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# STUDY ON THE OPTIMIZATION OF PCM INTEGRATED AIR-CONDITIONING DUCT FOR THE DEMAND SHIFTING

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**Abstract.** The imbalance of the electrical grid between source and demand causes great decrement of grid efficiency and energy loss. The main reason for the imbalance comes from the fluctuation of electricity consumed by buildings. Numerous efforts have been conducted to mitigate the fluctuation of buildings electricity consumption. The phase change material (PCM) can store heat or cold to keep indoor thermal environment stable for a certain period without heat/cold supply from heating, ventilation, and air-conditioning (HVAC) systems. It can effectively shave the peak of HVAC electricity demand. Meanwhile, the electricity cost of running HVAC systems can also be cut down. Therefore, this paper proposes a novel type of air-ducts integrated with PCM and studies its performances of the indoor thermal environment through theoretical analysis and dynamic simulation. The simulation results show that the indoor thermal environment can be kept within the comfortable range when turn off chiller during the peak load period using the proposed PCM integrated air conditioning ducts.

## 1. INTRODUCTION

Due to the huge difference of electricity consumption between daytime and nighttime in buildings, the imbalance of the electrical grid between source and demand causes great decrement of grid efficiency and energy loss. This imbalance has also intensified with the increase in renewable energy generation capacity such as wind power and solar photovoltaics. China's heavy reliance on coal-generated power makes grid difficult to effectively cope with the large fluctuation in the end-use power load. In 2014, the curtailment of wind power and photovoltaic power generation was more than 20% in China. The difference between the peak and valley of electricity consumption caused the loss of power grid by more than 5% in the power generation process as well as the power transmission and distribution process<sup>[5]</sup>. Therefore, Chinese governments put forward the time-of-use electricity tariffs, which is intended to encourage end-users to use more off-peak power thus the imbalance can be reduced<sup>[6]</sup>.

Building electricity consumptions accounts for nearly 40% of the total energy consumption in China. The energy consumption of the air conditioning system has also become the largest part of the various energy branches of the building. Therefore, reducing the load of air conditioning system is an important way to reduce the load of buildings during peak time. Meanwhile, it is the basic requirement for the building to provide comfortable working and living environment. A major challenge in the field of building environment that how to achieve the peak demand shifting and to improve the demand response level while ensuring the indoor comfort has now aroused great attention. Many scholars have proposed to use Phase Change Materials (PCMs) for energy storage to change the inherent power consumption



mode of end users. Compared with common materials, PCMs have a higher energy storage density and can store a large amount of cold/heat in a range of extremely small temperature changes. Since the PCM has such an energy storage property, it can solve the problem of mismatch between the user side and the supply side in time or space. Therefore, the PCM is used as an effective way for energy storage, which can realize the peak demand shifting of the building electrical load, reduce the indoor temperature change after the air conditioner is switched off, and reduce the operating cost of the Heating Ventilation and Air-conditioning (HVAC) system.

In the actual application process, the daily outdoor environmental parameters are different, such as the fluctuations of temperature and solar radiation. The application PCMs in the building envelopes, such as phase change temperature, capacity and deployment etc., is often optimized for the whole season or the outdoor weather conditions of a typical day. This can lead to the fact that PCMs cannot be stored and discharged under desired conditions. Therefore, this paper proposes a new application method of PCM, combining PCM with air-conditioning duct of HVAC system to actively control the storage and discharge of PCM and thus change the electricity consumption of HVAC system and achieve the goal of demand shifting.

This study uses Simulink platform to build the model of PCMs applied to the air-conditioning ducts. The dynamic changes of indoor thermal environment are explored. The applicability and timeliness of PCMs applied to air-conditioning system to maintain indoor thermal environment are verified. Also, this study proposes the optimizing control strategy of the air conditioning system of a typical office room with PCM integrated air-conditioning ducts, and the economic benefits of air-conditioning system combined with PCM are analyzed.

## 2. SIMULATION MODEL

### 2.1. Mathematical model of room

The room simulated in this study is a typical office room located in Beijing. There is an exterior south-facing wall and window in the building, and the rest of the envelopes are 5 interior envelopes which are surrounded by air conditioning environment. The parameters of the room model are shown in the following Table 1 and the thermal parameters of room envelopes are from a design handbook<sup>[4]</sup>.

