Energy Analysis of Phase Change Wall Integrated with Night Ventilation in Western China

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Abstract

Recently, research on energy saving in buildings attracts more and more attention. In present work, the effect of phase change material wall (PCW) and night ventilation (NV) on energy saving of a typical office building in five key cities (Lhasa, Xi'an, Kunming, Chengdu and Urumchi) in Western China, is investigated using EnergyPlus 8.6. The influences of different climate conditions, phase change temperature, NV rates on mean indoor temperature are carefully studied. Suitability and energy saving potential of PCW integrated with NV are also analysed. The results contribute towards a more comprehensive evaluation and understanding of interaction effects between PCW and NV.

Introduction

The report from Building Energy Conservation Research Center of Tsinghua University showed that, energy consumption of buildings would account for more than 35 % of total primary energy use in China in 2020 (Building Energy Conservation Research Center of Tsinghua University (2013)). In order to reduce the energy consumption of the buildings sector while the human comfort remains unchanged, different design strategies of energy saving are proposed, mainly containing active design strategy and passive design strategy. Considered from energy conservation and economic efficiency, passive buildings show larger advantages than active buildings. Integration application of NV and thermal mass in buildings could effectively reduce cooling and heating load, and further building energy consumption (Wang et al. (2014), Shaviv et al. (2001) and Ramponi et al. (2014)). According to Yang and Li (2008), thermal mass is mainly the thermal materials in buildings, which absorbs heat, stores heat, and then releases heat. Thermal mass in buildings generally includes building envelopes, internal walls, furniture and additional thermal mass (Sadineni wt al. (2011)). Heat storage capacity of thermal mass play an important role to determine the thermal performance of buildings (Li et al. (2013)).

Rencently, to understand passive design strategy and climatic stuitability of NV, several related studies have been lauched and some useful conclusions have been drawn. Givoni (1998) found that, for buildings with light envelope, the effect of NV on maximum indoor temperature was quite limited. On the contrary, for buildings with heavy envelope, it was quite effective in reducing the maximum indoor temperature. Santamouris et al. (2010) concluded that, under the specific conditions, the potential contribution of NV increased with the increase of cooling demand of the buildings. Lam et al. (2006) studied energy saving potentials of passive strategies such as NV with thermal mass in China. Based on these analyses, passive design zones were divided based on different climates. Liu et al. (2017) proposed a porous building model to investigate unsteady flow and heat transfer around and through an isolated high-rise building based on NV and thermal mass. Recently, Yang (2010) investigated climatic suitability of NV design strategy and obtained climatic cooling potential (CCP) distributions of NV in northern China (see Figure 1). Figure 1 dipicts that, most parts of northern China are quite suitable to perform NV, due to most values of CCP are larger than 10. The previous investigations show that, passive design zones (including NV and thermal mass) have been divided and the influences of NV on indoor temperature have been obtained. However, functional supplement of PCM and NV has not caused enough attentions in passive design in China.

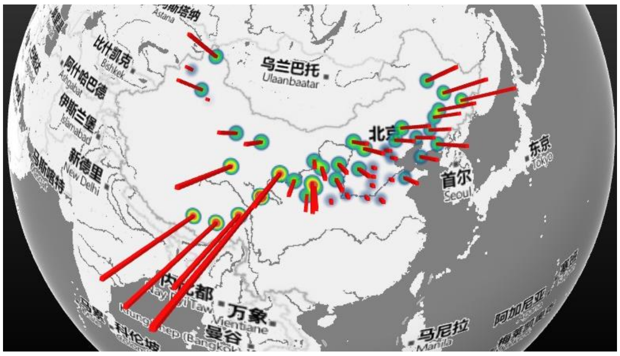
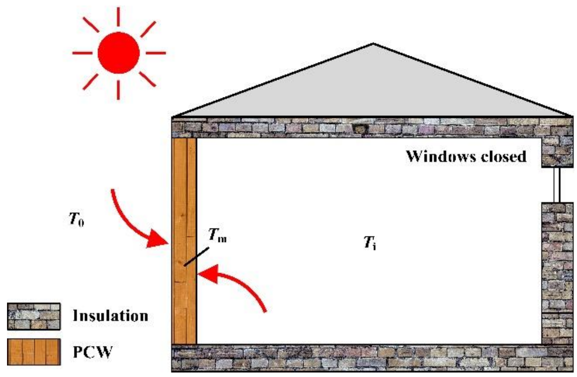


