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Experimental investigation of demand response potential of buildings: Combined passive thermal mass and active storage

Yongbao Chen [a], Peng Xu [b,*], Zhe Chen [b], Hongxin Wang [b], Huajing Sha [b], Ying Ji [c,d], Yongming Zhang [e], Qiang Dou [f], Sheng Wang [f]

[a] School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China
[b] School of Mechanical and Energy Engineering, Tongji University, Shanghai 201804, China
[c] College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100124, China
[d] Beijing Key Laboratory of Green Built Environment and Energy Efficient Technology, Beijing University of Technology, Beijing 100124, China
[e] Sino-German College Applied Sciences, Tongji University, Shanghai 201804, China
[f] Qingjian Group Co., Ltd, Qingdao 266071, China

HIGHLIGHTS

- Energy flexibility in demand response building is experimentally investigated.
- Passive building thermal mass and active energy storage systems are coupled.
- Pre-cooling and temperature reset are considered to assess energy flexibility.
- Short-term (0.5 h) and intermediate-term (2 h) demand response are achieved.

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ABSTRACT

Heating, ventilation, and air conditioning (HVAC) systems, combined with the internal thermal mass of buildings, have been deemed to be promising means of providing demand response (DR) resources, particularly for buildings with active energy storage systems. DR resources, such as peak-load reduction potential, can provide grid-responsive support resulting in a high degree of grid involvement and high flexible electricity demand. In the DR field, the potential of HVAC load flexibility has been considered in buildings. In the future smart buildings, it is important to take advantage of demand-side resources to achieve real-time energy supply–demand balance sustainably. In this context, DR potential and characteristics of buildings play a pivotal role in DR programs. However, few studies have investigated the internal thermal mass's heat release and DR characteristics of buildings. Thus, a systematic experiment is conducted to study the DR potential and characteristics of internal thermal mass and active storage systems. The DR resources include the passive cooling storage from furniture, building envelope and an active water storage tank. Two DR control strategies, including pre-cooling and temperature resetting, are analyzed in this study. The experimental results show that the strategies are effective for short-term (0.5 h) and intermediate-term (2 h) DR programs. For a long-term DR program, active energy storage technology such as a water storage tank is required to satisfy the occupant's comfort requirements. Hence, we conclude that passive thermal mass and active storage systems should be simultaneously considered in practical DR programs for better DR implementation.

1. Introduction

With the soaring of seasonal air conditioning (AC) loads and the development of intermittent renewable energy pouring into the grid, the discrepancy between power grid supply and end-user demand has been increasing yearly. Heating, ventilation, and air conditioning (HVAC) systems make up a large part of the electricity demand in buildings. The seasonal HVAC loads are estimated to increase to 20–30% due to the growing

* Corresponding author.
E-mail address: xupeng@tongji.edu.cn (P. Xu).

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installation of heat pumps [1]. In addition, in the aspect of intermittent renewable energy development, solar power and wind power will contribute about 35% of the total power capacity by 2035. This number will reach 50% by 2050 in high renewable energy utilizing European countries, according to the prediction of the International Energy Agency [2]. Traditionally, some power plants have been established as variable-load plants (VLP) to ensure that the load demand and safety requirements of the grid during the high peak load time are satisfied. The annual utilization hours of these power plants are very short when the plants are used as VLPs for peak load use. This is, however, not economical for power companies and not environmentally friendly [3]. Thus, grid-interactive building technologies such as electric demand response (DR) programs have been proposed in recent years [4–5]. DR plays a pivotal role in balancing energy supply and demand in the electricity market by taking the advantage of energy flexibility [6–7]. Implementation of DR programs can bring the retail and wholesale electricity markets together, especially in developing countries to promote the development of power markets [8]. The goal of DR programs is to improve the flexible energy use of buildings to reduce the load during peak load time and increase the load demand during the off-peak load time.

Flexible loads play a key role in grid-interactive buildings, which can serve as a virtual power plants (VPPs) through load aggregation such as the integration of distributed renewable resources and batteries [9–10]. A VPP has considerable potential for providing grid ancillary services, such as frequency support [11–12]. HVAC systems have been deemed as promising devices to achieve the goal of developing flexible electricity use in buildings, especially when integrated with thermal energy storage technology [13]. Generally, the use of the heat inertia of building thermal mass, such as the building envelope and furniture, is a passive method by resetting the zone temperature; this indicates that no additional devices are required. The use of a storage device is an active way because it requires an additional storage tank and investment. The use of a building's internal thermal mass as a passive way to participate in electricity DR has been widely studied in recent years [14–16]. Jiang et al. [17] considered HVAC systems as flexible loads due to the inherent building thermal inertial, the results show that more than 55% voltage fluctuation reduction can be achieved. Commonly, thermal comfort has a compulsory range according to different indoor environment standards, such as that of the American society of heating, refrigerating and air-conditioning engineers (ASHRAE). The room temperature settings are, thus, flexible to a specific level. When the surrounding thermal environment is changing, the building thermal mass can release or absorb heat simultaneously.

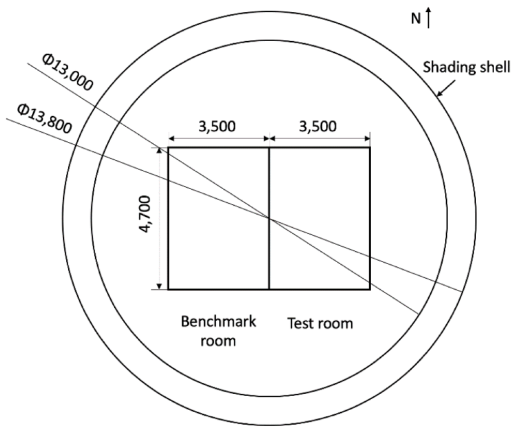
Zone temperature resetting and pre-cooling are two common passive DR control strategies by using the thermal heat inertia. Xu et al. [18] experimented with pre-cooling strategies for a commercial building, and showed that 80% of the peak load can be reduced in a DR event (2:00 PM to 5:00 PM) without receiving any customer complaints in a heavy-mass structure building. Pre-cooling strategies can significantly cool the air and the internal thermal mass, late at night, using off-peak or cheaper electricity, while utilizing the cooling capacity stored in the thermal mass during peak load time. Thus, the cooling load of HVAC systems can be reduced. It is worth highlighting that the total energy consumption of pre-cooling control is generally higher than that of normal control cases because there is more energy loss to maintain indoor environments at a lower temperature. There are four different types of pre-cooling strategies, including normal pre-cooling, light pre-cooling, intermediate pre-cooling, and extra pre-cooling [19]. For the temperature resetting technology, the zone temperature can be set to the upper limit. In a cooling case, a 25% peak load can be shifted for 20 min by resetting to 2 °C higher than the normal thermostat setting [20]. Dreau et al. [21] evaluated the short-term heat storage potential in the thermal mass of two residential buildings using the EnergyPlus simulation platform. They investigated different levels of thermal insulation and the influence of the air-tightness of the building envelope on the load flexibility potential. Foteinaki et al. [22] evaluated the energy flexibility by considering the thermal mass of an apartment block, they concluded that 40%–87% of energy use reduction during morning peak load time can be realized. The dynamic thermal behavior of buildings highly depends on the characteristics of the building envelope and the HVAC systems. These passive methods, mentioned above, can also be founded in other studies [23–24].