**Table 1.** Parameters of room model

Dimensions of the room	m	3×5×3
Indoor heat generation	W/m <sup>2</sup>	30
Air Change Rate (ACH)	h <sup>-1</sup>	2.0/0.5
$h_{ew,o}$ (convective heat transfer coefficient at exterior wall and window)	W/(m <sup>2</sup> .k)	18.6
$h_{iw,o}$ ( convective heat transfer coefficient at interior wall and window)	W/(m <sup>2</sup> .k)	8.7
thicknesses of walls	mm	240
thermal conductivity of walls	W/(m·k)	0.81
Specific heat capacity of walls	kJ/(kg·k)	0.84
thermal conductivity of external insulation	W/(m·k)	0.45
Solar radiation absorption rate of external wall surface	-	0.57
Area ratio of window-to-wall	-	0.3
Transmittance of the window	-	0.51
Air supply volume	m <sup>3</sup> /h	360
Dimensions of the air-duct (d)	m	0.2×0.2

The energy balance equation of indoor air is shown as follows:

$$\rho_a C_{p,a} V_R \frac{dt_{in}}{dt} = \sum Q_{w,i} + Q_{eq} + Q_{people} + Q_{supply} + Q_{win} + Q_{fresh}$$

$Q_{supply}, Q_{w,i}, Q_{fresh}$  are calculated by the below equations:

$$Q_{supply} = \rho_a C_{p,a} G_s (t_{in} - t_s)$$

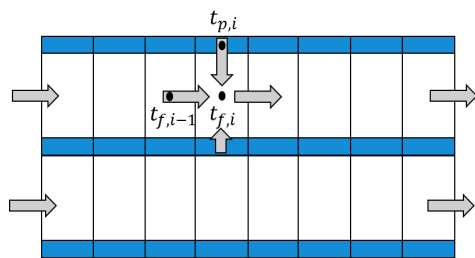
$$Q_{w,i} = h_{in} A_{w,i} (t_{w,i} - t_{in})$$

$$Q_{fresh} = \rho_a C_{p,a} V_R (t_{out} - t_{in}) \cdot ACH$$

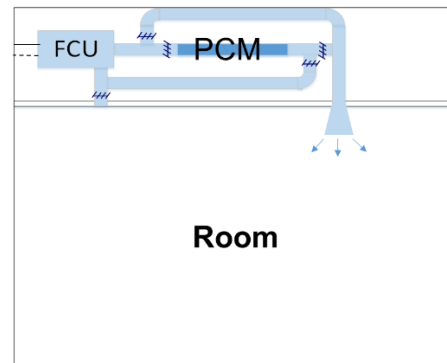
ACH is set at 2 h<sup>-1</sup> at night for the purpose of using free cooling during night and ACH is 0.5 h<sup>-1</sup> during the daytime.

## 2.2. Mathematical model of PCM air-conditioning duct

A section of air-conditioning duct integrated with PCM is shown in Figure 1:



**Figure 1.** PCM duct model



**Figure 2.** PCM air-conditioning duct system

The thermal dynamics of heat transfer between air flow and PCMs in a duct can be explained by the below equations:

$$m_{f,i} C_{p,f,i} \cdot \Delta t_{f,i} = m_{f,i} C_{p,f,i} \cdot (t_{f,i-1} - t_{f,i}) - (t_{f,i} - t_{p,i}) / R_f$$

