector in APEC economics, and enhancing energy efficiency and sustainable forest management and rehabilitation. Improving energy efficiency can reduce energy consumption and promote the building process of low carbon town.

E4. Energy saving strategies of heating, ventilation and air-conditioning (HVAC);

HVAC system is the major energy consumption of building, accounting for more than 25% of the primary energy consumed in commercial buildings in the U.S. Reducing the energy consumption of HVAC system can directly reduce the energy consumption of buildings.

E5. Improved ways for environmental quality including air, water, light, noise and transportation;

The aim of low carbon town is to make human being more comfortable and enjoy their life more. The living environment includes not only building but also air, water, light, noise, transportation and so on; so one of the themes focuses on the living conditions.

E6. Computational optimized designs and applications;

It is necessary to monitor the operation of low carbon town in a long time to see whether all the new technologies and skills are useful for reducing energy consumption before building the real town. And it is difficult to observe the running of real town. If the town has been built without simulation, the cost of retrofitting is hard to estimate.

E7. Automatic control and artificial intelligence of building services;

High efficient building without automatic control and artificial intelligence is like an advanced machine without operator. Without intelligent control, the maximum effects of all technologies and skills cannot be achieved successfully.

E8. Assessment of application potential of physical energy storage;

Physical energy storage is proposed recently; there is no assessment system for the using of energy storage technology in different climate regions. Through the discussion about this topic, a new assessment method may be got.

E9. Design and analysis of physical energy storage equipment;

The application of physical energy storage system in buildings is mainly on walls, window shutters, under-floor heating systems and ceiling boards; so it is how to design and analyze physical energy storage equipment is important.

E10. Testing, commissioning, and operation and maintenance;

Once physical energy storage equipment is installed in buildings, it is inevitable to test and maintain the operation. Effective maintenance can promise the smooth operation of all equipment and prolong its lifetime.

5.3. Conference contents

Tens of new advanced technologies were presented during the conference for buildings, such as solar PV generator, building with physical energy storage, building with night ventilation, building with solar wind and technologies for HVAC systems, such as solar heat pump system, waste water source heat pump, absorbed air conditioning system, et al. All the technologies are ways for low carbon town in APEC regions.

3.1 Technologies to low carbon town

Prof. Zhai from University of Colorado at Boulder introduced the active and passive energy conservation technologies used in buildings, as shown in Fig.5.1 and Fig.5.2. Active technology means that some active methods will be adopted to generate high efficiency of the system. Passive technology means that it is not necessary to add more power to the system when this technology is running.

Fig.5.1 shows five kinds of active ways, including PV panels, energy conservation and management, Li-Ion Battery, connection to grid and metering and distribution, to reduce energy consumption of a building. PV panel can be used to collect solar energy with high efficiency for lighting, heating or cooling. Li-Ion battery is used to store the solar energy which is collected by PV panels. It is hard to use solar energy directly, for the reason that it is varying minute by minute. Consequently, solar energy is changed to electricity and stored in Li-Ion battery which can connect to grid and metering. Proper management can promise all the technologies work together smoothly and generate best effects.

Fig.5.2 shows six kinds of passive energy saving technologies, including proper shading, passive solar heating, thermal mass, continuous insulation with no thermal bridge, continuous air barrier and heat recovery ventilation. Proper shading can help reduce heat coming into the building without blocking the light, reducing energy consumption of air conditioning system. Passive solar heating can heat up the water to demanded temperature which is used for heating in winter to replace the traditional heating system. Thermal mass can smooth the load peak by delaying the time of peak load, reducing electricity consumption and stabilizing electrical grid. Continuous insulation with no heat bridge and air barrier can reduce cooling load in summer and heating load in winter of HVAC system. Heat recovery ventilation can help make use of waste heat to reduce ventilation load of HVAC system.

