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Adjacent heat transfer characteristics and energy efficiency optimization in university classrooms under partial-space heating by a numerical model based on field test

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ABSTRACT

Universities' course timetabling arranged by lecture conditions could cause different occupation schedules in classrooms, resulting in intermittent heating conditions. The adjacent heat transfer contributes to heating energy consumption. A new course timetabling was needed to decrease intermittent heating energy consumption by the reallocation of the adjacent room heat transfer. A university building in Chengdu, China, was chosen to conduct field study and measurement. The dynamic heat transfer between interior walls and its effect on the indoor thermal environment and heating energy consumption were investigated by EnergyPlus. The results showed that: (1) the differences between the heat transfer in adjacent walls under different conditions could exceed 50 %. (2) Increasing the heating synchronization rate, extending the heating duration, and reducing the interval improved the indoor thermal environment and reduced heating energy consumption by 37 %. (3) The recommended timetabling was that the adjacent classrooms both have 4 h of lectures in the morning and afternoon to meet the course demand. Compared with the benchmark, the heating load and carbon emission could be reduced by 40 % and 2.44 kg/h, respectively. The significance of this study is to improve occupant thermal comfort and reduce energy consumption in university buildings through developing educational timetabling.

Introduction

The building sector accounts for 37 % of carbon emissions and 36 % of global total energy consumption [1], which causes a large amount of greenhouse gas (GHG) emissions. Reducing carbon emissions in the building environment could efficiently reduce the growing GHG from buildings [2]. However, the energy consumed by HVAC systems in buildings is about 50 % [3]. Therefore, building design and operation optimizations have been conducted to achieve energy-saving [4,5].

As public educational establishments, educational buildings have a significant social responsibility. According to statistics [6,7], China has more than 3000 colleges and universities, which are responsible for 8 % of the total energy consumption. The energy performance of this type of building, therefore, is very significant [8]. Electricity consumption accounts for more than 90 % of the energy consumption in university buildings, while the energy consumption of HVAC systems has the highest share [9]. Many studies have proposed strategies to reduce energy consumption in university buildings by enhancing the thermal performance of the building envelope. Semprini et al. [10] found that up to 32 % energy-saving could be achieved by optimizing the building envelope materials of university buildings in Italy. Zhang et al. [11] found that the heating load of a university building with thermal insulation could be reduced by around 30 % compared to those without thermal insulation in Chengdu, China. Ge et al. [12] found that the annual heating loads of a university building would be reduced by 38.6 % with the optimized building envelope in Hangzhou, China. However, most studies focused on improving exterior building envelopes, including walls [13–15], windows [16,17], and roofs [18,19], while ignoring the interior envelopes.

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Nomenclature

Symbols

Q	Heat, W
V	Room volume, m^3
F	Wall areas, m^2
T	Temperature, °C
X	Outside CTF coefficient
Y	Cross CTF coefficient
Z	Inside CTF coefficient
q	Conduction heat flux, W/m^2
U-value	Heat transfer coefficient, W/(m^2·K)
$SHGC$	Solar heat gain coefficient
h	Combined convective-radiative heat transfer coefficient, W/(m^2·K)
$\tilde{q}$	Hourly adjacent wall heat transfer, kJ/(m^2·h)
$\tilde{Q}$	Total adjacent wall heat transfer, kJ
M	Measured value
C	Calculated value
N	Model validation total number of hours
C_p	Zone air specific heat, kJ/(kg·K)

Latin symbols

ρ	Zone air density, kg/m^3
Φ	Flux CTF coefficient
δ	Time step (s)
λ	Thermal conductivity, W/(m•K)
ω	Synchronization rate
τ	Heating duration, h
θ	Current time step (s)

Abbreviations

GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
AHU	Air handling units
CTF	Conduction transfer function
CSWD	Chinese standard weather dataset
RMSE	Root mean square error
CV	Coefficient of variation

Subscripts

hs	Indoor heat source
al	Air leakage
ac	Air-conditioner
sr	Solar radiation
be	Building envelopes
m	Material of each layer
ew	Exterior wall
iw	Interior wall
in	Indoor air
out	Outdoor air
ad	Adjacent room air
i	Interior surface
e	Exterior surface
c	Convection
r	Radiation
o	Operation
A,B	Room A and Room B
A	Room A
j	Node
v	The v-th model validation time
ave	Average value

In university buildings, classrooms have different spatial and functional capacities. The order and organization of classrooms correlate to the learning environment. The university admission departments always arrange course schedules based on lecture conditions, resulting in different occupancy schedules, which could impact building energy consumption [20]. The so-called timetabling problem focused on a certain number of courses and classrooms considering the time and other constraint sets [21]. Daskalaki et al. [22] and Nasser et al. [23] studied timetabling of universities to optimize classroom allocation. Admittedly, timetabling affects building energy consumption [24]. Based on a course timetabling algorithm, an energy efficiency procedure was proposed by Song et al. [25], and 4 % energy savings was achieved compared to the existing timetable. Besides, the energy saving could reach 5 % by removing some strict constraints. Jafarinejad et al. [26] embedded an optimized course timetable with a demand-driven control strategy of an air handling unit (AHU) system to save energy in university buildings. The energy-saving potential could be up to 18.97 % due to the integration of the proposed demand-driven control scheme. Sun et al. [27] optimized the university timetables via the genetic algorithm and enabled to reduce energy consumption by 3.6 % in the autumn semester. Liu et al. [28] did global timetable optimization on course schedule and opening strategy of self-study rooms. The energy-savings were 29.4 % and 13.4 % for the heating and cooling seasons, respectively.

Due to educational timetabling, partial-space operations of the AHU system can be found in university buildings, especially for the winter conditions in southern China. Due to government policy, this area does not have central heating in winter. Therefore, the heat transfer through interior walls between adjacent classrooms in the so-called intermittent air conditioning condition [29]. During intermittent operation, the heat transfer between adjacent walls without thermal insulation would be much larger than expected, which can be more than half of the total energy demand of AHU [30,31]. Therefore, reducing the heat loss from interior walls could effectively save energy consumptions of intermittent air-conditioned rooms, which requires improving the thermal performance of interior walls. Li and Chen [32] found that the heating condition of adjacent rooms significantly influenced the thermal performance of interior walls. Meng et al. [33] numerically studied the thermal characteristics of the interior walls under intermittent air-conditioning operation. The surface temperature response rate was the highest when the AHU in the adjacent room ran continuously. Xue et al. [31] found that the temperature difference between adjacent rooms and the number of heated adjacent rooms influenced the heat transfer between the interior walls. Thus, the spatial allocation of classes could reduce the heat loss of interior walls to achieve energy savings, which should be synchronized with the academic time schedule. Such issues for the educational buildings following a particular timetable wait to be exploited.