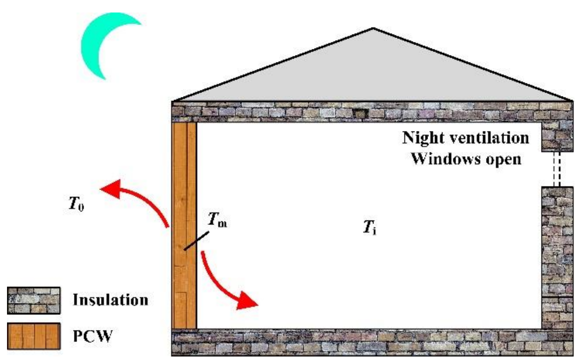
Figure 1: Climatic cooling potential distributions of NV in northern China.

Meanwhile, energy saving performance of PCM-based envelope, combination mode of building envelope and PCM are also investigated (Kuznik et al. (2011)). Lin et al. (2004) applied a kind of under floor electric heating system with PCM plates to charge heat by using cheap nighttime electricity and discharge the heat stored at daytime. Jin et al. (2016) optimized the location of a thin PCM layer in the frame wall. They found that, the optimal PCM location was closer to the interior surface of the wall with the increase of the interior surface temperature of the wall. Mi et al. (2016) conducted energy savings simulation and economic analysis of building integrated with PCM in different cities of China. Energy saving potential and PCM investment of different cities were compared. Roman et al. (2016) employed thermal energy simulation to determine the effectiveness of PCM roof technologies in mitigating urban heat island effects over seven climatic zones across the United States of America. Ascione et al. (2014) refurbished existing buildings by means of addition of PCM plaster on the inner side of the exterior envelope. The cooling energy savings were calculated with reference to a well-insulated massive building. Marin et al. (2016) obtained the potential of using PCM-enhanced gypsum boards in lightweight buildings, to increase the energy performance during both heating and cooling seasons in arid and warm temperate main climate areas. These studies show that, energy saving calculation model of PCM based envelope has been established and energy saving potential have been obtained. However, thermal storage enhancement effect of NV on PCM based envelope has not caused enough attentions.

In naturally ventilated buildings, it has been well studied and concluded that, the thermal mass could be employed to reduce the air temperature fluctuation and maintain it in a relatively small range (see Figure 2). To the authors' knowledge, little research work reported in the opening literature has made on the performance of PCW combined with NV in different climate zones, especially in western China with complex topography, scarce natural resources and slow economic development. Therefore, the purpose of the present work is to perform a simulation work of PCW on the indoor air temperature under NV conditions in summer. Different climate conditions of five typical cities in western China are employed. Different phase change temperature is also taken into consideration.



(a) Daytime



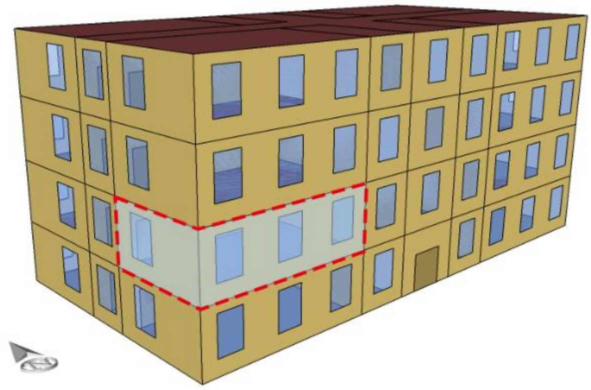
(b) Nighttime

Figure 2: Mechanism of PCW and NV.