Despite there being certain studies focused on thermal mass heat storage, most studies are related to building structural thermal masses such as floors, ceilings, and walls. The furnishing thermal mass, such as furniture, has not been considered because of two reasons. Thermal mass, like furniture, is usually irregular and is difficult to model accurately. Li et al. [25] proposed a novel method called the "effective area" method to calculate the thermal surface of irregular furniture, which could be an approach to dynamic furniture modeling. Whereas this method is lack of practical verification. Additionally, furniture in buildings is usually randomly arranged, making it difficult to formulate a quantitative description. Thus, an experimental approach is apt for studying the heat storage performance of furniture.

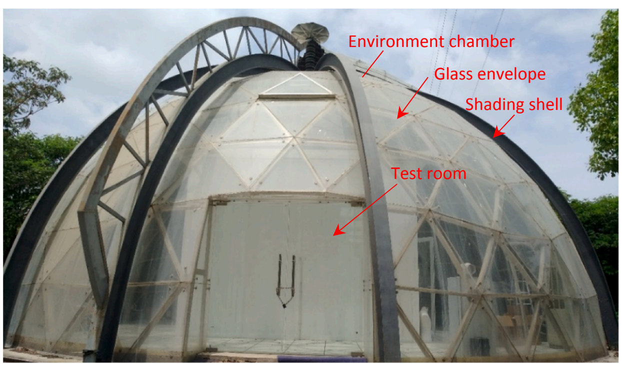
In addition to the passive ways, the water storage tank as an active approach that provides flexible load for buildings, which is most widely used due to its high specific heat capacity [1,26–27], especially in those districts which have great variation in the time-of-use price. With the development of energy storage technology, thermal energy storage capacity and performance have been hugely increased [28]. Besides, phase change material is widely used in storage systems to further improve this performance [29–30]. For HVAC systems, the chiller usually produces chilled water during off-peak load times at night. Meanwhile, the chilled water can be stored in an insulated water tank that discharges during peak load time, allowing the chiller to be closed or opened in partial load conditions to reduce the building's electricity load use. Chen et al. [31] investigated the energy flexibility potential of a sorption-assisted water storage in a residential building. The results showed that an appropriately sized water tank could independently provide adequate heating supply for an intermittent-term DR event. While simultaneously requiring additional investment, the utilization of a storage tank is still an effective way to upgrade the level of flexibility capacity [32]. In contrast to building internal thermal mass, active storage technologies have their advantages of providing greater and longer-lasting peak load reduction during a DR event. DR events can commonly be divided into three types, including short-term DR (0.5 h), intermediate-term DR (2 h) and long-term DR (4 h or more) [33]. For different DR events, the DR potential of internal thermal mass can be different. For example, due to the different heat release rates, thick masses can release heat for longer-term DR compared to thin masses. It is worth investigating the thermal dynamics of masses for different DR durations for a better DR control.

In summary of the abovementioned literature, there are three key points obtained: (1) The existing research mainly focused on the basic DR concept, lacking of experimental and theoretical research on different building DR resources. (2) Various studies of building dynamic behavior analysis assume empty rooms and do not consider internal thermal masses, like furniture and walls. However, thermal mass can have a significant impact on indoor thermal dynamics and plays a major role in passive heat storage, especially for buildings with light structure and a substantial amount of furniture according to our previous study [34]; (3) Due to the lack of method on energy flexibility quantification, the DR optimal control strategy on considering the real-time balance of energy supply and demand in buildings is absent. Considering these deficiencies in literature review, the objective of this paper is to accurately quantify the DR capacity of buildings so that optimal DR control strategies can be made before the DR. Thus, a novel approach was proposed to realize the goal, and the possible contributions of this work could be presented as follows.

- Firstly, in order to quantify the DR potential of the building's thermal mass, different DR resources including furniture, walls, and indoor air were analyzed. A novel model to fast quantify the DR potential of these resources is proposed. This methodology could be generalized for different types of buildings that have light or heavy structure and occupancy.



(a) Schematic view of the environment chamber



(b) Photograph of the environment chamber (Shading shell is open)

Fig. 1. Schematic of the experiment platform.

- Secondly, passive building thermal mass is effective for short-term DR programs, while for long-term DR, active energy storage systems are required. This paper coupled passive and active DR resources for long-term DR optimal control with high effectiveness; accordingly, this control strategy could be a reference for the DR programs in office buildings and other different building types.
- Finally, the overall DR performance of a single building could be a foundation for understanding the DR implement in a block of buildings.

This paper establishes an experimental platform to investigate the thermal dynamic and DR potential of internal masses, such as office desks and files, under different scenarios. The remainder of this paper is structured as follows: Section 2 establishes an experimental test and introduces the schemes to analyze the thermal dynamic behavior of internal thermal mass and active thermal storage under different building scenarios. Section 3 presents the DR potential results of different DR control strategies, then, discusses the control strategies for short-term (0.5 h), intermediate-term (2 h), long-term DR (4 h) program, respectively. The main findings and future works can be found in Section 4.

2. Experiment platform and schemes

2.1. Experiment platform description

The experiment platform consisted of a controllable environmental chamber with two identical rooms having an area of 16 m^2, each with a 3.4-m^2 south-facing window. One room (the eastern room) was regarded as the test room, and the other (the western room) was the benchmark room. The chamber's temperature and humidity were controllable within the range of 20–40 ℃ and 30%–80%, respectively. A shading shell was also installed; it completely covered the chamber to ensure that the effects of solar radiation could be excluded during the test. A schematic view of the experimental platform is shown in Fig. 1 (a), and an image of it is shown in Fig. 1 (b). Table 1 shows the geometric and thermophysical parameters of the building's thermal masses. Two independent air–water air conditioning (AC) systems were configured to control the temperature and humidity inside and outside the rooms to ensure independent thermal environments, both outside and inside the rooms.