The literature review indicated that studies on classroom scheduling mainly focused on timetabling optimization to improve energy efficiency. However, the specific energy consumption characteristics of classrooms were often neglected. The analysis of the adjacent heat transfer issue under intermittent operation of air conditioning due to classroom scheduling in universities needs further in-depth study. On the other hand, different AHU operation conditions could be found in adjacent classrooms because of the diversity and complexity of the classroom allocation. The adjacent classrooms may have multiple use conditions for the target classrooms. Therefore, it is important to propose an optimization strategy to reduce the heat loss to the adjacent classrooms from the adjacent walls from the perspective of operational energy saving in this special intermittent air-conditioning operation.

This paper explored the dynamic heat transfer between adjacent

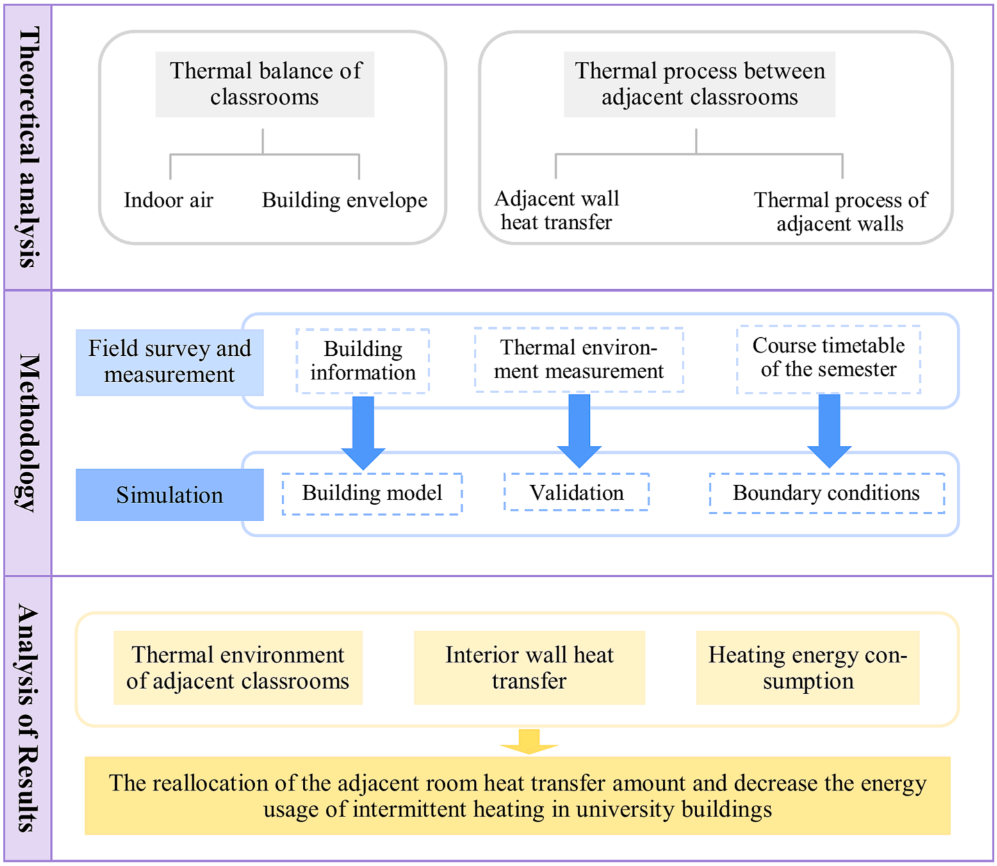

Fig. 1. Informative flow chart.

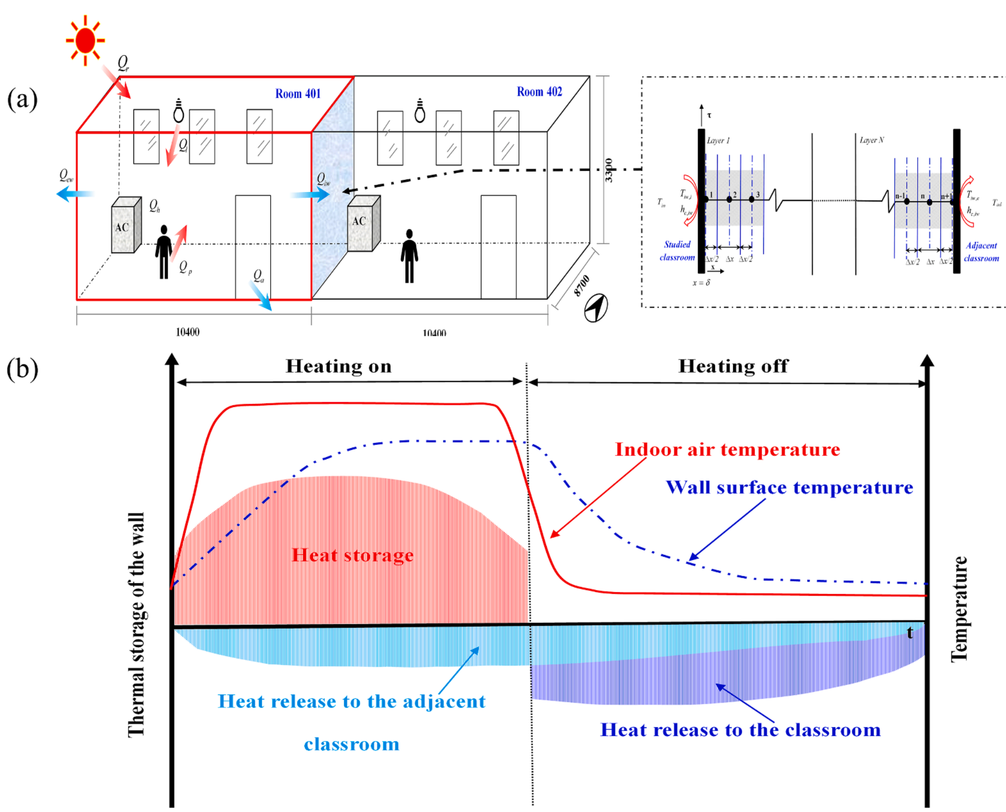

Fig. 2. Mathematical model of adjacent classrooms ((a) Energy balance model, wall grid arrangement, and boundary conditions; (b) Dynamic thermal process of adjacent walls during intermittent air-conditioning).