Fig.5.1 Active thermal storage technologies in buildings

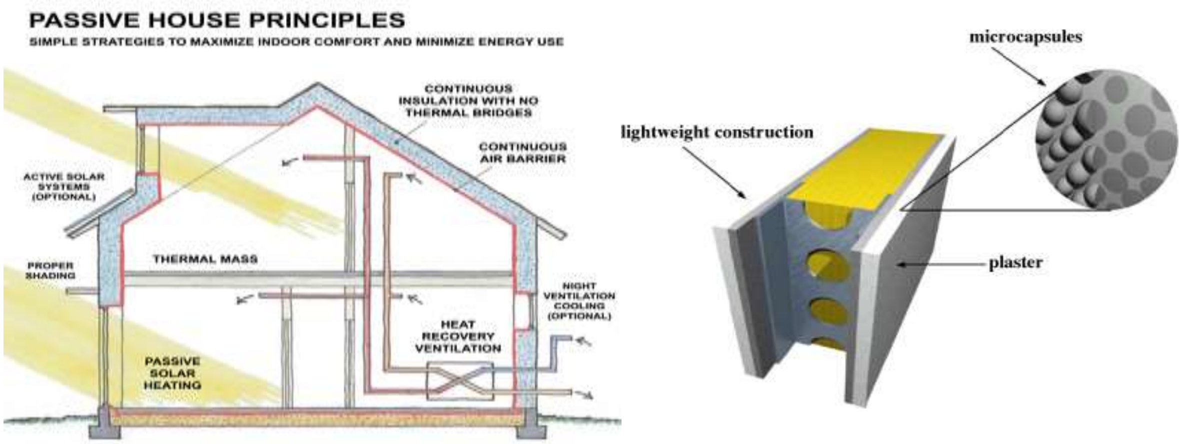

Fig.5.2 Passive thermal storage technologies in buildings

Prof. Yang from the Hong Kong Polytechnic University illustrated the method of sustainable energy supply system, as shown in Fig.5.3. All kinds of natural resource are used in this system, such as wind energy, solar energy, and weight energy. Wind drives the winder generator to produce electricity. PV panel and solar thermal power plant absorb solar energy to generate electricity. Also, electricity can be produced by water from upper reservoir to lower reservoir. From this diagram, all electricity is produced by natural resource without energy consumption. So it’s a method of energy sustainable supply.

Prof. Medina from the University of Kansas presented the building with phase change material in Fig.5.4. They have built two exactly same building models to see if phase change material can be really used for buildings. The inside surface temperature of wall with phase change material is 1 °C lower than the wall without phase change material in summer. And the peak load can be delayed about three hours. So the wall with phase change material can help reduce cooling load of air conditioning system in summer and smooth electrical grid.

