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Quantitative study on adjacent room heat transfer: Heating load and influencing factors

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ABSTRACT

Household heat metering plays a significant role in building energy efficiency and has become an inevitable trend in northern China. Precise supplying aims to ensure indoor thermal comfort while realizing energy saving with occupants' behavior. Due to the different indoor temperature, interior envelope material and occupancy rate of each room, the Adjacent Room Heat Transfer (ARHT) will greatly affect the fair heating charging under household heating metering. This study takes an office building in Beijing as the object to measure the indoor and outdoor temperature in winter. EnergyPlus is adopted to establish a building model and calculate the heating load. The time-dependent temperature of the simulated room is compared with the hourly measured temperature to validate model accuracy. The validated model is further adopted to calculate the ratio of ARHT under three different conditions. The result indicates all these three factors have important impacts on ARHT. The ratio of ARHT to the real total heating load could stay around 40% and even reach up to 70%. The result shows an unexpected influence of ARHT, while it provides a case study for fair allocation of heat charges, which is vital to the implementation of household heat metering in China.

1. Introduction

1.1. Heating energy efficiency retrofit

The issue of energy-saving for heating has attracted growing attention in the highly industrialized society under the background of global warming and the prevention of air pollution. Reducing consumption of fossil fuels and improving heating energy efficiency is a great challenge for countries around the world (Li, Yang, He, & Zhao, 2014). This condition, numerous scientific methods for heating energy efficiency retrofit are conducted in many countries (Shahrokni, Levihn, & Brandt, 2014).

Europe has taken many measures to deal with the serious problem of energy. District heating is widely used in heating buildings in European (Abdurafikov et al., 2017), which is developing towards the next future generation (Paiho & Reda, 2016). Zajacs and Borodiņecs (2019) proposed criteria for the assessment of district heating systems efficiency and found that heat losses would be reduced by approximately 35%. Compared with primary energy savings, energy savings values of district heating with cogeneration are considerably about 65% lower in Italy (Badami, Gerboni, & Portoraro, 2017).

Heating consumption in China is much larger than that in leading countries, which consumes a large proportion of the total primary energy use (Zhou et al., 2018), and more measures should be adopted in China. Lv and Wu (2009) examined the necessity for heating energy efficiency retrofit with PESTEL factors and recommended that retrofit technologies should be adapted to various climatic districts in China (Lv, Wu, & Sun, 2009). Zhou and Lin (2007) introduced an energy efficiency retrofit method that a heat meter device installed to specifically achieve heating renovation. Zhao, Wu, and Zhu, (2009) built a mathematical model to evaluate heat metering, and the retrofit project which reached the total target was evaluated as the grade of AA. Zhao, Zhu, and Wu, (2009) described a technology line suitable for heat metering and energy efficiency retrofit of existing residential buildings in northern heating areas of China. With this experience, household heat metering has been considered a significant measurement for energy efficiency and has attracted increasing worldwide attention (Olmos, Ruester, Liong, & Glachant, 2011).

1.2. Household heat metering

Household heat metering began in the 1920s and rapidly developed in the 1970s. Nowadays, the technology of household heat metering heating system design, meter selection, and heat fee allocation have

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Nomenclature

y_i	building hourly measured temperature value
$\hat{y}_i$	building hourly simulated temperature value
$\bar{y}$	building average temperature
N	the number of samples.
K	the heat transfer coefficient of the envelope structure
F	the area of envelope
t_n	indoor temperature (research room temperature)
t_w	outdoor temperature (adjacent room temperature)
α	the correction factor
Q_{EHL}	the envelope heating load
Q_{HL}	the actual heating load
Q_{ARHT}	the amount of ARHT
Q_{ARHL}	the amount of adjacent room heat loss
Q_{ARHG}	the amount of adjacent room heat gain
R_{ARHT}	the ratio of ARHT

been particularly mature (Tu, Xu, Wang, & Fang, 2000). According to EU directive 2012/27/EU, independent heat metering devices must be installed to measure heat consumption and hot water consumption (European Parliament, Directive 2012/27/EU, 2012) to promote the European heating metering work (Sarah, 2012). The most common method for household heat metering abroad is to install the heat metering device before building inlet. With the development of high technology and country's consciousness of energy consumption (Kang, Cho, & Kim, 2012), heat metering of China began in the 1990s by imitating Europe countries and got popularized around the country in the 21 st century. The The Energy Conservation Law of the People's Republic of China (2016) emphasizes heat meters control devices need to be installed to realize heat metering, and the heat metering system transformation should be carried out with the renovation of building energy conservation (2010). Yuan and Xu (2015) established and validated a sustainable evaluation model to evaluate the sustainability of heat metering technology in China. Yuan, Xu, and Liu, (2016) reviewed the heat metering development situation and adopted an effective model to further promote the heating policy. Compared with the traditional method of determining housing area, household heat metering aims to realize energy saving from users' behavior (Li, 2009) while ensuring the indoor thermal comfort (Yang, Yan, & Lam, 2014) simultaneously.

