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An Evaluation on the effect of thermal mass to modulate overheating in the cold climate in China and the role of shading devices and night ventilation

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ABSTRACT

Overheating in buildings is a growing challenge in the context of climate change and global warming. Many researchers are focusing on developing different passive strategies to minimize overheating and cooling electrical consumption in buildings. Thermal mass provides thermal energy storage, which could be utilized to store extra heat during hot summers to avoid overheating. To fulfil the cyclical behaviour of the thermal mass, it must be discharged to store heat again and follow this charging-discharging process on a daily basis to modulate overheating. Night ventilation performs the discharging phenomenon to maximize the effect of the thermal mass. Shading devices prevent the penetration of solar radiation into the building in summer. The aim of this study was to evaluate the effect of thermal mass and night ventilation to modulate overheating in the cold climates in Beijing, China. A model of the BESTEST ASHRAE Standard 140 Case 600FF was used to perform full-year dynamic building simulations with Energyplus at different levels of thermal mass. The results allow optimizing the thermal mass configuration according to each climatic condition and in accordance with the performance of night ventilation and shading devices availability. The results confirm the important role played of night ventilation and shading devices to modulate overheating with the potential to reduce maximum temperatures up to 20% by using heavyweight thermal mass compared to lightweight. The results of this study will help to develop the decision support systems to inform the implementation of thermal mass into regional and local building regulations.

Keywords: Thermal mass; night ventilation; shading devices; overheating; future weather.

1. INTRODUCTION

A decade ago, climate change had arguably not yet risen to the top of main worries among many communities[1]. Climate change has more specifically increased summer mean temperatures in the Northern Hemisphere. China in particular faces warmer summers, with extreme temperatures placing a significant burden on its buildings. Indeed, warmer summers and colder winters, observed in China and elsewhere, are raising the energy consumption of buildings by increasing the need for cooling and heating. There is a direct relationship between the energy consumption of buildings, which leads to greenhouse gases emissions, and extreme temperatures. Over 40% of the world's energy consumption comes from buildings and this share is increasing in a vicious circle between overall energy consumption and greenhouse gases emissions [2].

One of the most significant adverse effects of climate change on buildings is overheating, exacerbated by the phenomenon of urban heat islands. Growing overheating has been observed in many temperate climate regions, but also occurs in other areas [3]. It is worth noting that overheating directly harms human health, and high indoor temperatures seriously damage sleep quality [3]. Some overheating occurs as a result of building energy efficiency policies in some countries for reducing energy use and mitigating climate change [4].

In summer, the thermal inertia of heavy external walls delays the transfer of heat from outside to inside, generating energy savings [5]. The high thermal mass building acts like a battery, which effectively stores heat from the outside and through a slow transfer process. The capacity of such buildings to store heat is also beneficial in winter when solar radiations warm the external walls during sunny days, which store it and slow

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its dissipation. Research and real-world buildings show that thermal inertia can be used to mitigate overheating and thus decrease the energy consumption of buildings.

In summer, night ventilation can eliminate heat stored from heavy walls to indoor areas [5]. Shaviv et al.[5] investigated the effect of night ventilation and high thermal mass on the mitigation of overheating in Florida and found that this passive cooling strategy is not appropriate in hot and humid climate regions.

Shading devices are widely used in some residential buildings in tropical regions which can reduce the amount of solar radiation entering the interior[6]. Overhang and fin are common for external shading, and blinds for internal shading. These shading devices are effective in preventing solar radiation entering the room directly and are also an effective passive cooling technique.

In order to explore the effects of thermal mass, night ventilation and different shading devices on overheating in the cold climate in Beijing, China [7]. A sizeable share of the academic literature on the impacts of climate change on buildings focuses on future weather predictions and the effects of climate change on building overheating. Jentsch et al[8]. have developed the CCWorldWeatherGen tool to generate future weather data for the periods of the 2050s and 2080s through EnergyPlus EPW file formats. Each future weather file has four different scenarios: A1FI(High); A2(Medium-high); B1(Medium-low) and B2(Low), which are based on IPCC assigned GHG emission scenarios.

This study aims to explore the potential of the concepts of different thermal mass, effective night ventilation and suitable shading devices to mitigate building overheating in Beijing, China.