Solenoid valves with proportion-integration-differentiation (PID) controllers were installed into the water loop to control the water flow. Fan coils were installed on the top of the ceiling, and the air volume of the fan coil was manually divided into three levels high, medium, and low rates. Under this circumstance, the temperature control accuracy of the rooms and the chamber were ± 0.5 ℃. Additionally, a 200 L water storage tank was integrated with the loop of the AC system, which was designed for the rooms.

2.2. Data acquisition

2.2.1. Measurement equipment

In this experiment, the temperature range of air and the wall was between 10 and 40 ℃. Sixteen T-type thermocouple thermometers were thus used for the experiment (the temperature measurement range is $-200 \sim 350$ ℃, the test accuracy is ± 0.1℃). These temperature sensors were calibrated using a standard thermostat before being used. The cooling load of the AC was measured using a calorimeter Shark-773, which has a high test accuracy and long service life. Two calorimeters were installed on the inlet pipe of chilled water for both the rooms. The chilled water temperature was measured using a PT-500 platinum resistor, and the water flow rate was measured using an ultrasonic flow meter (temperature test accuracy is $\pm$ 0.1℃, water flow test accuracy is $\pm$ 0.1 L/h). Advantech ADAM-4118 modules were used to acquire and transmit all the data through an RS-485 serial port.

2.2.2. Measuring point layout

Temperature and AC cooling capacity are two of the main measuring

Table 1
Detailed parameters of the test room.

Components	Types	Geometric parameters		Thermophysical parameters			
		Area m^2	Thickness M	Materials	Density Kg/m^3	Conductivity W/(m·K)	Specific heat kJ/(kg·K)
East wall	External wall	14.94	0.17	Plate + Insulation board	150	0.045	1.22
West wall	Partition wall	14.94	0.17	Plate + Insulation board	150	0.045	1.22
South wall	External wall	7.07	0.17	Plate + Insulation board	150	0.045	1.22
North wall	External wall	8.58	0.17	Plate + Insulation board	150	0.045	1.22
South window	External window	3.40	–	Glass	2,500	0.043	0.84
North door	External door	1.89	–	Glass	2,500	0.043	0.92
Ceiling	Suspend	14.89	–	Gypsum board	1,050	0.330	2.01
Ground floor	Suspend	14.89	0.04	Silicate board	7,850	58.20	0.48
Furniture	Internal mass	–	0.02 ~ 0.03	Plywood + Paper	600	0.170	2.51

Table 2
Detailed information of each measuring point.

Number	Measuring parameter	Position	Number	Measuring parameter	Position
T-1	Outdoor air temperature	1.5 m away from the ground and the wall	T-7	Furniture surface temperature of the test room	Middle of the biggest furniture surface
T-2	Internal east wall temperature of the test room	On the middle of the wall	T-8	File surface temperature of the test room	Middle of the biggest file surface
T-3	Internal west wall temperature of the test room	On the middle of the wall	T-14	Furniture surface temperature of the benchmark room	Middle of the biggest furniture surface
T-4	Internal south wall temperature of the test room	On the middle of the wall	T-15	File surface temperature of the benchmark room	Middle of the biggest file surface
T-5	Internal north wall temperature of the test room	On the middle of the wall	T-16	Backup	–
T-6	Indoor air temperature of the test room	On the middle of the room and 1.5 m higher the floor	T-17	Inlet chilled water temperature of the test room	Inlet pipe of the chilled water
T-9	Internal east wall temperature of the benchmark room	On the middle of the wall	T-18	Outlet chilled water temperature of the test room	Outlet pipe of the chilled water
T-10	Internal west wall temperature of the benchmark room	On the middle of the wall	Q-1	Chilled water flow rate of the test room	Inlet pipe of the chilled water
T-11	Internal south wall temperature of the benchmark room	On the middle of the wall	T-19	Inlet chilled water temperature of the benchmark room	Inlet pipe of the chilled water
T-12	Internal north wall temperature of the benchmark room	On the middle of the wall	T-20	Outlet chilled water temperature of the benchmark room	Outlet pipe of the chilled water
T-13	Indoor air temperature of the benchmark room	On the middle of the room and 1.5 m higher the floor	Q-2	Chilled water flow rate of the benchmark room	Inlet pipe of the chilled water

parameters in this experiment. There were 22 measuring points in total. Table 2 gives a detailed description of each of these.

2.3. Experiment schemes

This section presents the experiment schemes used to investigate the DR potential of the thermal mass and the storage tank. Fig. 2 shows the schematic of the experiment schemes. The experimental schemes aim to a) investigate the heat release of the internal thermal mass when the surrounding thermal environment changes; b) investigate the thermal dynamic and DR potential of pre-cooling and higher temperature resetting control strategy; and c) investigate the DR potential of the building with a thermal storage tank.

2.3.1. Internal thermal mass

There are considerable differences in the volume and layouts of the thermal masses inside different buildings. The internal thermal mass is considered as a thermal cushion during peak load time, to ensure that the room temperature can be maintained at a relatively stable value even when the HVAC system is closed. The impact of these differences on the building's HVAC loads is unclear. The internal thermal mass mainly includes objects such as interior walls, floors, and furniture. In this experiment, several scenarios were set by changing the volume of thermal mass. The scenarios are as shown in Table 3. The layout of the thermal mass in scenarios 4 (test room) and 1 (benchmark room) are shown in Fig. 3.

To ensure comparable results under each scenario, the test room and the benchmark room were used for experiments simultaneously. The temperature of the room, the thermal mass surface, and the cooling load of the AC were measured when resetting the rooms' temperature to 26 □ from the stable 24 ℃. By comparing scenarios 1 and 4, the net heat released from the internal thermal mass is equivalent to the HVAC cooling load reduction. Scenarios 3 and 2 can be used to investigate the cooling capacity release with different volumes of building thermal mass.