However, a new problem will arise with the implementation of household heat metering. Due to the different indoor temperature, interior envelope materials and occupancy rate of each room, the Adjacent Room Heat Transfer (ARHT) will occur through the interior wall and the floor (Tu, Li, & Gao, 2002). Under this condition, the real heating consumption may be much larger than the expected heating load and users' requirements, which will greatly affect the fairness of heating charges (Liu, Fu, & Jiang, 2012).

1.3. Heating system, heat fee, and ARHT

In recent years, many scholars research on household heat metering in three aspects: the heating system of household metering, the collection of heat fee and the calculation of ARHT.

Zhou, Zhang, Tian, and Li, (2004) analyzed the adjustment method applicable to the household heat metering system and derived the variable flow calculation formula. Jiang (2006) proposed to install mixed water devices in hot inlet of the building and implement the "large flow, small temperature difference and low water temperature" heating mode to reduce local overheating. Although these works are benefit for heating energy saving, the heat meter is still not accurate enough for heating charges.

Refer to the fair heating fee, Liu, Fu, Jiang, and Guo, (2011) proposed to install an on/off valve on the branch for each household and regulate water flow according to room temperature. The accumulated on-time of each household is measured, and the total heating fee of a building is determined according to the cumulative on-time as well as floor space of each household. A cost-efficient method was developed for reallocation of heating costs based on heat transfers between the adjacent apartments (Siggelsten, 2014). However, these fee collection methods do not consider the accurate ARHT and the applicability remains to be investigated.

Tian and Wang (2003) established a mathematical model to calculate ARHT under different temperatures. Zhao, Dong, Feng, and Zhang, (2002) proposed a housing type correction model for heating metering charging. Fang (2002) studied the heating requirements of household heat metering on the adjacent interior walls and floors to correct the minimum economic thermal resistance of the wall heat transfer coefficient. Zhang and Huang, (2000) and Cai (2001) studied the effects of building envelope, occupancy rate and area on the ARHT. These above studies calculated ARHT under different circumstances, but the real

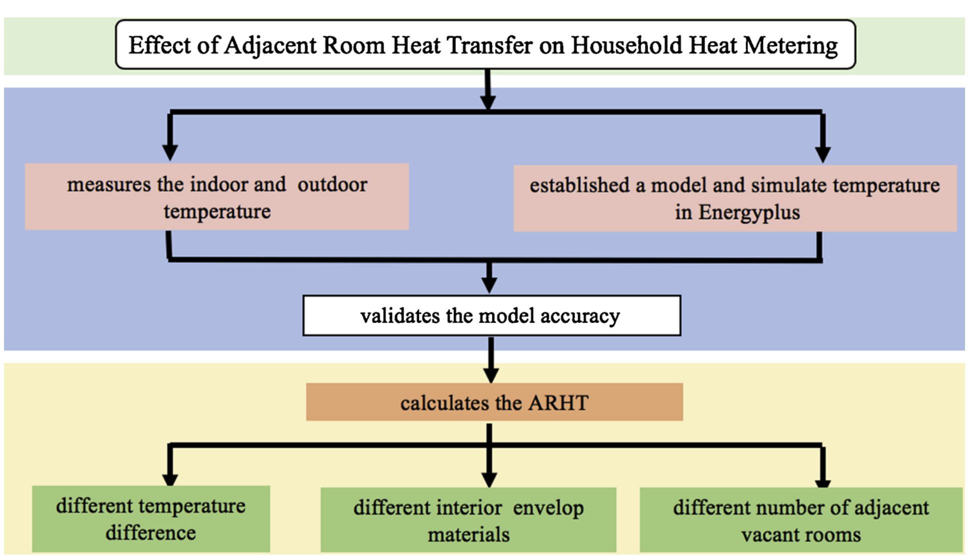

Fig. 1. Rationale and content of ARHT.

weight of ARHT in room's total heating load needs further clarification. Mathematical modeling (Satyavada & Baldi, 2016) could help analyze the influencing factors of the ARHT problem.