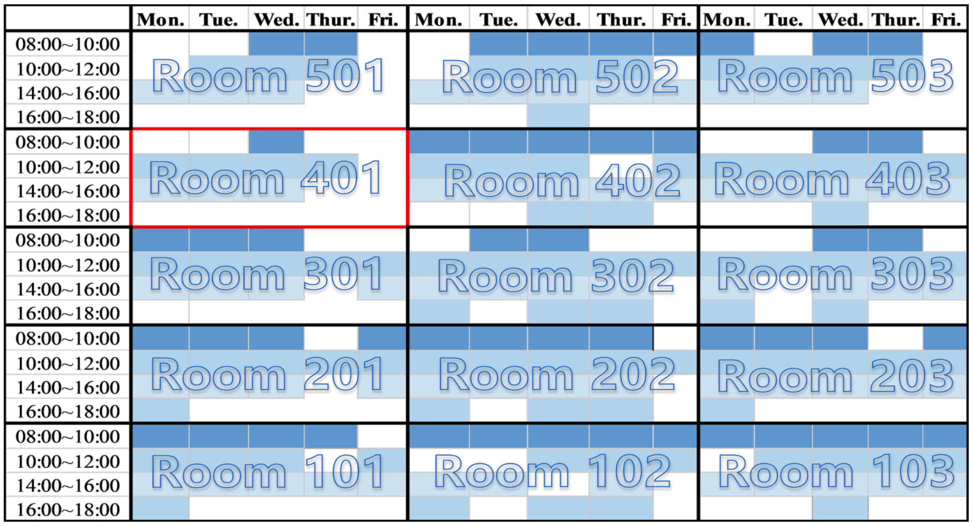

Fig. 3. Field survey results of the timetables for the autumn semester of 2021.

classrooms and its effect on heating energy consumption. The heat transfer between interior walls and heating load of different intermittent conditions were calculated through EnergyPlus software and compared to optimize the energy efficiency of classrooms according to the spatial allocation of classes to courses and the time. Fig. 1 presents the flow chart of this study. The objective of this study is to realize the reallocation of the adjacent room heat transfer amount and decrease the energy usage of intermittent heating in university buildings. The novelty of this study is to provide new insights into developing the educational timetabling and demand-driven control approach of AHU systems in universities, which would be vital for operational management and energy-saving.

Heat transfer process between the adjacent classrooms

The heat transfer model of adjacent classrooms was established to investigate the dynamic heat transfer between adjacent classrooms and its impact on the indoor thermal environment and heating energy consumption under different intermittent air-conditioning operations, as shown in Fig. 2(a). The partial-space operation of AHU is found in intermittent heated/cooled classrooms, where heat transfer takes place between the indoor air and the building envelope. The indoor air temperature variation is affected by ambient weather conditions, indoor occupation, building envelope thermal performance, etc. The indoor air temperature variation can be obtained by Eq. (1).

$$\rho C_\rho V \frac{dT_{in}}{d\tau} = Q_{hs} + Q_{al} + Q_{ac} + Q_{sr} + Q_{be} \tag{1}$$

The heat transferred through the exterior building envelope Q_{ew} is calculated by Eq. (E.1) in Appendix E.

Due to the different operation schedules in adjacent classrooms, the interior wall becomes a quasi-external envelope, which causes a certain heat loss during intermittent heating. Therefore, the heat transferred through the interior building envelope Q_{iw} is calculated by Eq. (E.2) in Appendix E.

The heat loss through adjacent walls accounts for a large part of the heating load, so the analysis of dynamic heat transfer between adjacent walls is imperative to find energy-saving procedures. The Conduction Transfer Functions (CTFs) method is employed to analyze the wall heat transfer from the interior surface and exterior surface as follows [34]:

For the interior surface:

$$q_i = -Z_0 T_{i,\theta} - \sum_{j=1}^{nz} Z_j T_{i,\theta-j\delta} + Y_0 T_{e,\theta} + \sum_{j=1}^{nz} Y_j T_{e,\theta-j\delta} + \sum_{j=1}^{nx} \phi_j q_{i,\theta-j\delta} \tag{2}$$

For the exterior surface:

$$q_e = -Y_0 T_{i,\theta} - \sum_{j=1}^{nz} Y_j T_{i,\theta-j\delta} + X_0 T_{e,\theta} + \sum_{j=1}^{nz} X_j T_{e,\theta-j\delta} + \sum_{j=1}^{nx} \phi_j q_{e,\theta-j\delta} \tag{3}$$

The wall dynamic adjacent heat transfer is shown in Eq. (E.3) and Eq. (E.4) in Appendix E. Fig. 2(a) shows the illustration of wall grid arrangement and boundary conditions. Fig. 2(b) demonstrates the dynamic thermal process of adjacent walls during intermittent heating. During intermittent heating in university buildings, the adjacent wall is the partition wall between one occupied classroom with the heating on and one empty classroom with the heating off. After heating, heat is transferred into the interior wall and stored partly. Meanwhile, another part of the heat is lost to the adjacent classroom through the interior wall. When the heating is off in the target classroom, most of the heat stored in the interior wall will be simultaneously released to this classroom and the adjacent classrooms. It can be seen that a major portion of the heat transferred into the adjacent walls is lost to unoccupied adjacent classrooms and cannot be exploited to improve the thermal environment of the target classroom. Moreover, the surface temperature of the interior wall is low because the heating is off in the empty adjacent classroom. During the preheating stage, the heat input is primarily and massively used to heat the adjacent wall. Therefore, this partial-space heating can lead to a large amount of energy dissipation and cause inefficient heating, which significantly increases the energy consumption of university buildings. Thus, under this kind of intermittent heating conditions, optimizing educational timetabling and proposing a demand-driven control approach of AHU systems in university classrooms may enable a great energy-saving.

Case description

To analyze the dynamic heat transfer in adjacent walls and its effect on the heating energy consumption under spatial-space heating, a representative university teaching building in Chengdu, China, was selected to analyze.

Building overview and field survey

In Chengdu (longitude 104.06°E, latitude 30.67°N), the coldest month has an average temperature of 5.6 °C, and the coldest winter temperature is −3.9 °C [35]. The heating degree-day for base temperature of 18 °C is 1371 °C·d in this region [36].

Table 1
The timetable of operation cases.