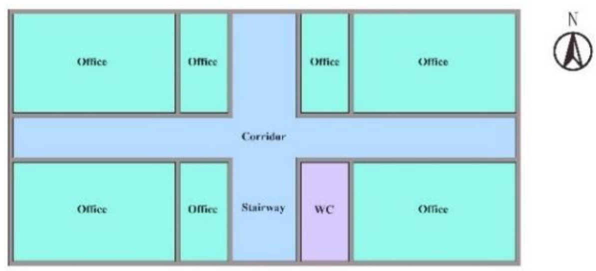
Methodology

Building description

In present work, a typical four-story office building is employed for simulation. The Sketchup model and ground floor plan are illustrated in Figure 1. Each story of the building has a height of 3.6 m and floor area of 504 m^2 (31.9 m × 15.8 m). The window has an area of 3.3 m^2 (1.5 m × 2.2 m) and the distance between the bottom of the window and the floor is 0.9 m. The ratio of window to wall area of the south wall and north wall is 0.25, which is in the range recommended by the Civil building thermal design code of China (Thermal design code for civil building (1993)). In the present study, the PCMs are arranged in the south wall of the building. The details of the building envelopes follow the Design standard for energy efficiency of public buildings (Design standard for energy efficiency of public buildings (2015)).



(a) The Sketchup model of the building



(b) Ground floor plan

Figure 3: A typical four-story building.

Climate in five typical cities

Locations and climate conditions of five typical cities in western China is illustrated in Figure 4. Detailed descriptions are as follows (Lam et al. (2006) and Yang et al. (2003)):

Lhasa is the capital of the Tibet Autonomous Region in China. It is in the cold climate zone with an annual mean temperature of 8.3 ºC. It has a long winter with short, rather cool, summer. Daily diurnal temperatures tend to be large, around 12-18 ºC. Its maximum mean outdoor temperature is 22.8 ºC and 22.2 ºC in June and July.

Xi'an is the capital of Shaanxi province. It is in the cold climate zone but very close to the boundary of the hot summer and cold winter climate region. It has distinct seasonal variations with hot summer and cold winter characteristics. Its annual mean temperature and neutral temperature are 13.3 ºC and 23.7 ºC, respectively. It is hot and humid, especially in July and August.

Chengdu is the capital of Sichuan province. It is located in hot summer and cold winter zone with an annual mean temperature and neutral temperature of 16.2 ºC and 24.7 ºC, respectively. January is the coldest month of the whole year with mean temperature ranging from 2.4 ºC to 9.5 ºC while July is the hottest month of the whole year with mean temperature ranging from 22.0 ºC to 29.6 ºC.

Kunming is the capital of Yunnan province. It is known as spring city, bears a subtropical plateau monsoon climate. The weather is relatively moderate with no chilly winter and hot summer. The annual mean temperature and neutral temperature are 14.6 ºC and 22.1 ºC, respectively. The temperature in the coldest month (January) range from 2.2 ºC to 15.3 ºC in January while in the hottest month (July), the temperature range from 16.9 ºC to 23.9 ºC. Kunming has a large temperature difference between the day and night.

Urumchi is the capital of the Xinjiang Uygur Autonomous Region in China. It is located in a severe cold zone and has an annual mean temperature and neutral temperature of 7.1 ºC and 21.8 ºC, respectively. January is the coldest month of the whole year with mean temperature ranging from -17.9 ºC to -8.4 ºC while July is the hottest month of the whole year with mean temperature ranging from 19.1 ºC to 31.2 ºC.