$$m_{p,i} C_{p,p,i} \cdot \Delta t_{p,i} = (t_{f,i} - t_{p,i}) / R_f$$

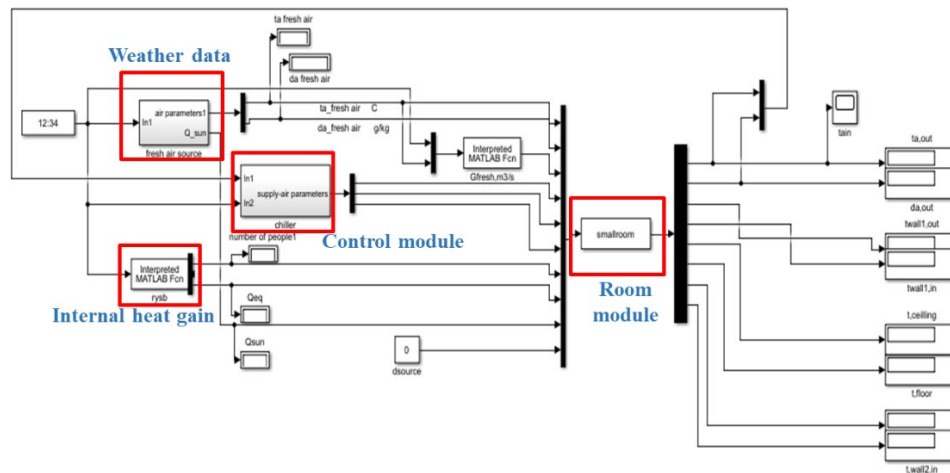
$$Nu = 0.0214(Re^{0.8} - 100)Pr^{0.4} \left( 1 + \left( \frac{d}{L} \right)^{\frac{2}{3}} \right) \left( \frac{t_{f,i}}{t_{p,i}} \right)^{0.45}$$

In order to highlight the essence of physics and simplify the problem rationally, the following assumptions are set:

- The outer surface of the duct is insulated, and the convection heat transfer between the PCM surface and the air in the duct is conducted.
- Ignoring the natural convection in PCM, the Nusselt number is calculated according to empirical formula.

## 2.3. Simulink model

There are four modules in the Simulink model, room module, outdoor weather parameter module, air conditioning and cooling control module, indoor heat generation module, and the last three modules' outputs are the inputs to the room module, as shown in Figure 3.

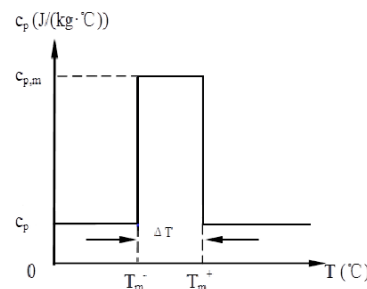
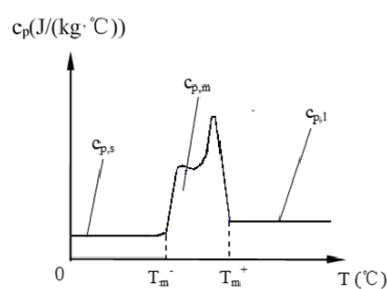


**Figure 3.** Simulation model

The room thermal dynamics are described with six parameters: indoor temperature, indoor humidity, external wall surface temperature, interior wall surface temperature, floor temperature, and ceiling temperature. Write the equation by using the S function in Simulink to describe the dynamic progress. The room module needs to input three types of outdoor weather parameters: temperature, humidity, and solar radiation to the south facing external wall. All weather data are picked from the website of simulation software DeST<sup>[1]</sup>.

### 3. OPTIMAL DESIGN OF PCM AIR-DUCT

The heat transfer mathematical model of PCM duct is established, and the phase change process is simplified by equivalent specific heat method. In general, the relationship between the specific heat capacity  $C_p$  and the temperature  $T$  of PCM is reflected in Figure 4. But due to its narrow phase change temperature range and its high latent heat, it can be generally thought that the specific heat capacity of the PCM is high in the phase change temperature range. So the PCM heat capacity is simplified using a step function as follows in Figure 5. <sup>[3]</sup>



**Figure 4.** Relationship between  $C_p$  and  $T$       **Figure 5.** Simplified  $C_p$  model

#### 3.1. Control strategy of air conditioning system with phase-change energy storage

PCM can be cooled by using the chiller at night through the bypass air channel without the air returning from the room, which ensures the cooling energy is not wasted when it needs not cooling during night. According to the predicted load in the daytime, the optimization method of minimum operating electricity cost is calculated to control the time of charge and discharge cold. In response to the time-of-use tariffs of the power grid, the air conditioning load during the peak period should be reduced as much as possible. In this way, the air conditioning control strategy can optimize the operation to achieve minimum cooling cost. The control strategy is shown in the Table 2.