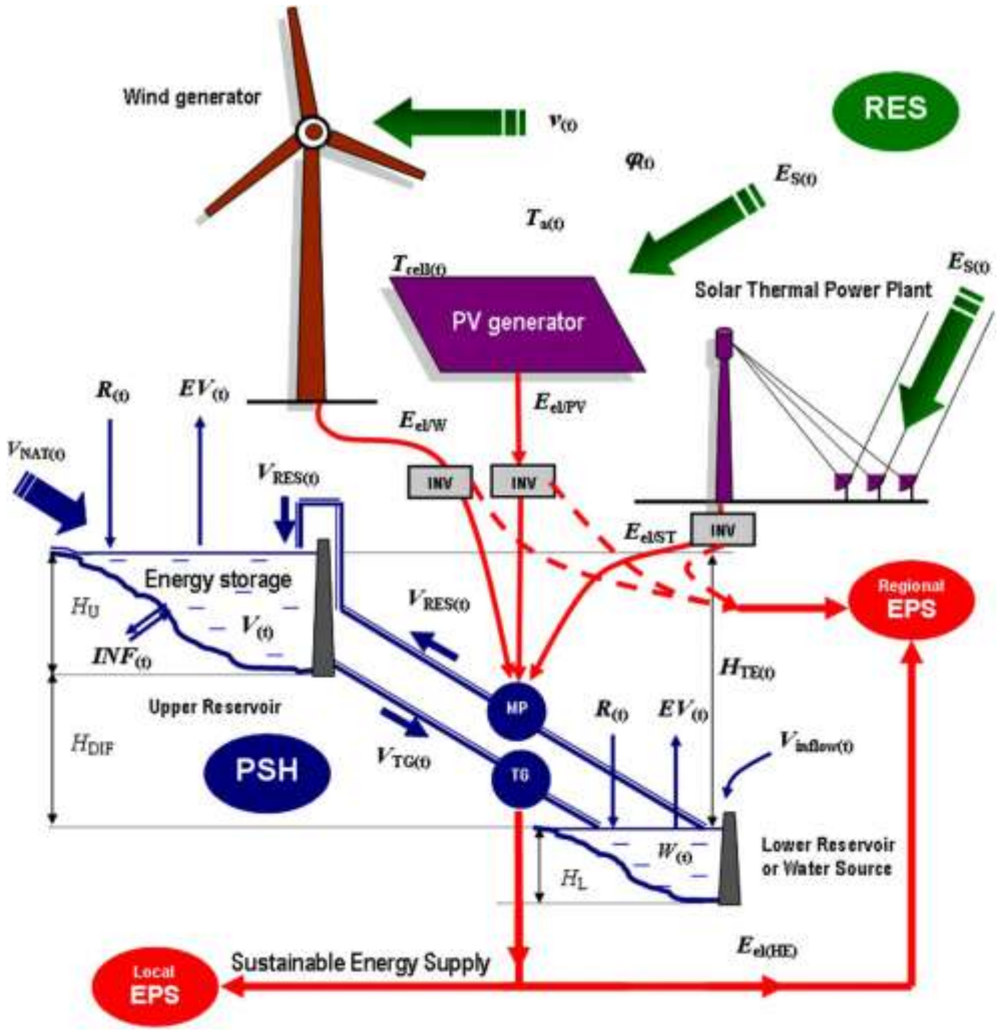

Fig.5.3 Diagram of sustainable energy supply

Prof. Zhang from Tsinghua University proposed the concept -"changing clothes for building". As shown in Fig.5.5, the temperature distribution varies like a wave; while buildings cannot change their clothes according to the temperature. If building can change its clothes to generate the comfortable temperature inside, there will be no need for air conditioning systems.

Prof. Zhou from PLA University of science and technology presented an air conditioning system which treat heat and humidity separately, as shown in Fig.5.6. Fig.5.6 shows the centralized AC system with local cooling unit, where zone A is the ordinary air conditioned area and zone B is the air conditioned area with high load. Because of its perennial need of cooling capacity, Zone B is equipped with a local cooling unit, which can be a radiation plate or dry FCU. Considering the dry FCU is more convenient for the transformation of existing underground engineering than the radiation plate, the dry FCU is adopted as research object. The cold source of FCU can be various, high temperature chiller is selected to supply high-temperature cooling water. Compared with low temperature chiller of AHU, the coil temperature for cooling can be considerably increased, e.g. from current 7 ℃ to 17 ℃, providing enough potential of energy saving for the optimal control of the system.