	Heating periods	ω
Case 1	Room A: 8:00–12:00 & 14:00–18:00 Room B: 8:00–12:00 & 14:00–18:00	100 %
Case 2	Room A: 8:00–12:00 & 14:00–18:00 Room B: 8:00–10:00 & 14:00–18:00	75 %
Case 3	Room A: 8:00–12:00 & 14:00–18:00 Room B: 8:00–10:00 & 14:00–16:00	50 %
Case 4	Room A: 8:00–12:00 & 14:00–18:00 Room B: 8:00–12:00	50 %
Case 5	Room A: 8:00–12:00 & 14:00–18:00 Room B: 8:00–10:00	25 %
Case 6	Room A: 8:00–10:00 & 14:00–18:00 Room B: 8:00–10:00 & 14:00–18:00	100 %
Case 7	Room A: 8:00–10:00 & 14:00–18:00 Room B: 8:00–10:00 & 14:00–16:00	66 %
Case 8	Room A: 8:00–10:00 & 14:00–18:00 Room B: 8:00–12:00	33 %
Case 9	Room A: 8:00–10:00 & 14:00–18:00 Room B: 8:00–10:00	33 %
Case 10	Room A: 8:00–10:00 & 14:00–16:00 Room B: 8:00–10:00 & 14:00–16:00	100 %
Case 11	Room A: 8:00–10:00 & 14:00–16:00 Room B: 8:00–12:00	50 %
Case 12	Room A: 8:00–10:00 & 14:00–16:00 Room B: 8:00–10:00	50 %
Case 13	Room A: 8:00–12:00 Room B: 8:00–12:00	100 %
Case 14	Room A: 8:00–12:00 Room B: 8:00–10:00	50 %
Case 15	Room A: 8:00–10:00 Room B: 8:00–10:00	100 %
Benchmark	Room A: 8:00–10:00 Room B: -	0 %

Building description and experiment

The selected teaching building on the Dujiangyan campus of Sichuan Agricultural University has five stories and 25 classrooms, with a building area of 2545 m^2. Fig. A1 in Appendix A presents the schematic diagram of the measured university building. The size of a typical classroom is 10.4 m × 8.4 m × 3.9 m. Each classroom is equipped with a split air conditioner (KFR-120LW) with a heating power of 2450 W. The indoor thermal environment measurements were conducted on 15th December 2020 in classroom 401 on the 4th floor, and the data was recorded with a time interval of 10 min. The temperatures were measured with two calibrated T-type thermocouples. One was placed in the center of the tested classroom to measure the indoor temperature, and another was placed outdoors at a height of 1.5 m above the ground to measure the outdoor temperature. The solar radiation intensity was recorded by a JTR05 solar radiation meter. The measuring instruments and measured parameters were given in Table A.1.

Field survey of the timetabling

A field survey was conducted in the university building to obtain the course timetable for the autumn term in 2021. Fig. 3 shows the autumn timetables for year 2021. The classroom timetables were based on the curriculum demand. Therefore, one occupied classroom could be surrounded by up to four empty classrooms. There were four lecture slots every day for the course timetabling, and the main timetabling periods were from 10:00 to 12:00 and 14:00 to 16:00. During the main periods, adjacent classrooms were using air-conditioning simultaneously. In the time slots of 8:00 ~ 10:00 and 16:00 ~ 18:00, only a few classrooms were scheduled, so that the air-conditioning of the adjacent classrooms ran asynchronously. For example, all adjacent rooms of Room 402, except for Room 302, were unscheduled from 16:00 to 18:00 on Thursday, with no air-conditioning.

The typical intermittent operation conditions of two adjacent classrooms were obtained according to the lecture slot summary based on the field survey. Room 401 and Room 402 were selected for a detailed analysis, which were defined as Room A and Room B, respectively. Table 1 describes the specific fifteen intermittent operations of two adjacent classrooms, which could be classified into synchronous and asynchronous intermittent operations. Meanwhile, Room A was scheduled for only one lecture slot, while the adjacent Room B was unscheduled, which was defined as the benchmark.

(1) Synchronous intermittent operations: Case 1, Case 6, Case 10, Case 13, Case 15.
(2) Asynchronous intermittent operations: Case 2, Case 3, Case 4, Case 5, Case 7, Case 8, Case 9, Case 11, Case 12, Case 14.

The heating synchronization rate (Eq. (4)) was proposed to describe the intermittent air-conditioning operation conditions in adjacent classrooms.

$$\omega = \frac{\tau_{A,B}}{\tau_A} \times 100\% \tag{4}$$

Simulation set-up

The dynamic heat transfer between adjacent classrooms and the heating energy consumption were calculated through simulation.

Building model

EnergyPlus software was employed. Appendix B.1 shows the building model established based on the tested building, which has interior walls with a high *U*-value (*U*-value of 2.45 $W/(m^2{\cdot}K)$). The thermal properties of building envelopes, and the thermophysical properties of the main materials are shown in Appendix B.2.

Validation

The Energyplus building model was validated by the field measurements. The test outdoor weather data were used as boundary conditions. The results of the comparison of the measured and calculated values of indoor air temperature of Room A were given in Fig. C.1 in Appendix C. Root mean square error (RMSE) and coefficient of variation (CV) Eq. (E.5) and Eq. (E.6) in Appendix E were used to evaluate the differences between the measured and calculated values. The variations of the measured value and the calculated value were approximately the same, with RMSE of 0.61 °C and CV of 2.4 %, which met the requirements of the ASHRAE criterion [37]. Therefore, the building model was accurate and could be used to investigate the indoor thermal environments and dynamic heat transfer between adjacent classrooms.

The effects of user behavior between two adjacent classrooms on interior wall heat transfer and air conditioning energy consumption under certain thermal parameters of the interior wall were studied in our former study [38]. Results showed that the set point temperature and air change rate had a great impact. Therefore, the dynamic heat transfer between adjacent classrooms and its effect on air conditioning energy consumption under real occupant conditions need to be explored.

Boundary conditions

The meteorological data of Chengdu in the Chinese Standard Weather Dataset (CSWD) [39] was chosen as the outdoor boundary conditions. The ideal load air-conditioning system (Zone: IdealLoadSystem) was adopted in the simulation, which means that 100 % of the consumed heat was provided to heat the room. The air-conditioning was only used when the classroom had lectures, and the thermoset was set to 20 °C during the heating period. The personnel density in classrooms and indoor lighting power was set to 0.8 person/m^2 and 3.7 W/m^2, respectively, based on the field survey. A representative school week (12th–18th January) in the coldest month was selected for the analysis, which included five working days and a weekend. The ambient weather condition of the selected study period was given in Appendix D.