2.3.2. Pre-cooling and temperature resetting

Pre-cooling is a common DR control technology. In this experiment, a pre-cooling of 2 ℃ is considered as the indoor temperature was set to 22 □ from 1:00 AM and to 26 ℃ when the DR occurred. Additionally, a high temperature resetting was studied. According to the ASHRAE guidelines, the indoor temperature setting range of office buildings is 22.2–26.7 ℃, and the highest indoor temperature should not exceed 28 ℃. Two acceptable ranges of higher indoor temperature resetting strategies were used, one set to 27 ℃, and the other set to 28 ℃.

2.3.3. Active thermal storage

A 200 L storage tank was utilized to improve the DR potential. The tank was fully charged during the off-peak load time with 9 ℃ chilled water and was discharged during the DR event to provide cooling for the rooms. When the storage tank satisfied the cooling demand for the rooms, the chiller was closed, which reduced the electricity load significantly. The room's temperature was to be maintained at 24 ℃, and was not allowed to over 26 ℃, failing which, the chiller would be opened as needed. Under this circumstance, the flow rate of chilled water adjusted synchronously to keep the room's temperature meeting the thermal requirement.

3. Results and discussions

3.1. DR potential of thermal mass in different scenarios

Different experimental scenarios reflected the influence of building thermal mass on the heat release and real-time cooling demand. The 2 ℃ room temperature increment allowed the thermal mass release cooling and reduce the cooling demand of the AC system. Fig. 5 shows the cooling load of all the scenarios. It is worth noticing that the experimental average temperature difference between indoor and outdoor was slightly different. The temperature differences between scenarios 1 and 4 was 6.1 ℃, and 5.9 ℃ between scenarios 2 and 4. These two experimental cases were, thus, analyzed separately. Additionally, when the room temperature was set to 26 ℃ from 24 ℃, the solenoid valve was fully closed after two minutes because of the solenoid valve's response lag. This denotes that the actual cooling load reached zero after two minutes, as shown in Fig. 4.

Fig. 4 shows the indoor air temperature variation and the different masses after the room temperature resetting. For all the scenarios, it was found that the indoor air temperature responded faster than the building's masses, and the room temperature fluctuated within ± 0.5 ℃ because of the control precision of the HVAC systems. The room's temperature reached setpoint in ~ 30 mins, while the temperature of the masses gradually increased from 24.3 ℃ to 25.8 ℃ over two hours, denoting that the thermal masses could release a certain amount of cooling capacity because of the temperature difference between indoor

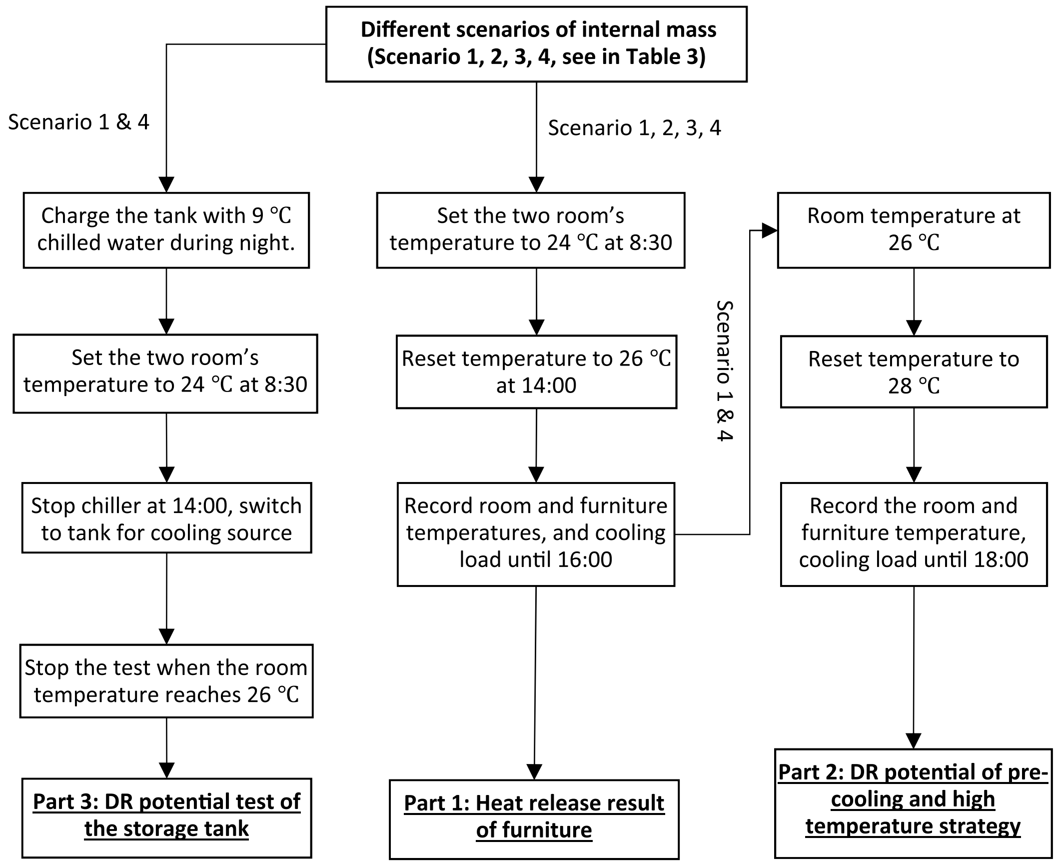


Fig. 2. Schematic of the experiment schemes.

air and thermal mass.

Comparatively, Fig. 5 (a) shows that the chiller could be closed for a considerable duration, i.e., around 42 and 38 mins for scenarios 4 and 1, respectively. Additionally, considering the cooling capacity provided by the AC, the peak cooling load demand of scenarios 4 and 1 were 1,589 W and 2,164 W, and the average cooling loads were 285 W and 375 W, respectively. This load difference of 90 W can be regarded as the DR potential of the furniture. Fig. 5 (b) shows that the available chiller closed time was around 33 and 25 min for scenarios 3 and 2, respectively. The peak cooling demand was 2,204 W and 2,629 W, and the average cooling load was 321 W and 352 W, respectively. The analysis of the cooling load demand highlighted that the larger volume of thermal mass scenarios (4 and scenario 3) required less cooling load to maintain the same room temperature due to the equivalent cooling capacity released from building thermal mass.