Fig.5.4 Building envelop with phase change material board

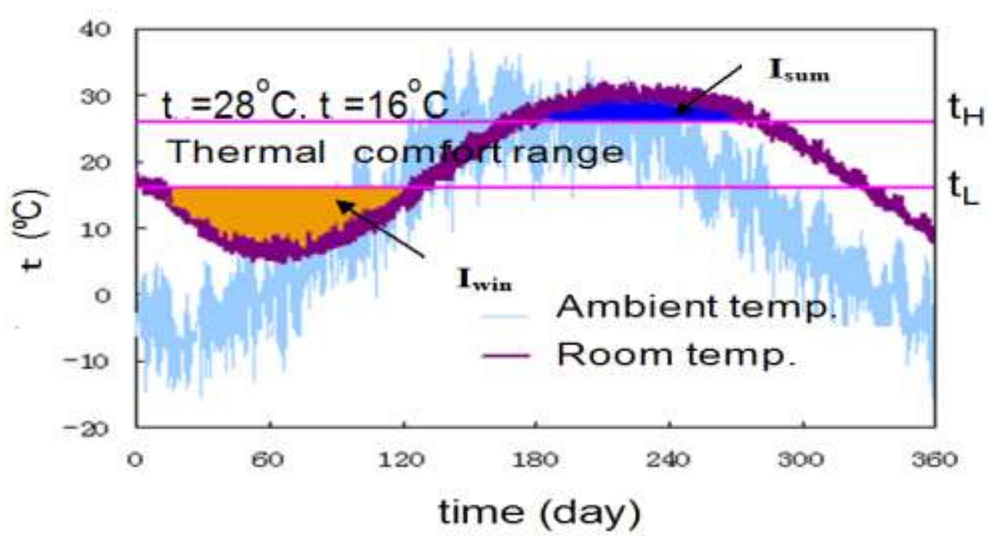

Fig.5.5 Temperature distribution in one year in Beijing

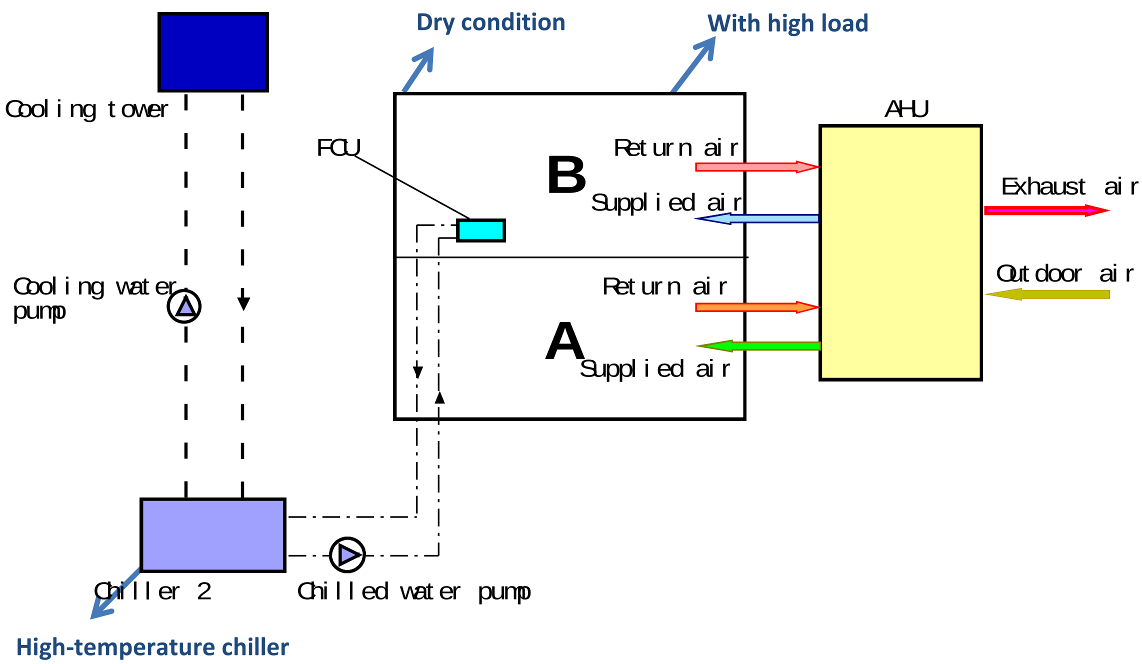

Fig.5.6 Air conditioning system treating heat and humidity separately

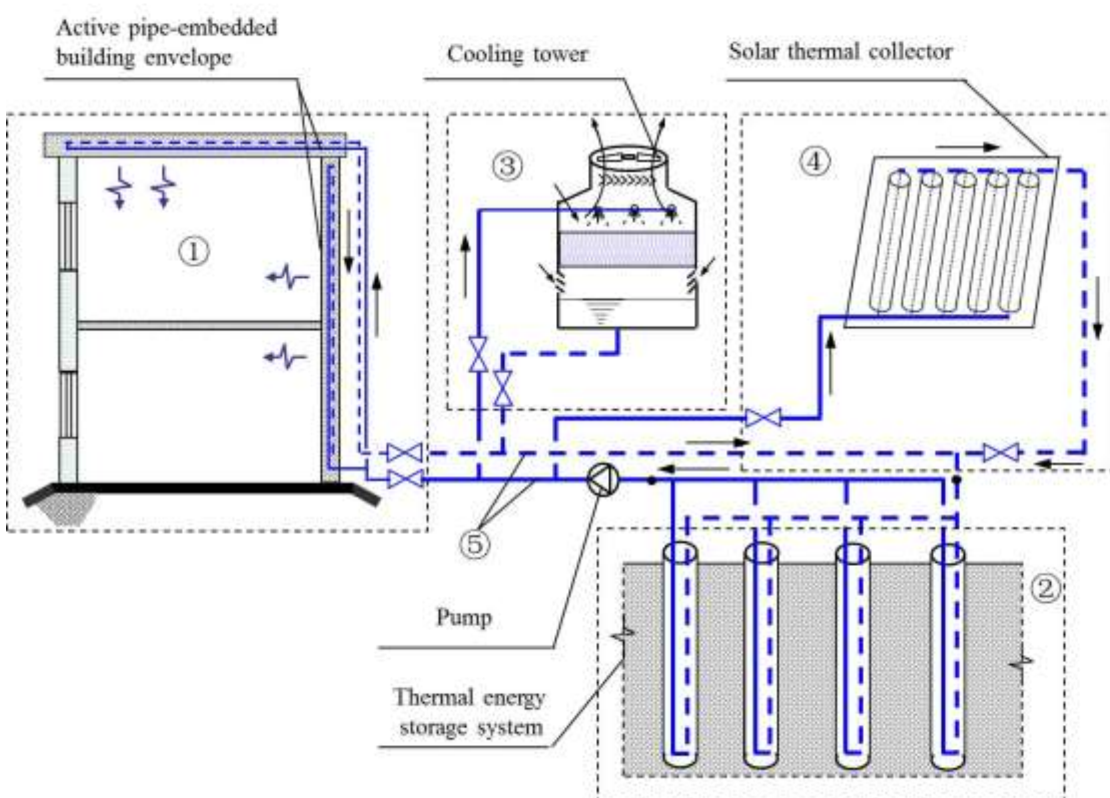

Fig.5.7 Active pipe-embedded building envelope system

Prof. Xu from Huazhong University of Science & Technology developed an active pipe-embedded building envelope system to reduce energy consumption, as shown in Fig.5.7. This system has five parts, i.e., heat exchange system of the building envelope, thermal energy storage system, auxiliary cooling source system, auxiliary heating source system, and power transport system. External walls or roofs with embedded pipes are acted as the heat exchange system of the active pipe-embedded building envelope, and the fluid (usually water is used) is circulating in the pipe to extract heat/coolth inside the structure directly and can intercept the heat or coolth from the ambient air to the indoor space resulting reduced cooling load or heating load.