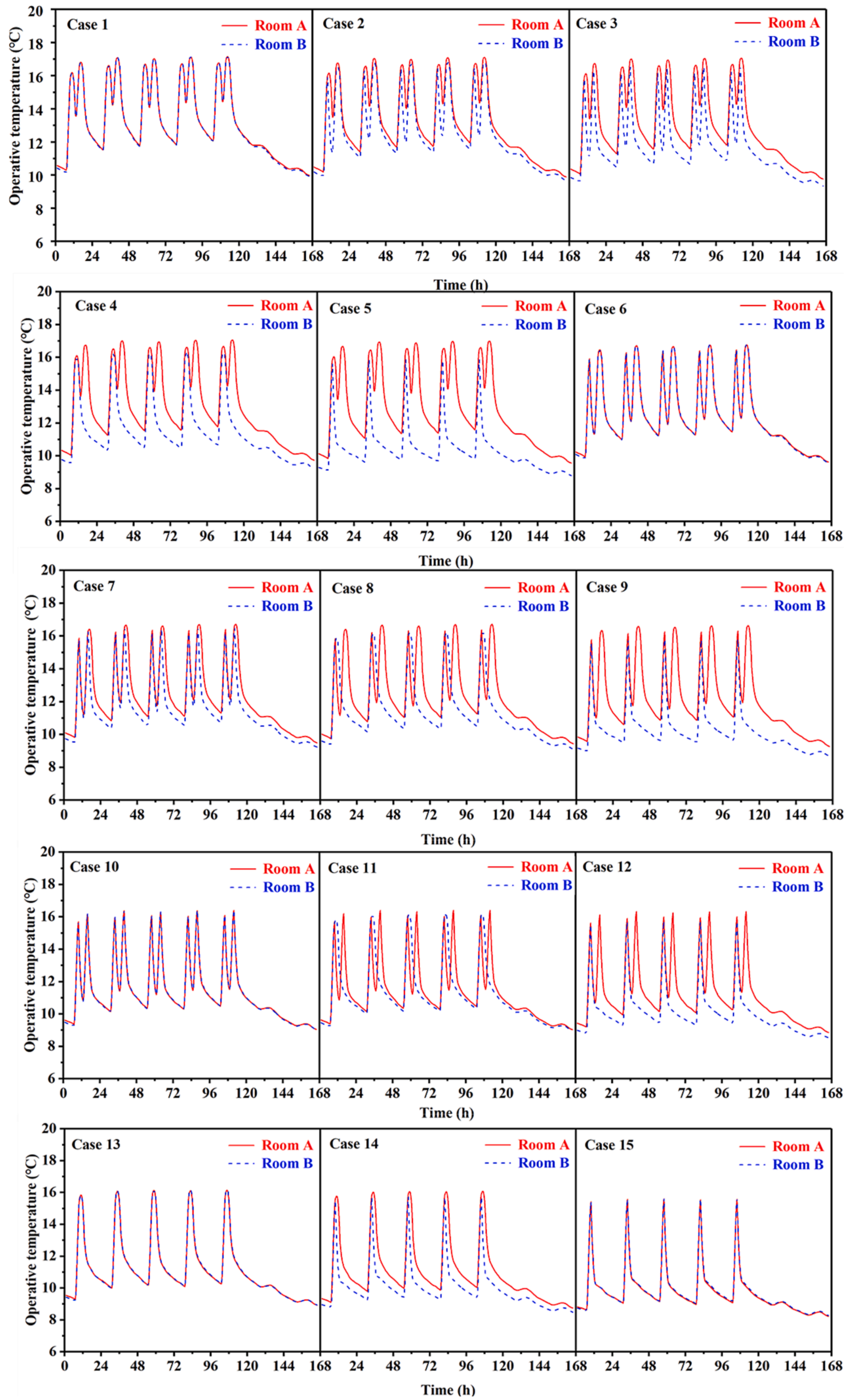

Fig. 4. Operative temperature variations for different intermittent conditions.

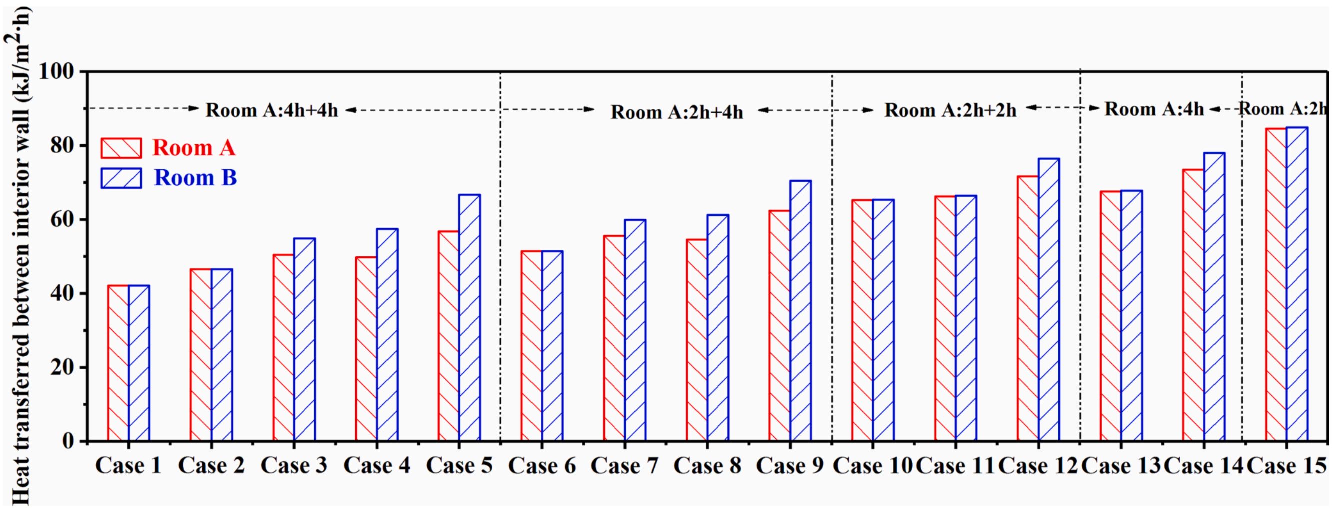

Fig. 5. The adjacent wall heat transfer under different intermittent conditions.

Results and discussion

The intermittent heating conditions of adjacent classrooms were assessed through indoor thermal environment and energy consumption.

Operative temperature variation

Operative temperature, combining the effect of mean radiant temperature and air temperature, shows human thermal experience in a space. Thus, the operative temperature (Eq. (E.7) in Appendix E) was chosen to investigate the effect of different intermittent heating conditions on the indoor thermal environments of adjacent classrooms.