3.2. *DR potential of pre-cooling and high-temperature setting*

Pre-cooling is a common strategy used to enhance the DR potential of an HVAC system. Fig. 6 shows the temperature variation under 2 °C, based on the pre-cooling strategy (i.e., the room temperature was set to 22 °C from 1:00 AM and reset to 26 °C during DR event). Fig. 6 shows that the test temperature of the indoor air and that of the surface of the thermal masses were 22 °C after the long-term pre-cooling. After the room temperature was reset to 26 °C, it increased rapidly and reached the setpoint after ~ 65 mins. During this test, the temperature difference between the indoor and outdoor was ~ 5.1 °C. The temperature of each mass slowly increased, and the final temperature, after three hours, was still lower than 26 °C. This indicates that thermal masses can still release cooling capacity. The rate of temperature rise of the office desk and files was almost the same, while that of the floor was relatively slower owing to its thicker body.

As seen from Fig. 7, the chiller was allowed to turn off for up to 73 min and 103 min, under this pre-cooling strategy, in scenarios 1 and 4, and the average cooling demand during the experiment was 206 W and 186 W, respectively. The results show that the pre-cooling strategy can reduce the load demand during the DR event significantly and extend the chiller's close span while still meeting the thermal requirement.

Table 3
Different scenarios of building internal thermal mass.

Scenarios No.	Weight of thermal mass	Notes
Scenario 1 (in the benchmark room)	Without any furniture	Empty room
Scenario 2 (in the test room)	Office desk and chair: 1 set, 60 kgFiles and closet: 75 kg Others: 50 kg	Simulate a light occupancy room
Scenario 3 (in the test room)	Office desk and chair: 2 sets, 120 kg Files and closet: 150 kg Others: 100 kg	Simulate a normal occupancy room
Scenario 4 (in the test room)	Office desk and chair: 4 sets, 240 kg Files and closet: 300 kg Others: 200 kg	Simulate a heavy occupancy room

(a) Scenario 4 (heavy occupancy room, test room) (b) Scenario 1 (Empty room, benchmark room)

Fig. 3. Scenarios of different building thermal mass.

For the higher temperature setting strategy, the room temperature was set to 28 ℃ after maintaining it at 26 ℃. Fig. 8 shows the temperature variation of the internal thermal masses. Due to the influence of the external environment, the wall temperature increased faster than the furniture. Fig. 9 shows the results of the room temperature and cooling capacity of scenarios 1 and 4. Due to the release of the cooling capacity from the internal thermal masses, the test room requires less cooling capacity to maintain the same temperature, thus lowering the peak cooling capacity. Under these experimental conditions (the indoor and outdoor temperature difference is ~ 4.9 □), the DR potential can be improved because the chiller can be turned off for additional time; thus, the end-users can participate in a longer DR project. Considering the accuracy of the room temperature control, the rooms' temperature exceeds the upper limit of the thermal comfort range, likely risking of end-users' complaints.

3.3. DR potential of the active storage

For an AC system with an energy storage tank, the load reduction potential could be effectively improved. The temperature of chilled water in this experiment was ~ 9 ℃. After the chiller was turned off, the fans and pumps remained operational. Fig. 10 shows the temperature curve of the supply and return water, and the room temperature. As the water tank discharges, the water supply temperature rises from 9 ℃ to 23 ℃ in ~ two hours. Finally, only a 0.4 ℃ temperature difference was recorded between the supply and return water, indicating that the cooling capacity in the tank was almost fully exhausted. Fig. 11 shows the cooling capacity of the storage tank for the rooms. It can be seen that, the capacity is equal to the load reduction for the rooms. The average cooling load of the tank in scenarios 4 and 1 were 751 W and 800 W, respectively. According to the analysis, we can conclude that a 200 L water storage tank with 9 ℃ chilled water can be maintained for two hours with the chiller closed, under the experimental conditions (AC area of 32 m^2, and average indoor and outdoor temperature difference of 7.2 ℃). Thus, the storage tank can easily realize a DR project without sacrificing the occupant's comfort.

3.4. DR potential of combining passive thermal mass and active storage tank

The combination of the active storage tank and passive thermal masses can provide a higher load reduction and execute a longer span of DR. Fig. 12 shows the results of using both strategies. In the first stage, the chiller was shut down as the storage tank was fully charged. Only the storage tank functioned, and the room temperature could be maintained at the design value 24 ℃. In the second stage, as the storage tank discharged, the room temperature was reset to the upper limit of 26 ℃. The storage tank and thermal mass contribute to load reduction simultaneously. In the last stage, the storage tank was fully discharged, and the passive thermal mass released its cooling load until the upper limit temperature setting was met.

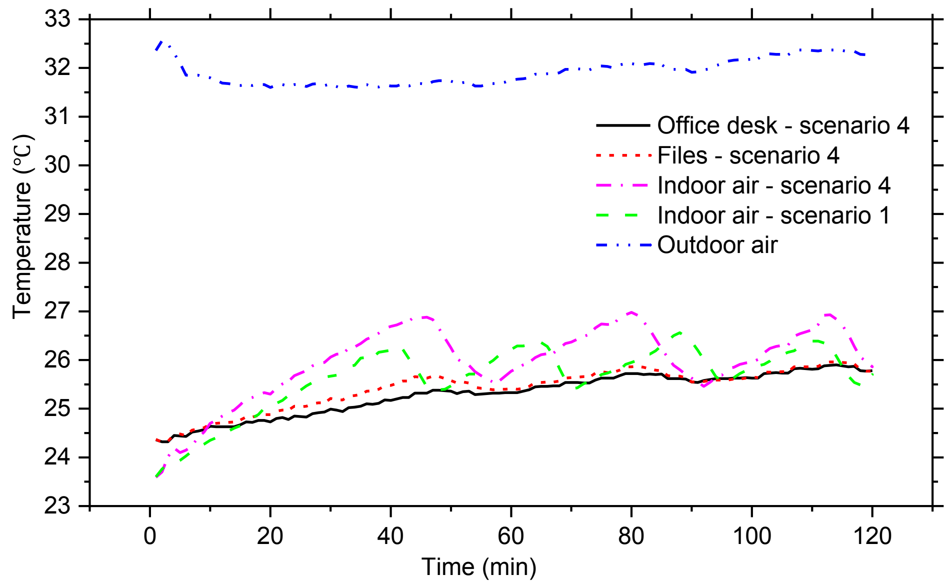
3.5. Discussions

DR potential (cooling load reduction) is related to the volume of internal masses. The cooling load demand was 375 W, 352 W, 321 W, and 285 W, for an empty, light occupancy, normal occupancy and heavy occupancy rooms, respectively. Thus, there was ~ 23 W, 54 W and 90 W of DR potential for two hours of the DR event for the light occupancy, normal occupancy, and heavy occupancy rooms, respectively. The heavy occupancy room has a higher cooling capacity released from building thermal mass. Additionally, the heat release rate of thermal mass is a vital factor for using a passive method to reduce cooling load during peak load time. For different DR events, short-term DR (0.5 h), intermediate-term DR (2 h), long-term DR (4 h) are commonly used. Fig. 13 shows the heat release rate of thermal masses of different thicknesses. For intermediate-term DR, ~75% of the total cooling capacity can be utilized for thin thermal masses such as furniture, while it is only ~ 19% for thick thermal mass, such as thick internal walls. It can be concluded that the thermal mass releases a part of its cooling capacity during DR. A thinner thermal mass is more efficient for short-term DR, whereas a thicker thermal mass can still contribute to cooling capacity for long-term DR.