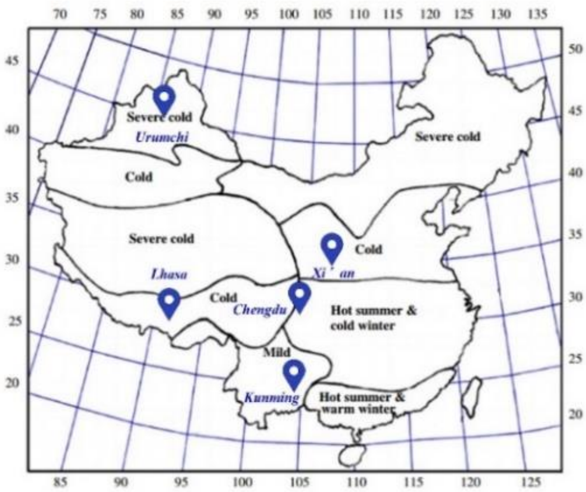


Figure 4: Locations and climate conditions of five typical cities.

Simulation details

In the present work, building energy simulation program EnergyPlus 8.6 is employed to conduct energy saving analysis. In EnergyPlus, finite difference method (FDM) is adopted for numerical formulation. Heat capacity method is adopted for latent heat evolution (AL-Saadi and Zhai (2013)). The simulations are performed in five typical cities in western China (Lhasa, Xi'an, LanZhou, Chengdu, KunMing and Urumchi) to find the effects of different climates on the energy consumption of the building with PCW and NV. The climate data for each city is based on the standard IWEC weather files (http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm (2016)). The conduction finite difference algorithm (ConFD) incorporated in EnergyPlus is employed to simulate the thermal performance of PCW. GroundHeatTransfer:Slab module of the EnergyPlus is employed to model the heat transfer between the floor and the ground (EnergyPlus (2016)).

According to Tabares-Valesco et al. (2012), time step of the simulation is set to 3 min. Due to accurate hourly performance is required, the node space is set to 0.1 (the default value in EnergyPlus is 3). In order to evaluate the energy saving resulting from the application of PCW, two simulations (with and without PCW) in each city are performed. Three BioPCMs with different phase change temperature are adopted, which are PCM 23 (21-25 ºC), PCM 25 (23-27 ºC) and PCM 27 (25-29 ºC). The latent heat of the BioPCMs is 219 kJ/kg. Enthalpy-temperature graph of PCM 27 is illustrated in Figure 5 (Muruganantham (2010)), which is obtained from the simulation program DesignBuilder.

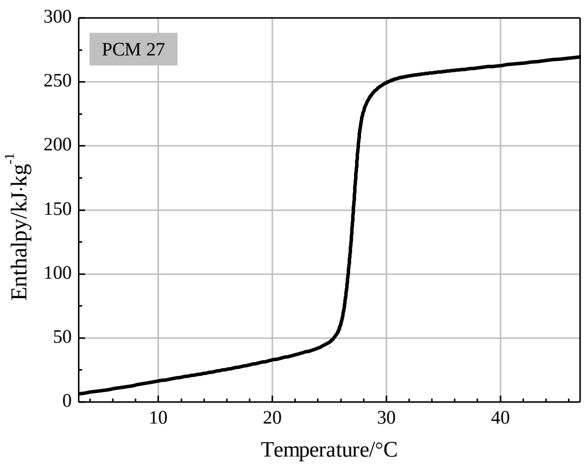


Figure 5: Enthalpy-temperature graph of PCM 27.

The enthalpy-temperature graphs for all other two BioPCMs are obtained by shifting the curve along *x*-axis according to their melting ranges. Differential equation of PCW is as follows:

$$\frac{\rho c_p \Delta x (T_{i,\,new} - T_{i,\,old})}{\Delta t} = \frac{\lambda (T_{i\text{-}1,\,new} - T_{i,\,new})}{\Delta x} + \frac{\lambda (T_{i+1,\,new} - T_{i,\,new})}{\Delta x} \quad (1)$$

where ρ is density, kg/m^3; c_p is specific heat capacity, J/(kg·ºC); Δx is layer thickness of PCW, m; T is node temperature, ºC; λ is thermal conductivity, W/(m·K); j+1 is new timestep; j is present timestep; i is present node; i+1 is adjacent node to interior of construction; i-1 is adjacent node to exterior of construction; Δt is timestep, s. The equivalent specific heat capacity of the PCW is not constant and the value at each time step is updated according to the following equation:

$$c_{eq} = \frac{h_{i,\,new} - h_{i,\,old}}{T_{i,\,new} - T_{i,\,old}} \quad (2)$$