2. METHOD

In the present section, the selection of simulation models and shading devices, the details of representative city are presented, and the future weather simulation method and the parametric analysis process are illustrated.

This study followed the steps below to analyze the effect of the thermal mass and the night ventilation to the overheating under the future climate conditions in China. First, the baseline model (the BESTEST ASHRAE Standard 140 Case 600FF) was built in the Sketchup software with the Openstudio Plugin, which aimed to prepare for setting the parameters in the Energyplus.

Second, to building the three models (i.e., Case650FF, Case900FF and Case950FF), the thermal mass conditions should be modified, and the schedule of the night ventilation and shading devices should be added in the baseline model. Third, the Weather Morph was adopted to generate Beijing' future EPW weather files, in which four different scenarios were included. Fourth, the building energy consumption and the indoor operative temperature were simulated in the Energyplus. Lastly, the overheating hours of each model were analyzed during the working time and the working days. The entire simulation consisted of three key steps:

1. The validation of the baseline model, i.e., modifying the lightweight thermal mass model to the heavyweight thermal mass models and add the night ventilation with different shading devices;
2. Generating future weather files in the Weather Morph;
3. Using the Energyplus and the filter to generate the hourly indoor operative temperature during the working periods.

2.1 Baseline model (Case600FF)

An exemplar test room was selected from the BESTEST ASHRAE Standard 140 Case 600FF (Figure 1.), which was modelled with the dimensions of 8m x 6m x 2.7m. The test room was built by adopting the Sketchup software with the Openstudio plugin.

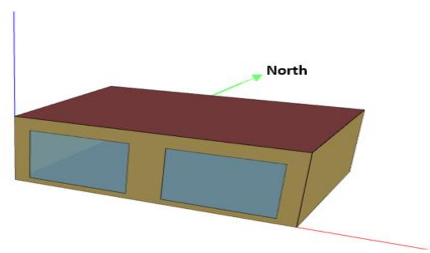

Figure 1. Baseline model Case600FF for simulation

Specific to the dynamic computational simulation in the Energyplus, the following parameters were set[9]:

1) The setting of materials for the baseline model Case600FF in Table 1;
2) Settings of south-facing windows shown in Table 2;
3) Infiltration: 0.5 air change/hour;
4) Internal Load: 200 W continuous, 60% radiative, 40% convective, and 100% sensible;
5) Soil Temperature: 10C continuous.

Table 1. Materials' information of Case600FF

Construction Sectors	Thickness (m)	U (W/m²-K)
Roof	0.1408	0.318
Floor	1.0280	0.040
Wall	0.0870	0.514

Table 2. Setting of windows

Window Properties	
Number of panes	2
Pane thickness	3.175mm
Air-gap thickness	13 mm
Thermal Conductivity of glass	1.06 W/mK
Density of glass	2500 kg/m^3
Specific heat of glass 7	50 J/kgK

2.2 Models with different shading devices

The parameters of the model in the BESTEST ASHRAE Standard 140 with the different shading devices were shown in following tables:

Table 3. Setting of the overhang:

Overhang Properties	
Height above windows	100mm
Tilt angle from windows	90deg
Left extension from the window	200mm
Right extension from the window	200mm
Depth of the overhang	500mm

Table 4. Setting of the fin:

Fin Properties	
Left tilt angle from windows	90deg
Right tilt angle from windows	90deg
Left extension from the window	200mm
Right extension from the window	200mm
Depth of the fins	500mm

Table 5. Setting of the blind:

Blind Properties	
Slat width	25mm
Slat separation	18.75mm
Slat angle	45deg
Front side slat beam solar reflectance	0.5
Back side slat beam solar reflectance	0.5
Front side slat diffuse solar reflectance	0.5
Back side slat diffuse solar reflectance	0.5

2.3 Models with different thermal mass conditions and night ventilation

The models in the BESTEST ASHRAE Standard 140 with the different conditions of the thermal mass and the night ventilation are listed in Table 7[9].