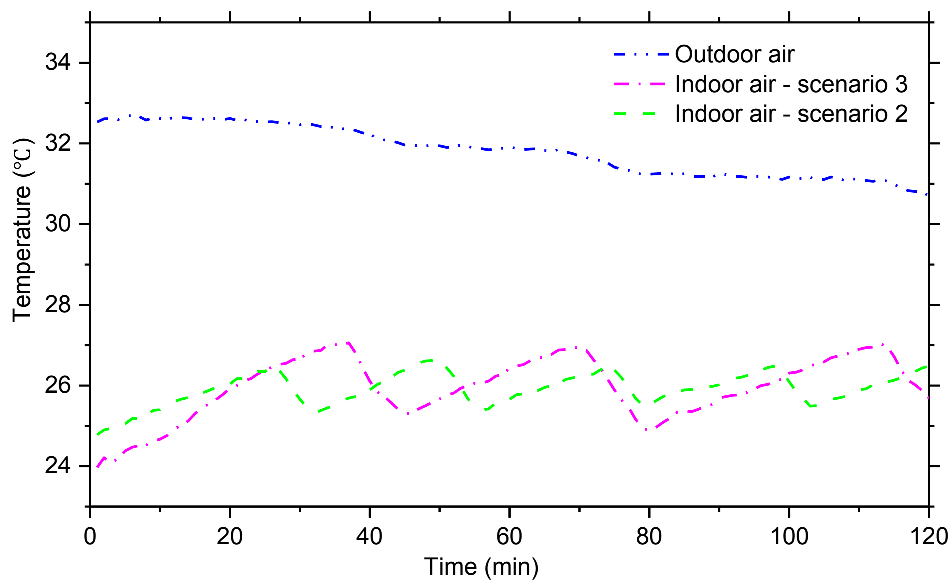
Building thermal mass is commonly used as a passive strategy to provide load reduction. This study investigated the load reduction capacity, which is affected by the volume of thermal mass. Fig. 14 shows the relationship between thermal mass weight and load reduction capacity. The load reduction capacity increases with an increase in the thermal mass weight; however, this increment decreases after the weight of the thermal mass exceeds 120 kg/m^2. The main reason for this is that the thermal mass lumps up to a large bulk, making it harder to release its stored cooling capacity. Furthermore, when an active storage tank and passive thermal mass are combined, more load reduction and a longer DR span can be achieved.

4. Conclusions

Electricity load reduction during peak load time is particularly important for the grid. Combining building thermal mass with HVAC systems is an efficient and economical method to reduce electrical load. A building's load reduction potential during the peak load time can be considerably influenced by its thermal mass and energy storage devices.



(a) Temperature curve of scenario 1 and 4



(b) Temperature curve of scenario 2 and 3

Fig. 4. Temperature variation during 2 h of DR event.

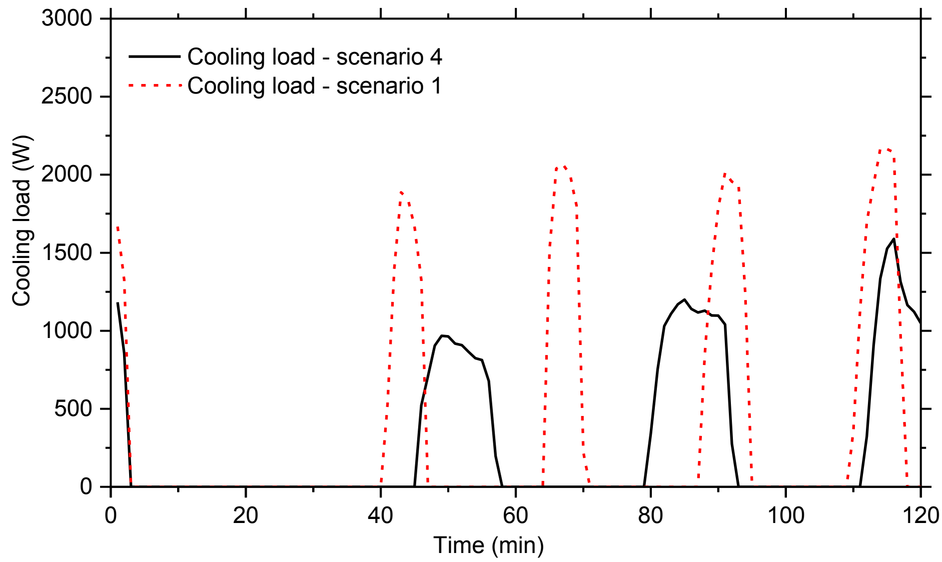
Thus, an experiment was conducted to investigate the load reduction potential obtained by combing a building's thermal mass and HVAC system; this enabled the evaluation of the contribution of different types of passive thermal masses and active storage tanks. This experiment considered, not only a passive means of DR control, using the internal thermal mass including office desks, files, and walls, but also an active way, using a water storage tank. The main conclusions of this study are as follows.

(1) The heat release rate highly depends on the thickness and the thermophysical characteristics of the thermal mass. Thinner internal thermal masses, such as office desks and files, are more useful for a short-term DR, while thicker masses, such as the internal walls, continue to release cooling capacity for a long-term DR. The heat release rate of furniture is 28%, 75%, and 93%, and 5%, 19%, 35% for a thick internal wall, for a short-term, intermediate-term, and long-term DR respectively.