In order to perform natural ventilation in night, Zone ventilation model is employed (Jamil et al. (2016)). In the model, the air flow rate through the windows is based on schedule fraction, temperature difference and wind speed. A fraction multiplier schedule is adopted to control start-up and shut-down of night ventilation. The ventilation period is set 9 pm to 7 am during night (Barzin et al. (2015)). The minimum fresh air of 0.5 ACH is provided by the leakage of windows and doors. The windows are opened and closed when NV is started and ended.

The thermophysical properties of the building materials are listed in Table 1. Construction information and operating conditions are also listed in Table 2 and Table 3.

Table 1: Thermophysical properties of building materials.

Name	**Conductivity (W/m·K)**	**Density (kg/m³)**	**Specific heat (J/kg·K)**
Mortar	0.93	1800	1050
Concrete	0.84	1600	1050
Reinforcement concrete	1.74	2500	920
Thermal insulating material	0.085	1000	920
Timber	0.159	721	1260
EPS	0.04	15	1400
PCM	0.2	235	2400

Table 2: Construction of the single house.

Name	**Construction (outside to inside layer)**
Roof	40 mm reinforcement concrete, 25 mm thermal insulating material, 50 mm concrete, 10 mm mortar
External wall	5 mm mortar, 200 mm reinforcement concrete, EPS, 12 mm mortar
External wall with PCM	5 mm mortar, 200 mm reinforcement concrete, EPS, 10 mm PCW, 12 mm mortar
Internal wall	5 mm mortar, 100 mm reinforcement concrete, 5 mm mortar
Floor (Ceiling)	5 mm mortar, 100 mm reinforcement concrete
Ground slab	200 mm reinforcement concrete, EPS, 12 mm mortar
Door	Timber
Double-glazing	3 mm glazing (solar transmittance is 0.45, visible light transmittance is 0.7, thermal conductivity is 0.9 W/m·K), 14 mm air gap, 3 mm glazing

Table 3: Operating conditions.

Parameters	**Value**	**Schedule**
Time step (min)	3	/
People (m²/person)	15	7 am-8 am: 0.1; 8 am-9 am: 0.5; 9 am-12 am: 0.95; 12 am-14 pm: 0.8; 14 pm-18 pm: 0.9; 18 pm-20 pm: 0.3; 20 pm-24 pm: 0
Metabolic rate (W/person)	70	/
Office lighting (W/m²)	6.3	7 am-8 am: 0.1; 8 am-9 am: 0.5; 9 am-12 am: 0.95; 12 am-14 pm: 0.8; 14 pm-18 pm: 0.9; 18 pm-20 pm: 0.3; 20 pm-24 pm: 0
Corridor lighting (W/m²)	2	
Electric equipment (W/m²)	1.875	7 am-8 am: 0.1; 8 am-9 am: 0.5; 9 am-12 am: 0.95; 12 am-14 pm: 0.5; 14 pm-18 pm: 0.9; 18 pm-20 pm: 0.3; 20 pm-24 pm: 0

Validation

In the present work, a single house model is established to verify the adopted algorithm and the PCM module. The building is located in Melbourne, Australia. The geometries and dimensions of the building is strictly based on the building adopted by Alam et al. (2014). Detailed description of the building could be found in Ref. (Alam et al. (2014)). In Ref. (Alam et al. (2014)), the zone mean air temperature with and without PCM based ceiling in April 1 to 2 in Melbourne is obtained. A simulation work is launched and zone mean temperature is compared with that reported in Ref. (Alam et al. (2014)) in Figure 6. The maximum deviation of zone mean temperature between the present work and results of Alam et al. (Alam et al. (2014)) is less than 5 %. This indicates that, the simulation model and PCM module presented in this study are credible to analysis thermal performance and energy saving potential of the PCM-based building.