**Table 2.** Control strategy of air conditioning system with PCM ducts

time	Electricity price (for Beijing)	Cooling command	State of PCM
0:00-7:00	Valley	Off	Cold storage
7:00-10:00	Ordinary	Cooling, tset=26°C	PCM bypassed
10:00-11:00	high	Cooling, tset=26°C	PCM bypassed
11:00-13:00	peak	Air supply, tset=28°C	Melting
13:00-15:00	high	Cooling, tset=26°C	PCM bypassed
15:00-16:00	ordinary	Cooling, tset=26°C	PCM bypassed
16:00-17:00	peak	Air supply, tset=28°C	Melting
17:00-18:00	ordinary	Air supply, tset=28°C	PCM bypassed
18:00-0:00	-	Off	Cold storage

### 3.2. Estimate method of optimal PCM characteristics

The temperature change of PCM is small during its cold storage and discharge period, and the area of heat transfer and heat transfer coefficient in the air-duct can be considered to be constant. Therefore, the phase change temperature of the required PCM can be estimated as follows:

$$(T_m - T_s)/(T_r - T_m) = \tau_{\text{melting}}/\tau_{\text{cold storage}}$$

Where  $T_m$  is the phase change temperature,  $\tau$  is the process time.

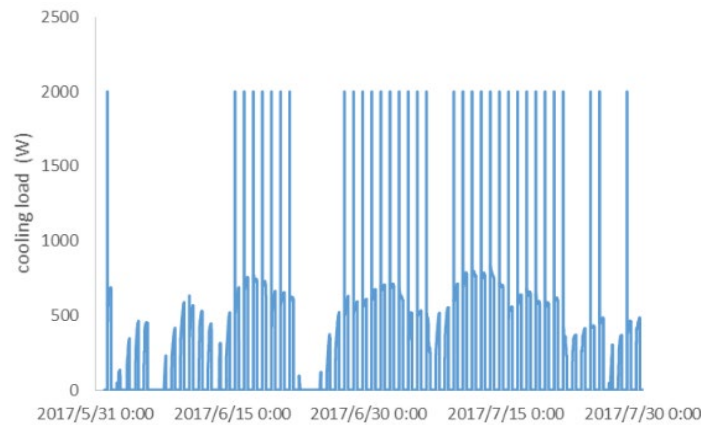
Based on the air conditioning control strategy described above, the discharge duration for PCM is 3 hours (11:00-13:00, 16:00-17:00). Assuming that the cold storage time is 6 hours (0:00-6:00),  $T_r$  is about 26~28°C and  $T_s$  is higher than 14°C, the required temperature of PCM can be estimated to be 18.5 °C. Through the literature research, the mixture of capric acid and lauric acid is finally determined as PCM to storage energy for air-duct. Dimaano and Escoto carried out continuous heating and cooling experiments on this mixture in 1998<sup>[2]</sup>. The components were not separated which indicates its good chemical stability. The thermophysical properties of the mixture are shown in Table 3.

**Table 3.** Thermophysical properties of PCM

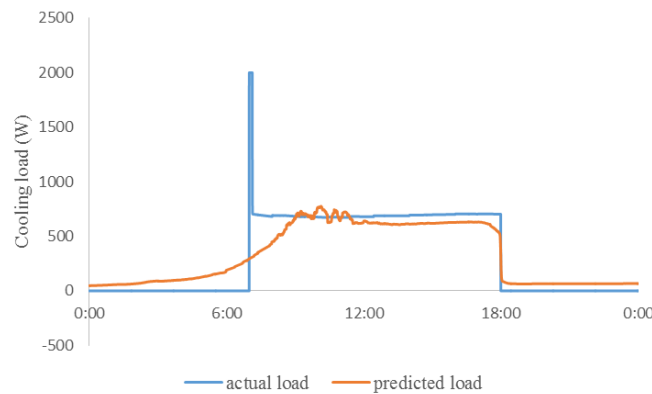
	C-L acid mixture (65%:35%)
Melting point(°C)	18.0-19.5
Heat of fusion(kJ·kg <sup>-1</sup> )	140.8
Density (kg·m <sup>-3</sup> )	900
Specific heat (kJ·kg <sup>-1</sup> ·K <sup>-1</sup> )	2.24
Thermal conductivity (W·m <sup>-1</sup> ·K <sup>-1</sup> )	0.14

### 3.3. Load prediction and Simulation results

Before the daily storage and cooling strategy is optimized, the cooling loads on the following day need to be predicted, so the neural network method is used to predict the cooling loads. By using simulation, the historical data of the room cooling load is obtained as training data of the neural network model. Time, outdoor temperature and solar radiation are used as the neural network inputs. The cooling loads are the neural network outputs.