1.4. The purpose of this study

This study aims to calculate the heating load generated by the building envelope on each side of the target room and indicate the portion of the ARHT under various conditions. Energy simulation is adopted to calculate the heating load and heat transfer proportion with the validation of on-site measurement, and the result shows an unexpected amount of ARHT. This research provides a case study for future fair allocation of heat charges, which is vital to the implementation of household heat metering in China.

2. Methodology

This research takes a Beijing office building as an object and investigates the ARHT with both simulation and experiment methods. The research process is shown in Fig. 1 and it can be schematized into the following steps:

1) measures the hourly temperature of each room and corridor in the office building and outdoor temperature;
2) establishes a building physical model in EnergyPlus based on the real building plan and envelope materials, and outputs time-dependent temperature of the target room;
3) compares simulated hourly temperature of the targeted room with the measured result to validate the model accuracy;
4) calculates the heating load of the targeted room generated by the envelope structure on each side and the ratio of ARHT to the total heating load;
5) reveals the ratio of ARHT to the total heating load under various conditions.

2.1. Building overview and experiment

The office building has 3 storeys and 34 rooms with a total construction area of 476 m^2. There are three types of rooms with 1, 2 or 3 windows and the lengths are 3.3 m, 6.6 m and 9.9 m respectively. The room wide and height are 5.7 m and 3.6 m. The heating system is a double-tube lower-floor heating system, as shown in Fig. 2.

This study imitates the process of closing the radiator valve under the household heat metering method by opening the windows in some rooms due to the limited heating system form. The process of opening the windows will cause a temperature difference between measured room and adjacent rooms so that the cases for ARHT could be easily set and studied.

The on-site measurement was carried out in the buildings from January 22nd to February 5th, 2018. The daily experimental time was from 9 a.m. to 5 pm in all south-facing rooms, and the distribution map of experimental rooms is shown in Fig. 3. Those rooms colored in blue are the window-opening rooms. The Testo-174H thermometer (with temperature range: $-20\tilde{} + 70$ °C; accuracy: ± 0.5 °C) is adopted to measure the temperature of each room.

2.2. Simulate set-up

This study adopts building energy simulation software EnergyPlus for building modeling and heating load calculation. In order to guarantee the model for further evaluating the ratio of ARHT under different conditions, this model is thereafter validated.

2.2.1. Building modeling

The building model is established according to the real building plan and envelope materials. The target building model is shown in Fig. 4 and building envelope materials and the heat transfer coefficients are shown in Table 1. Each room is an independent heating calculation area.

2.2.2. Model validation

Before the calculation, a model should be validated to confirm all building materials are accurate because the hourly heating load cannot be directly measured. With the validated model, the actual temperatures are used to calculate the amount of heat transfer. Room 13 was selected as a validated room with an indoor radiator of 700 W, window of 3.78 m^2 and the heating area of 18.81 m^2. The information of adjacent rooms is shown in Table 2.

The field test was conducted from January 22nd to February 5th, however, the outdoor climate changes much in winter especially the solar radiation. Solar radiation intensity has a great influence on outdoor parameters and indoor heat gains. To make the result more reasonable, three continuous sunny days are selected for simulation. The simulation date started from January 30th to February 1st, 2018, and the measured hourly temperatures, including the validated room, adjacent rooms and outdoor, are set as boundary conditions of the simulated room. According to the specification from ASHRAE GUIDELINE 14–2014 (ASHRAE, 2014), the error analysis adopts a coefficient of variation of the root mean square error - CVRMSE (Eq. 1) and a normalized mean bias error - NMBE (Eq. 2) to compare the difference between calculated and measured hourly temperatures of room 13. The established model could be used for subsequent simulation studies if the CVRMSE is controlled within 15% and NMBE is controlled within 5%. With the validated model, the ratio of ARHT under different conditions can be calculated.

$$\text{CVRMSE}= \frac{\sqrt{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2/(\text{ n}-1)}}{\bar{y}} \times 100 \tag{1}$$

Fig. 2. Exterior view of the office building.

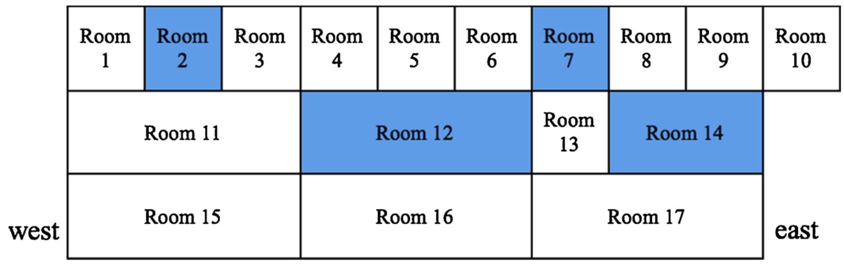

Fig. 3. Distribution map of experimental rooms.