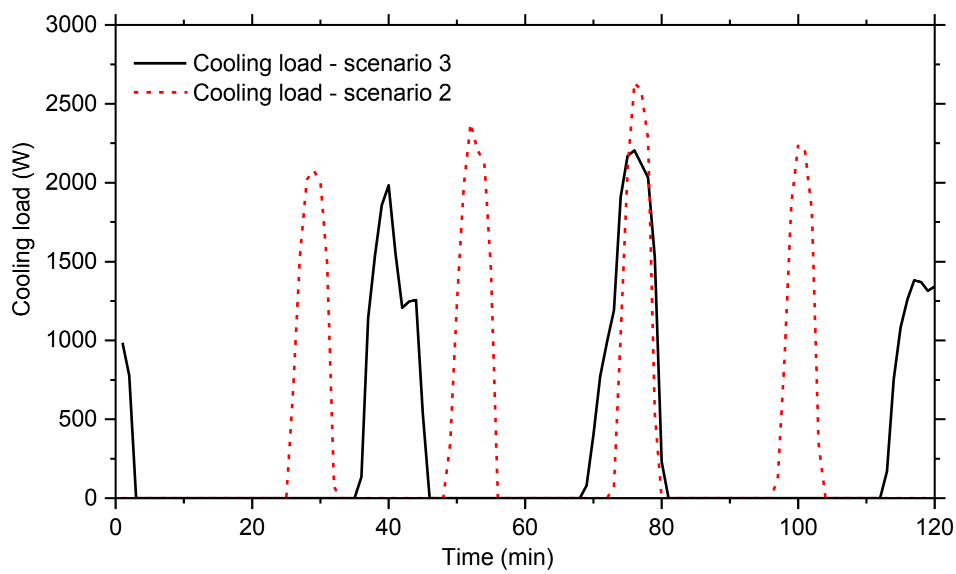
(2) Heat release from the internal thermal mass is a slow process, especially for thick masses. For a passive DR control strategy, a higher mass weight does not indicate a better DR response. The optimal value observed under the tested experimental conditions was ~ 120 kg/m^2. The quantification formula of load reduction capacity (y, kWh/m^2) and weight of internal thermal mass (x, kg/m^2) is achieved.

(3) Pre-cooling is an important strategy that should be considered to enhance a building's peak load reduction. It can enable more cooling capacity stored in the internal thermal mass and significantly reduce the load demand during peak load time. Under the experimental conditions tested, the chiller could be turned off for over 90 mins without compromising the thermal comfort of occupants, which is effective for a short-term DR program.

(4) A high temperature resetting in the cooling case or a lower resetting in the heating case is a feasible DR strategy to enhance the load reduction potential. The level of temperature changing and the temperature control precision, however, should be



(a) Cooling load of scenario 1 and 4



(b) Cooling load of scenario 2 and 3

Fig. 5. Cooling load of the AC system during 2 h of DR event.

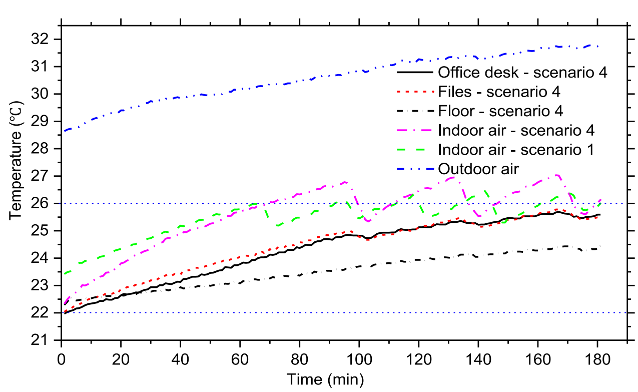


Fig. 6. Temperature variation of the pre-cooling control strategy.

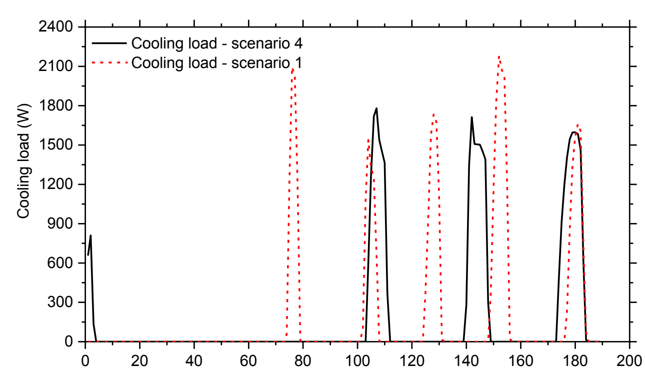


Fig. 7. Cooling demand for pre-cooling control strategy.

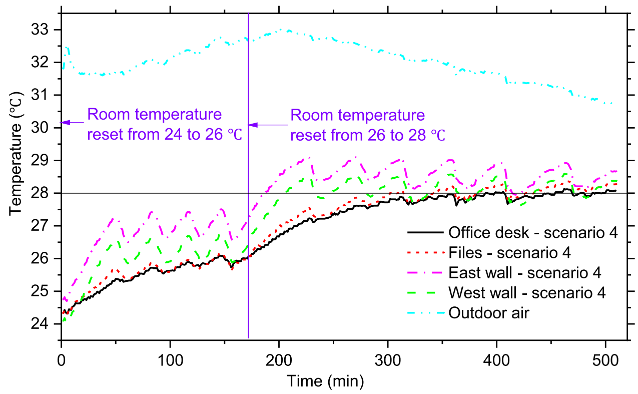


Fig. 8. Temperature variation for higher temperature resetting strategy.

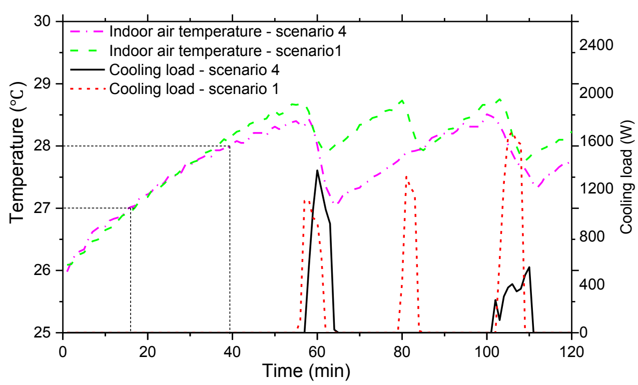


Fig. 9. Cooling demand for higher temperature resetting strategy.