Fig. 4 shows the comparison of the operative temperature variation under different intermittent conditions. The operative temperature variation of the adjacent classrooms was similar when sharing the same schedule. The longer the heating time on weekdays, the higher the operative temperature during the heating period. The heating synchronization rate was 100 % for Case 15 (heating: 2 h) and Case 1 (heating: 4 h + 4 h), respectively. During the heating period, the average operative temperature in Case 1 was 16.8 °C, which was 1.4 °C higher than in Case 15. For the adjacent classrooms with the same heating synchronization rates and duration, the operative temperature was mainly impacted by the interval time. The heating synchronization rates were both 100 % for Case 10 and Case 13, and the daily heating durations were both 4 h. However, the interval in Case 10 was 16 h between two school days, while that in Case 13 was 20 h. The average operative temperature during the daily heating period in Case 10 was 0.1 °C higher than that in Case 13. The reason was that the heat release time was shorter in Case 10, so that a large amount of heat was still stored in the adjacent walls. When the heating synchronization rate was different while the daily heating duration was the same, the operative temperatures of adjacent classrooms were different due to the adjacent wall heat transfer. The average operative temperature during the daily heating period in Case 10 was higher than in Case 11. The reason was that only a little heat transfer occurred through the adjacent wall when the two adjacent classrooms shared the same schedule in Case 10. However, the heating synchronization rate of Case 11 was only 50 %, which means that the heating in adjacent classrooms was asynchronous. Therefore, a large amount of adjacent heat transfer led to heat loss. Moreover, when the heating synchronization rate increased from 25 % (Case 5) to 100 % (Case 1), the average operative temperature increased by 0.1 °C and 1.1 °C for Room A and Room B, respectively. The operative temperature could be improved by adjusting the timetables to increase the heating synchronization rate and the heating time of adjacent classrooms. It was beneficial for building a comfortable learning environment.

Interior wall surface heat flow variation

The different indoor temperature variations in adjacent classrooms were found under different intermittent conditions, leading to different adjacent wall heat transfer. The heat transfer through the interior walls was calculated by Eq. (5):

$$\widetilde{q}_{iw} = \frac{\widetilde{Q}_{iw}}{F_{iw} * \Delta\tau} \tag{5}$$

Fig. 5 displays the hourly adjacent wall heat transfer under different intermittent conditions. A large amount of heat transferred between the adjacent walls could be found when the operation duration was short. Moreover, increasing the heating synchronization rate could significantly reduce the adjacent wall heat transfer. For example, the hourly adjacent wall heat transfer in Case 15 was about 50 % higher than in Case 1. When the synchronization rate was changed from 25 % (Case 5) to 100 % (Case 1), the interior wall heat transfers between Room A and B during the heating period in Case 5 were 26 % and 37 % higher than those in Case 1. The heat transferred through the adjacent wall could be reduced by shortening the interval duration for the adjacent classrooms with the same heating synchronization rate and term. The hourly adjacent wall heat transfer in Case 10 was 4 % lower than that in Case 13. Therefore, increasing the heating synchronization rate is favorable to reducing the adjacent wall heat transfer during intermittent heating, which is beneficial to improve energy efficiency.

Heating energy consumption

The adjacent wall heat transfer contributes to the heating energy consumption of intermittent heating classrooms. Fig. 6 compares fifteen intermittent heating cases in terms of the hourly heating energy consumptions. Although prolonging heating durations would increase energy consumption, the long heating time could cause low heating energy consumption per hour when the heating synchronization rate was the same. Synchronous heating operation in adjacent classrooms could be found in Case 1, Case 6, Case 10, Case 13, and Case 15, with the heating synchronization rate of 100 %. Case 15 (heating: 2 h) had the most significant hourly heating energy consumption during the heating period, which was 24346.4 kJ/h. The smallest one was found in Case 1 (heating: 4 h + 4 h), which was 16250.8 kJ/h. The reason was that the heating operation period in Case 1 was the longest, so the preheating process was finished quickly, and the heating power was mainly used to maintain the high indoor temperature. Moreover, the lower the heating synchronization rate, the larger the hourly heating energy consumption