Prof. Jiang from Harbin Institute of Technology presented an anti-freezing strategy of solar system in severe cold areas in Fig.5.8. The system consisted of solar collecting loop (anti-freezing loop), heat exchanging loop and terminal heating loop, as well as data acquisition and control system. In this system, a glycol-water mixture was used as the antifreeze fluid and the solar collecting loop was an open-loop subsystem. It can reduce the concentration of antifreeze fluid from 50% to 30%, even to 20% in some cases. This system can promise solar energy work well in severe cold regions.

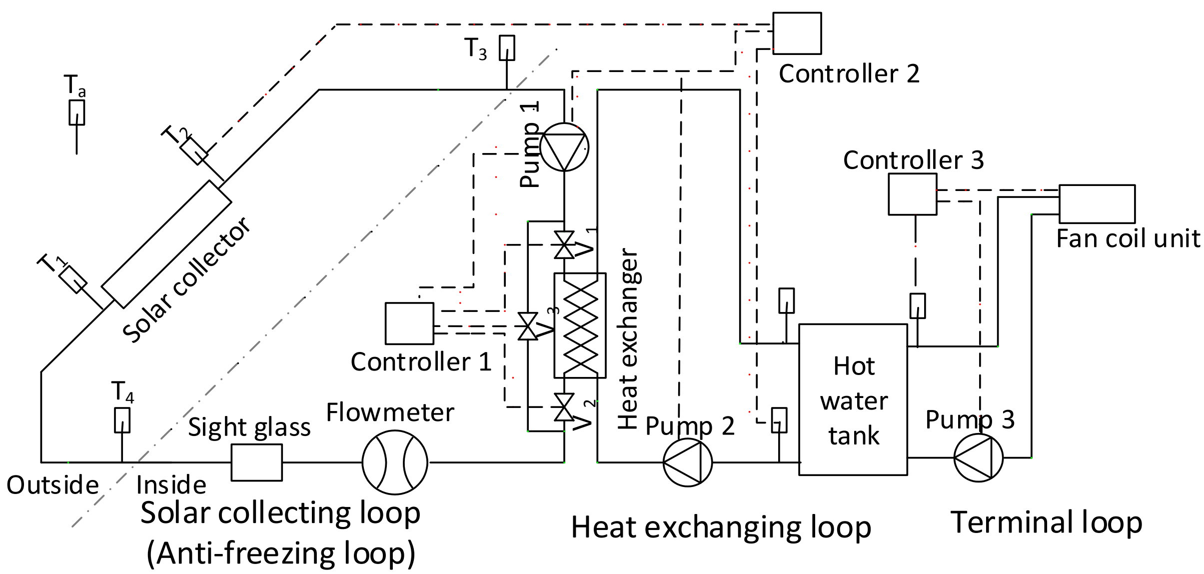

Fig.5.8 Schematic diagram of anti-freezing system

Prof. Andrew from the Hong Kong University of Science and Technology illustrated a water adsorption chiller with thermal storage in Fig.5.9. The solar collectors capture the heat from the solar radiation and the heat is transferred and stored at the HWT. The operations of the adsorbent bed take turns to execute the adsorption and desorption process. The heat of adsorption will be removed by the cooling water circulating the adsorbent bed. On the other hand during desorption process, heat (hot water from the HWT) will apply to the adsorbent and release the adsorbate. In the condenser, the refrigerant (water vapor) condenses and transfers heat to the cooling water. The condensed water flows naturally to the evaporator. In the evaporator, the refrigerant (water) vaporizes and removes the heat from the chilled water. The water vapor will enter the adsorbent bed for adsorption process to complete the cycle. The adsorption/desorption cycle switches at a cycle time that the water uptake of the adsorbent reaches equilibrium.