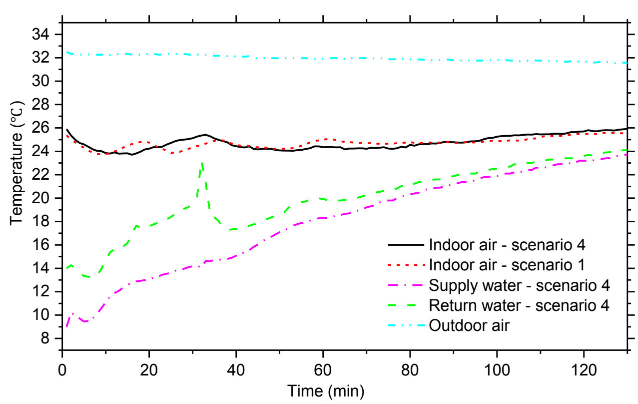


Fig. 10. Temperature variation using a storage tank.

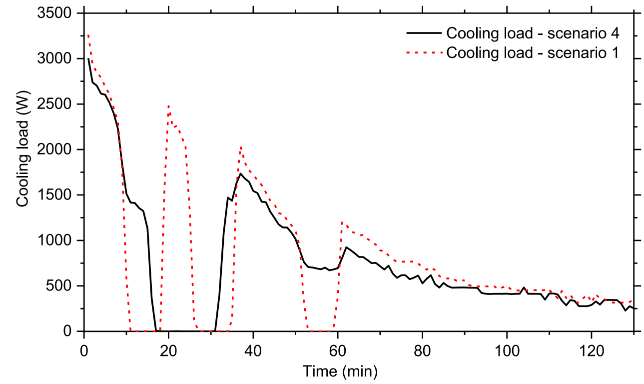


Fig. 11. Cooling load release curve of a storage tank.

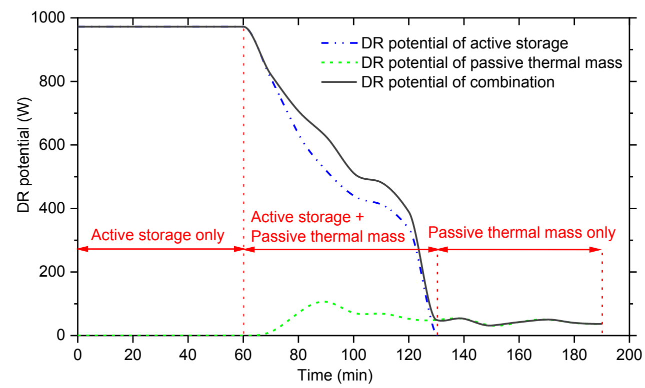


Fig. 12. DR potential combination (cooling release) of passive and active strategy in scenario 4.

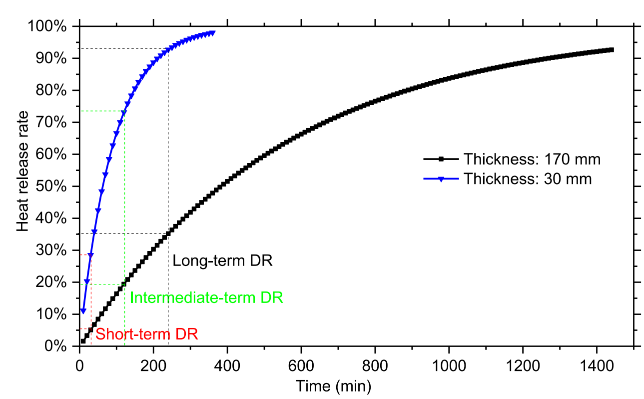


Fig. 13. Heat release rate of thermal massed of different thickness.

carefully considered, failing which, there will be a risk of complaints from occupants.

(5) A storage tank, as an active approach, can provide a significant load reduction, although additional investment is required. In typical subtropical weather zones, a 200 L water storage tank with 9 °C chilled water can independently meet the cooling demand over two hours for a 32 m^2 AC area. Storage tanks are the ideal and important devices for future DR programs.

(6) Active storage tanks and passive thermal masses can be easily combined to provide a higher load reduction, and a longer DR span. With an optimal control strategy, this coupled system brings an average of 532 W cooling load reduction in three hours.

This experimental work aimed to quantify the load reduction ability of different internal thermal masses to reduce the cooling load of the HVAC system. A reduction in load at peak load time and a load increase at off-peak load time, has a meaningful impact on the grid. In the future, with the fast development of renewable energies, flexible electricity capacity will be an advantage for grid-integrated buildings, although the total energy consumption may be higher than traditional buildings. In several countries, newly built power plants are extremely restrained owing to surplus power or environment protection considerations. Therefore, future energy strategies will focus on not only energy efficiency, but also energy flexibility. Flexible electricity management strategies, such as DR, could be used to alleviate grid imbalance and increase the use of renewable energy penetration in the power market. Accordingly, a mechanism and industry standard for evaluating electricity flexibility are encouraging to be established in both existing and

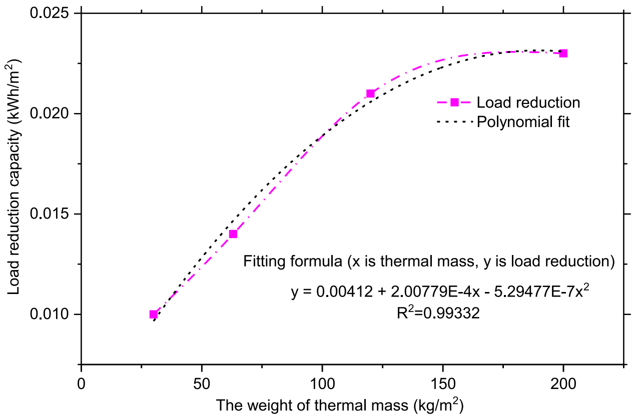


Fig. 14. Relationship between load reduction capacity and weight of internal thermal mass.

newly constructed buildings in the future.

CRediT authorship contribution statement

Yongbao Chen: Conceptualization, Methodology, Writing - original draft, Formal analysis. **Peng Xu:** Supervision. **Zhe Chen:** Writing - review & editing, Visualization. **Hongxin Wang:** Visualization, Investigation. **Huajing Sha:** Writing - review & editing. **Ying Ji:** Resources. **Yongming Zhang:** Funding acquisition. **Qiang Dou:** Funding acquisition. **Sheng Wang:** Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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