Table 7. Conditions of the thermal mass and the night ventilation for baseline models

Model Name	Thermal mass Condition	Night Ventilation Condition
Case600FF	Lightweight	No Night Ventilation
Case650FF	Lightweight	With Night Ventilation
Case900FF	Heavyweight	No Night Ventilation
Case950FF	Heavyweight	With Night Ventilation

2.4 Model with the heavyweight thermal mass (Case900FF).

The Case900FF of the tests using the identical building model was employed for the Case600FF tests, except that the floor and wall construction were changed to use heavier materials. The other settings related to the building remained unchanged. The characteristics of the heavier mass wall and floor are listed in Table 8[9].

Table 8. Materials' information of Case900FF

Construction Sectors	Thickness (m)	U (W/m²-K)
Roof	0.1408	0.318
Floor	1.0870	0.039
Wall	0.1705	0.512

2.5 Models with the night ventilation (Case650FF and Case950FF)

The Case 650FF and the Case950FF were identical to the Case600FF and the Case900FF except that the following scheduled night ventilation was applied:

1) From 6pm to 7am, vent fan = on;
2) From 7am to 6pm hours, vent fan = off;
3) Vent fan capacity = 1703.16 standard m^3 /h (besides specified infiltration rate).

2.6 Simulation city and future weather simulation method

In the present study, Beijing located in the cold climate in China was selected for the simulation. To generate the future weather data, the basic weather files of Beijing was uploaded on Weather Morph, which is Climate Change Weather Data Generator online platform with HadCM3 scenarios. Such a platform refers to a web-based application, capable of generating the future weather data for four emission scenarios in over 2100 locations worldwide for three future periods (i.e., the 2020s, 2050s and 2080s). The four scenarios complied with the IPCC (Intergovernmental Panel of Climate Change) emission, which were classified into four levels. On that basis, the future GHG emission was simulated, i.e., Scenarios: Low (B1), medium-low (B2), medium-high (A2) and High (A1FI)[10], [11]. The basic weather files originated from [12], and the details of the simulation location is shown in Table 9.

Table 9. Details of the simulation city — Beijing[7]

Details of Beijing	
Location	39°48'-116°28'
Altitude(m)	31.5
Climate Condition	Cold
Weather Simulation Locations	Beijing Capital International Airport

2.7 Parametric analysis process

The hourly indoor operative temperature was selected as the variable of the simulation. 8760 hours constitutes a year, and the indoor air operative temperature in each hour was collected in the respective model. The models were adopted to simulate the future office overheating, so the filtering tool in the EXCEL was employed to filter the indoor operative temperature for the office use time, in which the working days ranged from Monday to Friday, and the working periods ranged from 8am to 6pm. After the filtering, 2871 hours in the rest were used for the analysis.

In the present study, the baseline models were simulated only under natural conditions, instead of under any cooling or heating system; the number of hours when the indoor operative temperature was above 28°C [13]was filtered for the analysis.

3. RESULTS

3.1 Comparison with different thermal mass conditions

To investigate the effect of different thermal masses on building overheating issue, different scenarios and future weather conditions based on Beijing have been simulated. Figure 2 shows the overheating hours and percentages of the overheating hours during the working period in a total of 2871 working time in five cities based on the Case600FF and the Case900FF with different thermal masses in Beijing.

With the use of the heavyweight thermal mass in the construction, the overheating can be to a certain extent reduced. In 2050s and 2080s, by using the high thermal value of materials, the overheating hours decreased. It is noteworthy that in Beijing located in the cold climate zone, the average drop was nearly 10%. As revealed from the comparison across different GHG emission scenarios in the 2050s and 2080s in Beijing, with the gradual increase in the emissions, the number of the overheating hours increased, which proved that global warming is one of the reasons for the overheating of buildings.

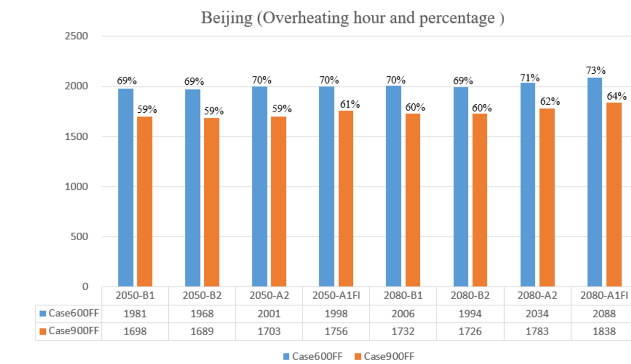

Figure 2. Comparative results of Case600FF and the Case900FF in different scenarios in 2050s and 2080s based on the number of the overheating hours and the proportion of the overheating hours in 2871 total working hours in Beijing.