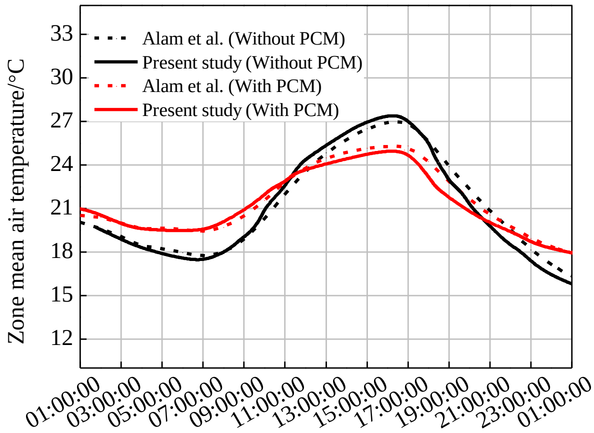


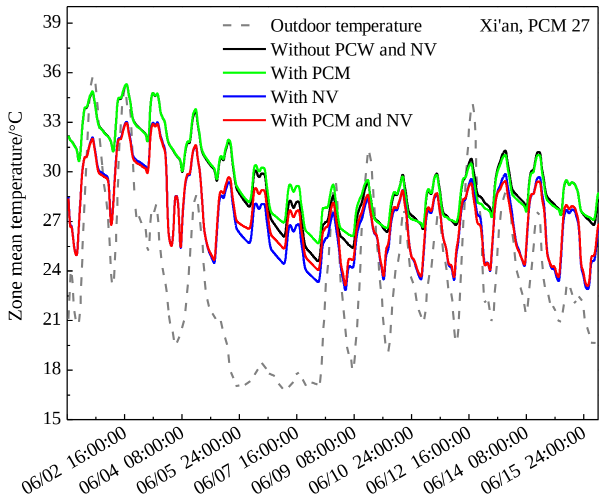
Figure 6: Zone mean indoor temperature of a simple building model.

Results and Discussion

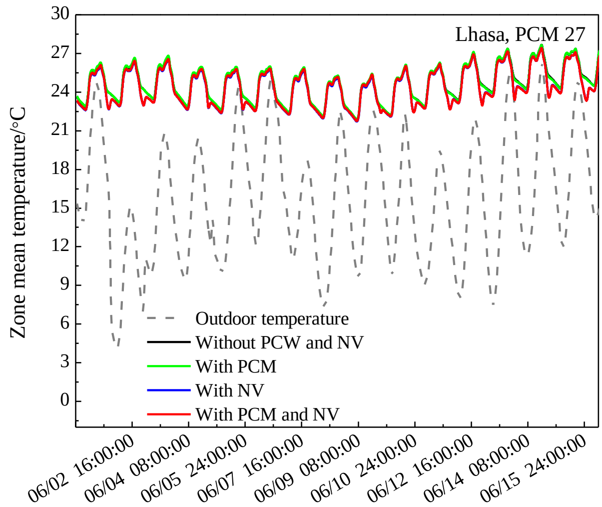
After validation, the established model and methods are employed to investigate the effectiveness of PCW and NV on indoor mean temperature under five different climate conditions. The influences of phase change temperature and NV rate are also studied. The simulations are carried out from June 1 to June 30. The results of the simulations are as follows (take south house in the second floor of 10.5 m × 6.5 m as an example):