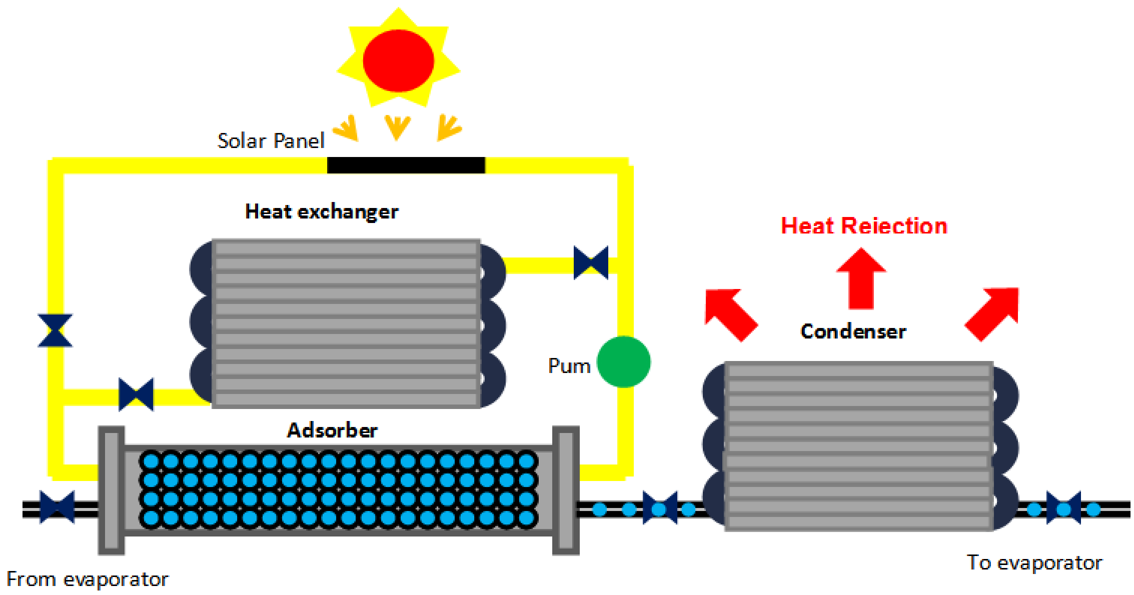

Fig.5.9 Water adsorption chiller with thermal storage

Fig.5.10 Meixi Lake-Ecology and Community of the Future City-KPF

Ms. Cheng from KPF introduced their design of the Meixi Lake, ecology and community of the future city in Fig.5.10. This design seeks to establish a paradigm of man living in balance with nature, a city with the highest standards of sustainable living through its social, ecological and environmental balance and integrated system. To help mitigate freshwater shortfall, Meixi Lake is implementing a tiered approach to freshwater usage. An urban center generates a large amount of blackwater, which is collected and delivered to a treatment facility where it is filtered and treated using modern wastewater biotechnology. The clean, disinfected graywater is then distributed back to the city for toilet flushing, road cleaning, and irrigation of parks and urban green spaces. A network of sidewalk and roadway median biofiltration planters cleans the rainwater before flowing to the canals and the lake. Green roofs are utilized throughout the city for collection and filtration of rainwater for onsite use. Over time, this system will save a substantial amount of daily fresh water consumption. This multilayered network will optimize water use efficiency within Meixi Lake and limit city demands on this invaluable resource. The design of Meixi allows the vitality of a dense metropolis to be combined with the beneficial qualities of a natural setting. This forward looking community will benefit from and promote the development of new technologies.

3.2 Project Exhibition

Changsha Maxxom High-tech Co., Ltd. exhibited three different kinds of air handling units and five kinds of PCMs, as shown in Fig.5.11, Fig.5.12 and Fig.5.13. They developed the air conditioner with phase change material, which consisted compressor, evaporator, condenser, throttle and energy storage module. When outdoor air temperature is lower, it can reduce the indoor air temperature and store the cold energy to PCM. When outdoor air temperature is higher than indoor temperature, the stored energy will be released to cool down the indoor temperature without demands the running of compressor. This unit can help shorten the running time of compressor, the main component which consumes most electricity of air conditioner.

Fig.5.11 Air conditioner with phase change material

Fig.5.12 Air handling unit with phase change material

Fig.5.13 Heat pipe with phase change material and phase change materials

Air handling unit with PCM absorbed outdoor low temperature air to indoor environment when outdoor air temperature is low enough. And when the outdoor air temperature is lower, the unit has the capacity of cooling down the indoor air temperature as well as charging energy storage module. Outdoor air solidifies PCM, which then enters the building to reduce the indoor air temperature.