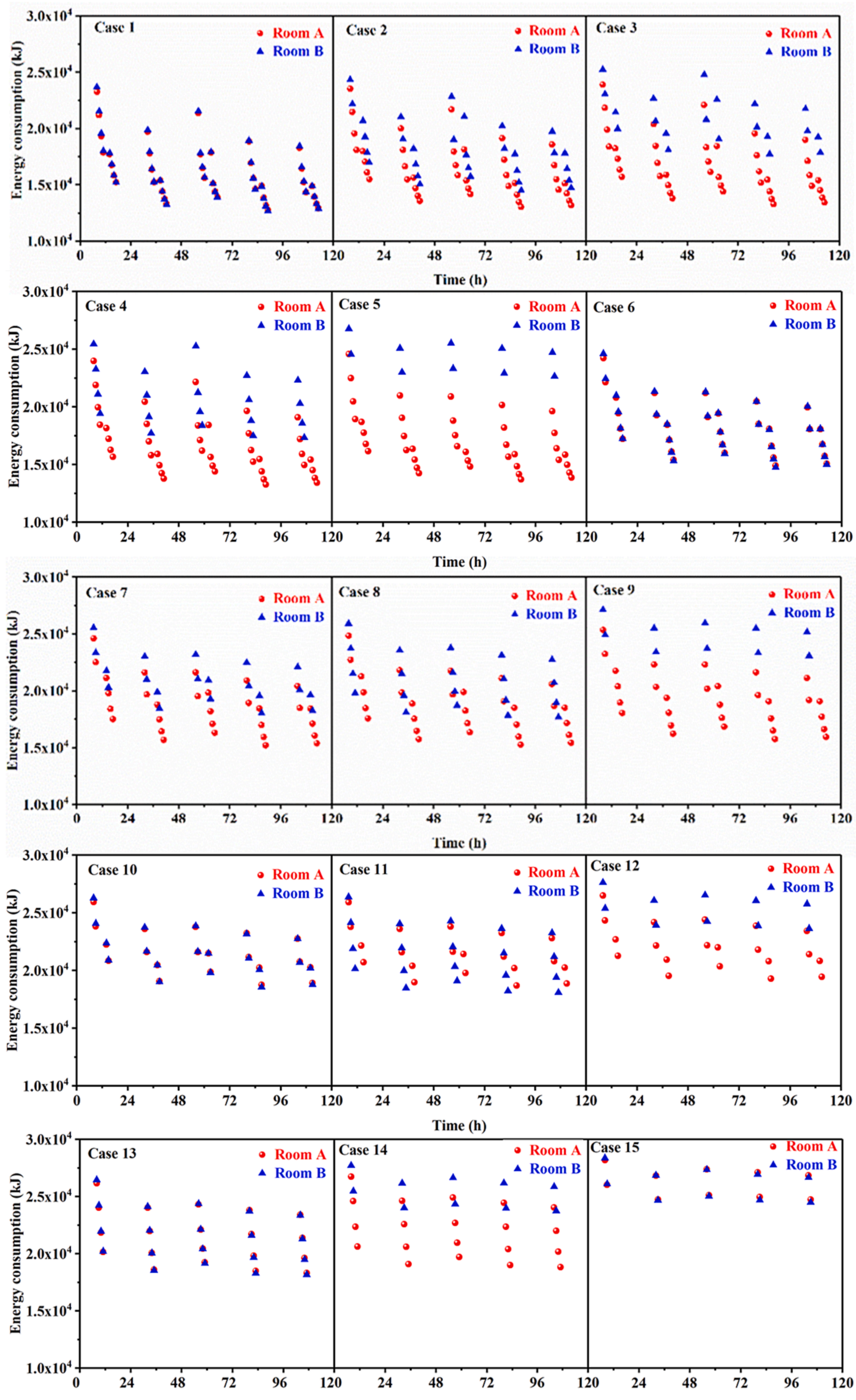

Fig. 6. Variations of hourly heating energy consumption under different intermittent heating conditions.

Table 2
Heating load of the adjacent classrooms.

Case	Room A	Room B
Benchmark	7579.84 W	–
Case 1	4514.11 W	4529.74 W
Case 2	4589.09 W	5085.15 W
Case 3	4674.70 W	5857.18 W
Case 4	4682.24 W	5776.28 W
Case 5	4783.13 W	6763.44 W
Case 6	5069.02 W	5076.04 W
Case 7	5170.11 W	5807.24 W
Case 8	5196.94 W	5817.29 W
Case 9	5340.56 W	6878.36 W
Case 10	5924.99 W	5921.42 W
Case 11	5931.95 W	5938.62 W
Case 12	6128.20 W	7027.72 W
Case 13	5963.49 W	5959.99 W
Case 14	6119.20 W	7056.14 W
Case 15	7273.30 W	7251.68 W

difference between adjacent classrooms. The heating synchronization rate was 25 % and 75 %, respectively, for Case 5 and Case 2. The hourly heating energy consumption of Room A in Case 5 was about 4 % higher than that in Case 2.

The heating load was used to examine further the energy efficiency of the two different classrooms. Table 2 shows the heating load of the adjacent classrooms under various intermittent conditions. It is evidently seen that the heating load decreased by extending the heating operation time. For Case 15 and Case 10, with the same heating synchronization rate of 100 %, the heating load of both two classrooms could be reduced by about 18 % when the heating time was extended from 2 h in Case 15 to 4 h in Case 10. By further increasing in the heating time to 8 h in Case 1, the heating load could be reduced by about 37 %. The heating load of adjacent classrooms with a synchronous schedule was smaller than the asynchronous operation schedule. When the heating synchronization rate was changed from 25 % (Case 5) to 100 % (Case 1), the heating energy-saving rate of Room A and Room B could reach 6 % and 33 %, respectively. Meanwhile, when the heating synchronization rate and time were the same, a small heating load could be found when the interval time was short. Compared to Case 13 with 20 h intervals, Case 10 with 16 h intervals reduced the heating load by about 1 %. By comparing fifteen intermittent heating conditions to the benchmark, the minimum heating load value was found in Case 1, which was the most favorable for energy saving and had the highest energy efficiency. Compared to the benchmark, the heating load of Room A in Case 1 could be reduced by 40 % with an energy saving of 3.07 kWh per hour during the heating period. Therefore, 2.44 kg/h carbon dioxide emission reduction could be achieved during the heating period according to the National Bureau of Statistics [40], indicating a great economic and ecological value. Therefore, in terms of classroom arrangement, the most recommended timetabling has highest heating energy efficiency, which is that the adjacent classrooms both have 4 h of lectures in the morning and afternoon to meet the course demand. The management department of the university should arrange the courses consecutively in the same classroom and the courses at the same time to the adjacent classrooms to minimize the energy consumption of AHU. The same timetabling optimization could also contribute to the arrangement and management of self-study rooms and student dormitories in universities.

Conclusion

This study numerically evaluated the dynamic heat transfer between adjacent classrooms and its effect on the indoor thermal environment and heating energy consumption of a university building in Chengdu, China. Reallocation of the adjacent classroom heat transfer was proposed and the energy efficiency optimization of intermittent air-conditioning in the university building was assessed. The results are concluded as follows:

(1) The dynamic thermal process of the adjacent walls was influenced by the different partial-space heating conditions in university buildings. The difference in the heat transfer variation in the interior walls could be more than 50 % under different operation conditions in adjacent classrooms.
(2) The heating synchronization rate was proposed to analyze the adjacent classrooms' intermittent operation conditions. Reallocation of the adjacent classrooms' timetable with a high heating synchronization rate could effectively augment the indoor thermal environment as well as decrease energy consumption. When the synchronization rate was changed from 25 % to 100 %, the average operative temperature in the two adjacent classrooms increased by 0.1 °C and 1.1 °C, respectively. The hourly adjacent wall heat transfer was reduced by 26 % and 37 %, and the heating energy saving rate of two adjacent classrooms could reach 6 % and 33 %, respectively.
(3) Extending the heating duration and shorting the interval was crucial for improving the indoor environment and energy efficiency when the heating synchronization rate was the same. The average operative temperature in two rooms of 8 h heating duration was 1.4 °C higher than that of the case with 2 h heating duration with the same synchronization rate of 100 %, and the heating load was lower by about 37 %.
(4) Under intermittent air-conditioning, the most recommended timetabling was the adjacent classrooms both have 4 h of lectures in the morning and afternoon to meet the course demand. The heating load of Room A could be cut by 40 % compared with the benchmark while achieving 2.44 kg/h carbon dioxide emission reduction during the heating period.

This work is helpful for the design and operation management of the timetable of university buildings. However, only the spatial-space heating condition with two adjacent classrooms was considered based on the field study. Other scenarios, such as the heat transfer between other adjacent walls in different directions of the adjacent classrooms, will be studied in our future research.

CRediT authorship contribution statement

Yanru Li: Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Wanliang Li:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Xin Liu:** Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Yubin Jian:** Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Müslüm Arıcı:** Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing. **Lili Zhang:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Tai Zhou:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Ying Cao:** Formal analysis, Methodology, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. On-site measurement details

A.1 Measured university teaching building

Fig. A1. Schematic diagram of the representative university building ((a) exterior and interior view; (b) sketch and measurement arrangements of classrooms).