The effect of climate conditions

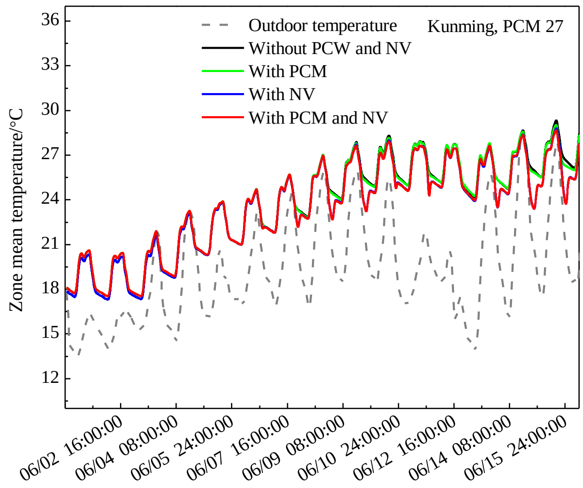
In the first place, the effect of climate conditions on indoor temperature is investigated. Under four design conditions (without PCW and NV, with PCW, with NV and with PCW and NV), indoor mean temperature is obtained in five typical cities (see Figure 7). The night ventilation is performed when the following two conditions are satisfied: (1) The deviation between indoor and outdoor temperature is more than 1 ºC; (2) The outdoor temperature is in the range from 20 ºC to 26 ºC. It could be concluded that, cooling potential in different cities are different due to different climate conditions. In Xi'an, Kunming, Urumchi and Chengdu, outdoor temperature is in the range from 20 ºC to 26 ºC in most time. Therefore, night ventilation is performed and an obvious reduction of indoor temperature is depicted in Figure 7 (a), (c), (d) and (e). It's worth noting that in first half in June, no obvious effects of night ventilation are found due to local climate factors. In Lhasa, the difference in zone mean temperature in four cases are quite small. This is because the indoor temperature in Lhasa lies outside of the range of phase change temperature of PCM 27. In Lhasa, the conditions of night ventilation are not satisfied due to outdoor temperature is below 20 ºC. For PCW, peak clipping effect is observed in only certain days. In these days, the indoor zone mean temperature is reduced compared with other three conditions. In the remaining time, the cooling effect of PCW is limited. This may be explained that in the present range of indoor temperature, the functions of PCW don't work well. It is caused that the outdoor temperature does not drop enough to solidify the PCW. Therefore, the PCW does not play well its roles in maintaining the indoor temperature. In future research, the phase change temperature, arrangement, thickness of PCW could be further studied.



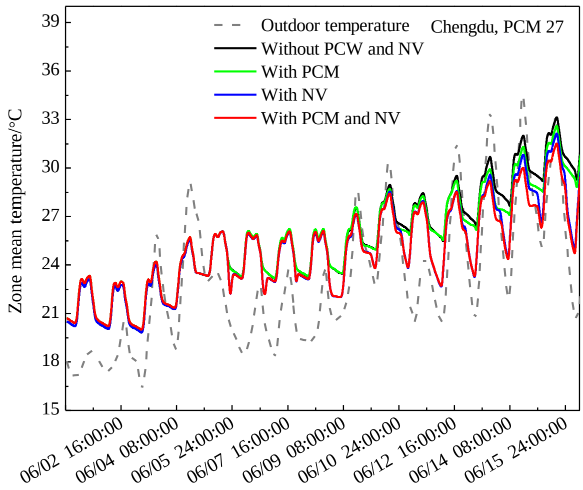
(a) Xi'an



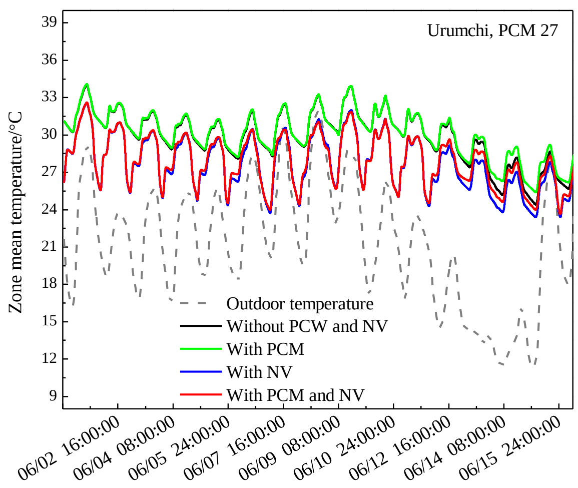
(b) Lhasa



(c) Kunming



(d) Chengdu



(e) Urumchi

Figure 7: Indoor mean temperature of southern room in June.