Heat pipe unit adopts liquid-gas PCM. The working medium in indoor part becomes to gas state from liquid when it absorbs the heat generated in building. The gas medium goes up because of the density difference between liquid and gas medium to the outdoor part. Then the gas in outdoor part is cooled down by outdoor cold air and changes to liquid state, which is pumped back to the indoor part to complete the circulation and transfer the indoor heat to outdoor environment.

Phase change material is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage (LHS) units.

5.4. Conference summary

An APEC Conference on Low Carbon Town and Physical Energy Storage was held at Changsha on May 25th and May 26th. More than 200 experts from 11 economies took part in the conference and presented their latest research about low carbon town and physical energy storage. The conference focused on how to reduce the energy consumption of building and how to build a low carbon town. Advanced technologies mainly on building envelop and HVAC systems were illustrated by experts. Building envelop with phase change material was discussed in the form of envelop with PCM board, envelop embedded with PCM pipe, and tent with PCM board. New HVAC systems were presented, including heat pump system driven by photovoltaic, solar adsorption cooling systems, and hybrid ground source heat pump systems. And three kinds of air handling units with PCMs which can reduce the energy consumption of air conditioning system by 20% and five kinds of PCMs were exhibited.

Fig. 5.14 The participants of the conference

5.5. Annex 1 Conference Greetings

GREETING FROM CHAIRS

On behalf of the organizers and sponsors we are pleased to welcome you to the APEC Conference on Low Carbon Town and Physical Energy Storage. Why should you participate in the conference? To hear the latest results on research, to meet and network with colleagues, or just to have a good time and visit new places. The programme includes outstanding speakers from all over the world who have been invited to deliver keynote lectures. In addition, we have invited well renowned experts from the APEC ecnomic regions who will share their experiences.

As a group, we have an important role to play in society. All over the world society's foremost challenges this century are global warming, sustainability and security of energy supply. These issues are altogether linked with global stability, economic prosperity, and quality of life. We focus on complementary research fields to find an integerated way to solve the issue of higher energy consumption in the world's urbanization process. Physical energy storage is an efficent way to utilize energy while resolving the mismatch between on-peak and off-peak loads. All participants are colleagues who come from various cities and countries. There will be no strangers, just a number of friends you have not yet met.

We thank all the contributors, participants, the International Scientific Committee, the chairpersons, members of the Organizing Committee, students, institutional sponsors, and, last but not least, our financial sponsors, without whom we could not have made this conference possible.

We welcome you to the APEC conference in beautiful Changsha City, China.

Chair and Co-chairs

Quan Zhang (Chair)	Professor, Hunan University
Hongxing,Yang (Co-chair)	Professor, The Hong Kong Polytechnic University
Mario A Medina (Co-chair)	Associate Professor, University of Kansas

5.6. Annex 2 List of International Scientific Committee Members

APEC
Asia-Pacific Economic Cooperation

APEC Conference on Low-carbon Towns and Physical Energy Storage
May 25-26, 2013, Changsha, China
Email: apec201305@163.com
Http://www.apec2013.net

ANNEX

Annex 1 List of International Scientific Committee members

Num	Name	Nationality and Region	Affiliation
1	Amporn Kunchornrat	Thailand	Srinakharinwirot University
2	Angui Li	China	Xian University of Architecture and Technology
3	Aumnad Phdungsilp	Thailand	Dhurakij Pundit University
4	Baizhan Li	China	Chongqing University
5	Bin Chen	China	Dalian University of Technology
6	Chao Chen	China	Beijing University Of Technology
7	Chi-ming Lai	Chinese Taipei	National Cheng-Kung University
8	Chow Tintai	Hong Kong,China	City University of Hong Kong
9	Christopher Y H CHAO	Hong Kong,China	The Hong Kong University of Science & Technology
10	Deying Li	China	Beijing University of civil Engineering and Architecture
11	Enshen Long	China	Sichuan University
12	Fariborz HAGHIGHAT	Canada	Concordia University
13	Guanyi Chen	China	Tianjin University
14	Guohui Feng	China	Shenyang Jianzhu University
15	Guoqiang Zhang	China	Hunan University
16	Hanqing Wang	China	Hunan University of Technology
17	Hongwei Tan	China	Tongji University
18	Huanxin Chen	China	Huazhong University of Science and Technology
19	Huijun Wu	China	Guangzhou University
20	Janthana Kunchornrat	Thailand	King Mongkut's University of Technology