A.2 Information on measurement instruments

Table A1. Measuring instruments and measured parameters.

Instrument	Model	Quantity	Parameters	Range	Accuracy
Solar meter	JTR05	1	Solar radiation	0 ~ 2000 W/m^2	±2%
Data logger	JTNT	1	Temperature	−50 ~ 120 °C	±0.5 °C
Thermocouple	/	2	Temperature	−200 ~ 260 °C	±2%

Appendix B. Building model details

B.1 Building model

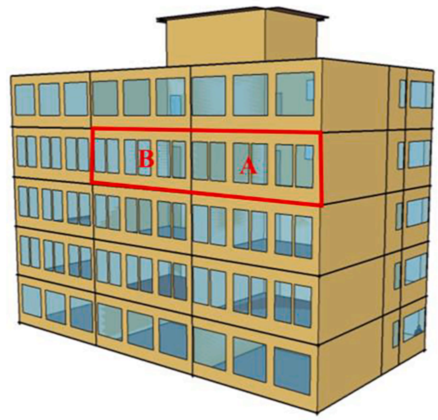

Fig. B1. EnegryPlus building model.

B.2 Detailed data of building envelopes

The thermal properties of building envelopes and the thermophysical properties of the main materials are shown in Table B.1 and Table B.2.
Table B1. Thermal properties of building envelopes.

Building envelope	Thickness and material of each layer from outside to inside	Thermal parameters
Exterior wall	Facing brick 0.01 m/Cement mortar 0.02 m/Expanded pearlite 0.02 m/Porous shale brick 0.2 m/Lime mortar 0.02 m	*U*-value = 0.95 W/(m^2·K)
Interior wall	Gypsum mortar 0.02 m/Cement mortar 0.02 m/ /Porous shale brick 0.2 m/Cement mortar 0.02 cm/ Gypsum mortar 0.02 m	*U*-value = 2.45 W/(m^2·K)
Floor and Ceiling	Cement mortar 0.02 m/ Reinforced concrete slab 0.12 m/ Slab of glass wool 0.04 m/Cement mortar 0.02 m	*U*-value = 1.09 W/(m^2·K)
Window	Double glazing (6 + 12A + 6)	*U*-value = 3.00 W/(m^2·K) *SHGC* = 0.49

Table B2. Thermophysical properties of the massive material layers.

Materials	Thermal conductivity W/(m·K)	Specific heat kJ/(kg·K)	Density kg/m^3
Facing brick	2.03	0.92	2400
Cement mortar	0.93	1.05	1800
Expanded pearlite	0.06	0.67	120
Porous shale brick	0.58	1.05	1400
Lime mortar	0.87	1.05	1700
Gypsum mortar	0.19	1.05	500
Slab of glass wool	0.04	1.22	40
Reinforced concrete	1.74	0.92	2500

Appendix C. Validation

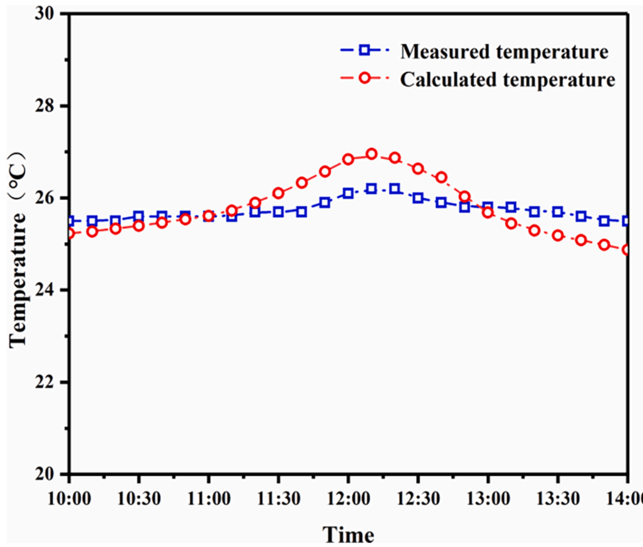

Fig. C1. Comparison of measured values to calculated values.

Appendix D. The ambient weather condition

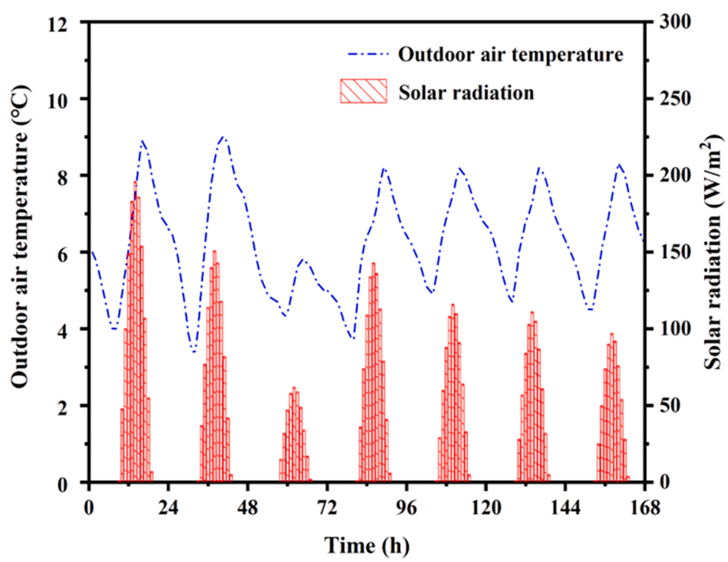

Fig. D1. Ambient weather condition variation of the selected week.

Appendix E. Equations

$$Q_{ew} = q_{ew}F_{ew} = h_{ew}F_{ew}(T_{in} - T_{out}) \tag{E.1}$$

$$Q_{iw} = q_{iw}F_{iw} = h_{iw}F_{iw}(T_{in} - T_{ad}) \tag{E.2}$$

$$-\lambda\frac{\partial T}{\partial x} = h_{c,iw}\left(T_{in} - T_{iw,i}\right) \tag{E.3}$$

$$-\lambda\frac{\partial T}{\partial x} = h_{c,iw}\left(T_{iw,e} - T_{ad}\right) \tag{E.4}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{v=1}^{N}(M_v - C_v)^2} \tag{E.5}$$

$$CV = \frac{RMSE}{M_{ave}} \times 100\% \quad (E.6)$$

$$T_o = \frac{h_c T_{in} + h_r T_r}{h_c + h_r} \quad (E.7)$$

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