The effect of phase change temperature

In this section, a simulation is carried out to examine the influences of phase change temperature. Figure 8 demonstrates the indoor mean temperature at different phase change temperature (take Xi'an as an example with NV rate of 4 ACH). It can be concluded from daily data that, the cooling effect of different PCM is significantly influenced by weather conditions. For instance, the cooling effect of PCM 25 is obviously better than PCM 23 and PCM 27 in June 12. However, in other three days in Figure 8, the cooling effect of PCM 25 is equal to PCM 27. The results indicate that the daily cooling effect analysis is insufficient to conclude which PCM is work better. Our future research will focus on the cooling effect in a relatively long period to reduce the influence of random weather conditions.

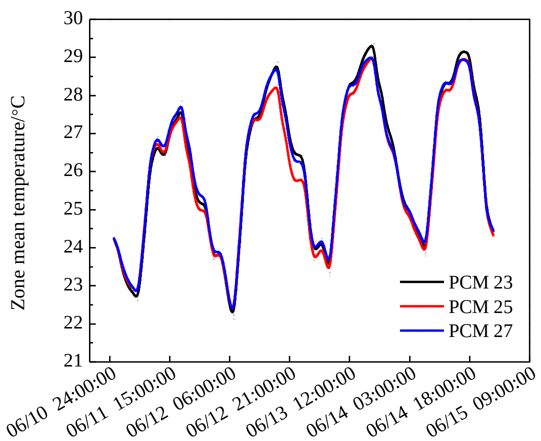


Figure 8: Indoor mean temperature at different phase change temperature.

The effect of NV rates

The effect of NV rates on the indoor mean temperature is numerically investigated. Figure 9 illustrates indoor mean temperature at three different NV rates (take Xi'an with PCM 27 as an example). With the increase of NV rates (4 ACH to 16 ACH), the zone mean temperature tend to decrease. A maximum temperature reduction of 0.93 ºC is obtained between 4 ACH and 16 ACH. It is also found that, the downward trend is slowed when the NV rates increase from 8 ACH to 16 ACH. In other words, 8 ACH is recommended for the present building in Xi'an. The further research could be conducted to obtain the cooling effect over a relatively long period.

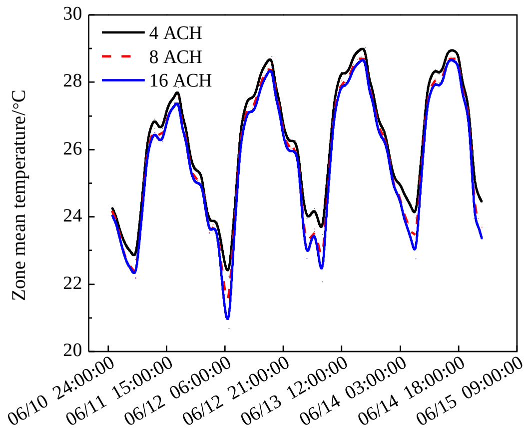


Figure 9: Indoor mean temperature at different NV rates.

Conclusions

1. In order to verify the EnergyPlus PCM model, a single house model is established in the first place. The maximum deviation of mean zone temperature between the present work and results of Alam et al. (2014) is less than 5 %. Therefore, the model and methods in present work are reasonable and reliable to deal with thermal analysis and energy saving analysis with PCW.
2. The influences of three design conditions (PCW, NV and PCW integrated with NV), PCMs with three different phase change temperature and three NV rates on indoor thermal environment are examined in five typical cities in western China. Suitable phase change temperature and NV rates are obtained in Xi'an.
3. Further research is recommended to investigate the quantitative cooling potential and energy saving potential. The cost benefits analysis of PCW and NV could also be conducted based on its economic cost model.

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