3.2 Impact of night ventilation in lightweight thermal mass

To verify the effectiveness of the night ventilation in reducing the building overheating, the Case650FF was based on the same settings as the Case600FF with the addition of a night ventilation simulation from 6pm to 7am. In Figure 3, the overheating hours and percentage during the working time in Beijing under the lightweight thermal mass are shown. As expected, the night ventilation could effectively reduce the building overheating in Beijing. Due to the application of night ventilation techniques, it can be noticed that the overheating in the room has been alleviated and the number of overheating hours has decreased by 1% to 2%.

To compare the difference between the Case600FF and the Case650FF in the various scenarios under the future climate, the overheating hours above 28°C were longer in the high emissions case than those in the other emissions cases. This was because high emissions will promote the global warming effects of climate change, thereby causing warmer and longer summers. In 2050s and 2080s, the effect of the night ventilation on the overheating reduction increased with the decrease in the emissions, and the night ventilation was more effective in reducing the overheating in 2050 compared with that in 2080s.

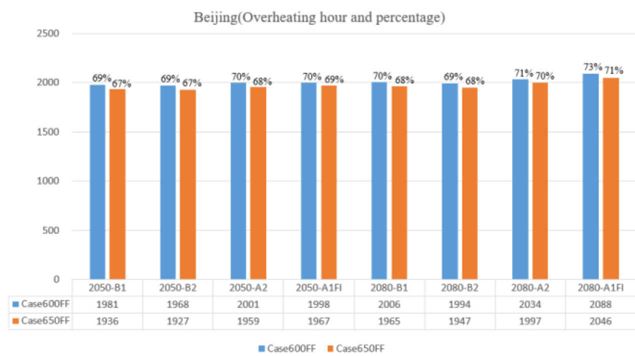

Figure 3. Comparative results of the Case600FF and the Case650FF with different scenarios in 2050s and 2080s based on the number of the overheating hours and the proportion of the overheating hours in 2871 total working hours in Beijing.

3.3 Impact of night ventilation in heavyweight thermal mass

In Figure 4, the percentage of the average overheating hours in Beijing decreased by 23% and 20.25% in 2050s and 2080s respectively. This result demonstrated that the combination of the heavyweight thermal mass and the reasonable night ventilation in temperate climates can significantly reduce the building overheating.

This study aimed to compare the effect of the night ventilation on the overheating under future weather conditions based on the heavyweight thermal mass. For this end, as indicated from the comparison of the hours of the overheating reduced by the night ventilation in 2050s and 2080s in Beijing, the average overheating hours in 2050s was lower than that in 2080s. In different GHG emission scenarios, the effectiveness of the night ventilation in reducing the overheating decreased with the increase in emissions.

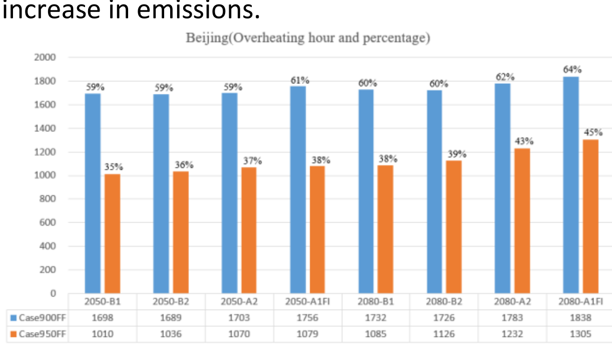

Figure 4. Comparative results of Case900FF and Case950FF with different scenarios in 2050s and 2080s based on the number of the overheating hours and the proportion of the overheating hours in 2871 total working hours in Beijing.