			Thonburi
21	Jen Chun Wang	Chinese Taipei	Chia Nan University
22	Jianping Ou	China	Central South University/ChangSha Energy Bureau
23	Jili Zhang	China	Dalian University of Technology
24	Jin-Li Hu	Chinese Taipei	National Chiao Tung University
25	John Zhai	USA	University of Colorado at Boulder
26	Jun Lu	China	Chongqing University
27	Mario A Medina	USA	University of Kansas
28	Mark Bomberg	Canada	McMaster University
29	Menghao Qin	China	Nanjing University
30	Meng Ni	Hong Kong,China	The Hong Kong Polytechnic University
31	Michael K.H. LEUNG	Hong Kong,China	City University of Hong Kong
32	Mohamed EL MANKIBI	France	University of Lyon
33	Nairen Diao	China	Shangdong Jianzhu University
34	Niu Jianlei	Hong Kong,China	The Hong Kong Polytechnic University
35	Qihong Deng	China	Central South University
36	Qingyan Chen	USA	Purdue University
37	Quan Zhang	China	Hunan University
38	Ryozo Ooka	Japan	The University of Tokyo
39	Shengming Liao	China	Central South University/ChangSha Energy Bureau
40	Shengwei Zhu	China	Huazhong University of Science and Technology
41	Shijun You	China	Tianjin University
42	Wang Shengwei	Hong Kong,China	The Hong Kong Polytechnic University
43	Wei Xu	China	China Academy of Building Research
44	Xiang Huang	China	Xi'an Polytechnic University
45	Xiaosong Zhang	China	Southeast University

46	Xinhua Xu	China	Huazhong University of Science and Technology
47	Hongxing Yang	Hong Kong,China	The Hong Kong Polytechnic University
48	Yang Yao	China	Harbin Institute of Technology
49	Yanfeng Gong	China	Nanjing University of Technology
50	Yanping Yuan	China	Southwest Jiaotong University
51	Yi Wang	China	Xian University of Architecture and Technology
52	Yinping Zhang	China	Tsinghua University
53	Yiqiang Jiang	China	Harbin Institute of Technology
54	Youming Chen	China	Hunan University
55	Yuguo Li	Hong Kong,China	The University of Hong Kong
56	Yuebin Yu	USA	University of Nebraska-Lincoln
57	Zhenqian Chen	China	Southeast University
58	Ziping Feng	China	Guangzhou Institute of Energy Conversion,Chinese Academy of Sciences

5.7. Annex 3 List of Local Organizing Committee Members

APEC
Asia-Pacific
Economic Cooperation

APEC Conference on Low-carbon Towns and Physical Energy Storage
May 25-26, 2013, Changsha, China
Email: apec201305@163.com
Http://www.apec2013.net

Annex 2 List of Local Organizing Committee members

Num	Name	Position	Affiliation
1	Quan Zhang	Chair	Hunan University
2	Hongxing Yang	Co-chair	The Hong Kong Polytechnic University
3	Mario A Medina	Co-chair	University of Kansas
4	Xiaoqin Sun	General Secretary	Hunan University & University of Kansas
5	Ping Zhou	Secretary	Hunan University
6	Vivien lu	Member	The Hong Kong Polytechnic University
7	Nianping Li	Member	Hunan University
8	Guangcai Gong	Member	Hunan University
9	Changzhi Yang	Member	Hunan University
10	Ling Zhang	Member	Hunan University
11	Feng Xu	Member	Hunan University
12	Jin Zhou	Member	Hunan University
13	Hongqiang Li	Member	Hunan University
14	Yuanhao Wang	Member	The Hong Kong Polytechnic University
15	Junping Fu	Member	Changsha University of Science &Technology
16	Kaijun Dong	Member	GuangZhou Insititute of Energy Conversion,Chinese Academy of Sciences
17	Shuguang Liao	Member	Changsha Maxxom High-tech Cor. Ltd

5.8. Annex 4 List of Invited Guests

APEC
Asia-Pacific
Economic Cooperation

APEC Conference on Low-carbon Towns and Physical Energy Storage
May 25-26, 2013, Changsha, China
Email: apec201305@163.com
Http://www.apec2013.net

Annex 4 List of invited guests

Num	Name	Nationality & Region	Affiliation
1	John Zhai	USA	University of Colorado at Boulder
2	Mario A Medina	USA	University of Kansas
3	Winston K.H. Chow	USA	United States Department of Energy
4	Dale Manty	USA	National Center for Environmental Research
5	Mark Bomberg	Canada	University of Kansas
6	Ryozo Ooka	Japan	The University of Tokyo
7	Zhiwei Lu	Singapore	APEC Secretariat
8	Hongxing Yang	Hong Kong, China	The Hong Kong Polytechnic University
9	Yinping Zhang	China	Tsinghua University
10	Xiaowei Xu	China	Shenzhen Institute of Building Research LT. CO