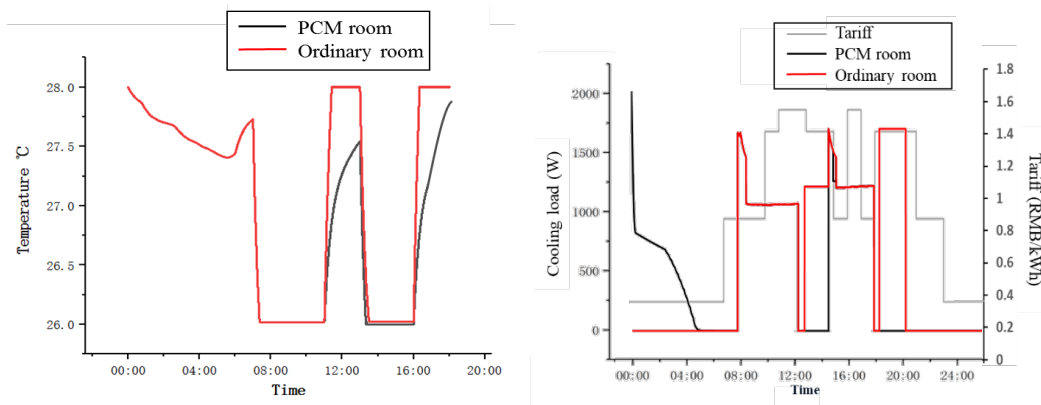
**Figure 6.** Cooling loads for training neural network



**Figure 7.** Comparison of predicted cooling load

The accuracy of the load prediction during peak time verifies that the prediction accuracy is acceptable for the PCM control of the air conditioning system.

According to the predicted load curve, the minimum daily electricity cost is taken as the optimization target. Use off-peak time power to cool the PCM to solid state. Turn on the air conditioning system for 6 hours during non-working hours at night to fully charge the PCMs. The PCM discharge is controlled according to the priority order of ‘peak period>high period >ordinary period’. Figure 8 shows an example on a summer day of 2017/07/13. PCMs melt during 11:00-13:00, 16:00-17:00, 17:00-18:00.



**Figure 8.** Indoor air temperature (left) and cooling load (right) comparison between rooms with ordinary air duct and PCM air duct

During the peak period, the room with PCM duct has more thermally comfortable indoor environment and room temperature rises more slowly. There is no need for cooling by chiller.

The optimized control strategy makes full use of the off-peak electricity to store cold for PCM. The room can be cooled by the melting process of PCM during the peak period. Thus the air conditioning loads in the daytime are shifted a lot to the electric off-peak period at night. The comparison results are shown in Table 6. From Table 6, it can be seen that the use of PCM duct can achieve peak demand shifting and can save electricity cost up to 15.6%.

**Table 4.** Comparison on the consumption of ordinary room and PCM room

2017/7/13	Ordinary room	Room with PCM duct
Consumption of chiller (kWh)	2.9	2.94
Consumption of fan (kWh)	0.36	0.6
Electricity cost (RMB)	3.26	2.75
Cost saving		15.60%

#### 4. Conclusions

A new type of PCM duct is put forward. And the design method of PCM duct and the selection method of PCM components are proposed. The simulation model of a typical room with PCM air-conditioning duct is built on the platform of Simulink, and the influence of PCM cooling on indoor thermal environment and air conditioning load is simulated.

The control strategy of the air conditioning system with PCM duct is developed for the purpose of cooling demand shifting and electric costing saving. Taking the minimum daily electricity cost as the optimization objective, the simulation proves that under the developed control strategy, the electricity cost of the air conditioning system can be saved by 15.6% and it is an effective way for demand response.

#### Acknowledgement

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