3.4 Impact of different shading devices in lightweight and heavyweight thermal mass with the night ventilation

By adding the shading devices, comparative results of the overheating hours and the percentage of overheating hours' reduction are shown in Figure 5. This result demonstrated that shading devices are effective in mitigating the overheating of buildings in future climatic conditions, in Case600FF, which is the model of the lightweight thermal mass, the overheating relief effect of blinds can reduce the percentage of overheating hours by almost 10% to 20%, better than the effect of overhang and fin. However, for the heavyweight thermal mass model, Case900FF, the most effective shading device is overhang.

To compare the difference between Case600FF and Case900FF with shading devices in the various scenarios under the future climate, we found that due to global warming and rising carbon emissions in the future, the effectiveness of shading devices in mitigating overheating in building interiors is decreasing.

Cases		Case600FF				Case900FF			
Time	Scenarios	No shading	Overhang	Fin	Blind	No shading	Overhang	Fin	Blind
2050	B1	1981	1834	1900	1649	1698	1470	1620	1450
		%(reduction)	7.40%	4.10%	17.80%	%(reduction)	13.40%	4.60%	9.90%
	B2	1968	1827	1899	1653	1689	1460	1612	1453
		%(reduction)	7.20%	3.50%	16%	%(reduction)	13.60%	4.60%	9.90%
	A2	2001	1862	1926	1690	1703	1495	1639	1482
		%(reduction)	6.90%	3.70%	15.50%	%(reduction)	12.20%	3.80%	10.30%
	A1FI	1998	1879	1935	1715	1756	1542	1677	1491
		%(reduction)	6%	3.20%	14.20%	%(reduction)	12.20%	4.50%	10.50%
2080	B1	2006	1862	1928	1701	1732	1507	1665	1488
		%(reduction)	7.20%	3.90%	15.20%	%(reduction)	13%	3.90%	10.60%
	B2	1994	1866	1925	1680	1726	1526	1660	1514
		%(reduction)	7.40%	3.50%	15.70%	%(reduction)	11.60%	3.80%	7.90%
	A2	2034	1932	1979	1766	1783	1634	1719	1591
		%(reduction)	5%	2.70%	13.20%	%(reduction)	8.40%	3.60%	7.70%
	A1FI	2088	1981	2028	1809	1838	1701	1769	1664
		%(reduction)	5.10%	2.90%	13.40%	%(reduction)	7.50%	3.80%	5.80%

Figure 5. Comparative results of the lightweight and heavyweight thermal mass cases with various shading devices in 2050s and 2080s based on the number of the overheating hours and the proportion of the overheating hours in 2871 total working hours in Beijing.

4. CONCLUSION AND FUTURE WORK

The present study primarily aimed to investigate the building overheating in Beijing under the future weather conditions and to evaluate the effect of thermal masses the night ventilation and shading devices on the reduction of the overheating.

The results indicated that the use of thermal mass and night ventilation could reduce the overheating in the future. For thermal masses, in this study, lightweight and heavyweight thermal conditions were selected for the tests. After comparing the results of the overheating hours under different thermal masses buildings, this study found the relationship between overheating and climatic conditions, both in the low and high thermal mass cases where the number of the overheating hours increased as the climate conditions became warmer. By using heavyweight thermal mass materials, the overheating hours in Beijing decreased by approximately 10%.

Meanwhile, both in 2050s and 2080s, the night ventilation has impacted the reduction of the building overheating in cold climate. Moreover, the results confirmed that in lightweight thermal mass cases, the overheating hours decreased by nearly 1.5% with the insignificant mitigation effects; in heavyweight thermal mass cases, however, assisted by the night ventilation, the overheating hours in Beijing declined significantly by around 25% on average. These results suggested that the combination of the night ventilation and thermal substances could significantly reduce the building overheating. By installing three different shading devices, the number of overheating hours decreased significantly, however, different shading devices had different effects on mitigating overheating in the building, with the best effect being blinds in Case600FF and overhang in Case900FF.

Subsequent research is still required to investigate the influence of thermal masses, night ventilation and shading conditions due to the climate change in different climate conditions in China, and the effect exerted by thermal masses, the night ventilation and shading devices on the building overheating. Furthermore, the decision support systems for thermal material, night ventilation and shading devices are also necessary in order to provide guidance in the design phase of future buildings.

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