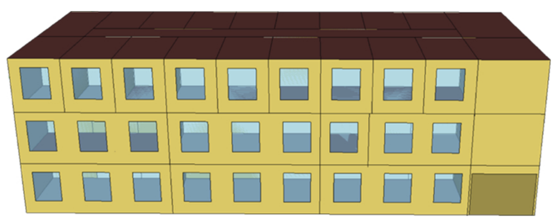

Fig. 4. Physical model of the target building.

$$\text{NMBE} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{(n-1)\times\bar{y}} \times 100 \quad (2)$$

2.3. Cases set-up

The mathematical modeling (Baldi, Yuan, Endel, & Holub, 2016) is adopted to analyze the influencing factors of the ARHT problem in further study. According to "Code for design of heating, ventilation and air conditioning for civil buildings" (Xu et al., 2015) in China. The heating load generated by the envelope (Eq. 3) and the ratio of ARHT (Eq. 4) are as follows:

$$Q_{EHL} = KF(t_n - t_w)\alpha \quad (3)$$

$$\text{R}_{\text{ARHT}} = \frac{Q_{ARHT}}{Q_{HL}} = \frac{Q_{ARHL} - Q_{ARHG}}{Q_{ARHL} - Q_{ARHG} + Q_{EHL}} \quad (4)$$

The amount of ARHT and the heating load is related to the temperature difference, the heat transfer coefficient, and the contact area between adjacent rooms (the number of vacant rooms). Therefore, the validated model will be further used to calculate the heating load portions under the following three types of conditions, and the target room temperature is set as the standard winter heating indoor design temperature, 20 °C (Lu, 1993):

(1) with the stable occupancy rate of the adjacent room, varies the temperature of the adjacent room to obtain the several temperature difference (3 °C, 6 °C, 9 °C, 12 °C and 15 °C);
(2) adopts different interior envelope structure between the target room and the adjacent rooms with different heat transfer coefficient;
(3) changes occupancy rate of the adjacent room (the number of vacant rooms around the target room) with a stable temperature difference between the target room.

3. Results and discussions

3.1. Model validation and composition of heating load

The thermal environment of the target room was calculated with EnergyPlus with the thermal boundary of all adjacent rooms, corridor and outdoor. The simulated temperature and measured temperature of the target room are shown in Fig. 5.

As shown in Fig. 5, the difference between hourly measured temperature and simulated temperature of room 13 is within 0.5 ℃ and their trend seems the same. With solar radiation increases, the room temperature raises from 6:00 am and reaches a peak at 18 ℃ at around 13:00 pm. With the sun going down, solar radiation decreases, and the indoor temperature quickly goes down to 14 ℃ and continues to the lowest level at 6:00 am. The CVRMSE error between measured and simulated temperature is calculated as 5.16% and NMBE error is calculated as 1.92% based on the ASHRAE GUIDELINE, which is less than the error of 15% and 5% of the specification. Therefore, building modeling is proved to be correct and could be applied for subsequent research.

With this validated model, the composition of target room's heating load is estimated. The heating load of the target room is assumed to include the basic heat loss from an envelope and adjacent room in six possible faces. The heat sources include solar radiation and radiator near the window. Each part of the target room's heating load is calculated and shown in Fig. 6.

As shown in Fig. 6, the total heating load reaches its peak at 13:00 pm every day and stays at the bottom from 21:00 pm to 6:00 am. Except for exterior wall, heat loss happens in the other four directions (heat transfer in the adjacent rooms) and takes up a great amount of heating load. The larger temperature difference between the target and adjacent room is, the more heat will transfer through the interior wall. To better reveal the heat loss amount, the hourly heating load on January 30$^{\text{th}}$ is adopted for cumulative analysis, and Table 3 presents the ratio of each part.

As shown in Table 3, the heat gain in 24 h is 25.32 kW h (a = b + c + d), and 5.48 kW h is generated by the ARHT, which accounts for 21.63 % (b/a). The heat loss of the room in 24 h is 25.55 kW h (e = f + g), among which 18.11 kW h is generated by ARHT. This ratio reaches high to 70.88% (g/e), which indicates ARHT is indeed a serious problem in heating metering. The net ratio of ARHT to total heating load is 62.93% (Eq. 5).

Table 1
Envelope materials and heat transfer coefficients.

Envelope	The building envelope material	Heat transfer coefficient W/(m2*K)
Exterior wall	External painting (20mm) + aerated concrete (200mm) + inner painting (20mm)	0.86
Interior wall	Concrete partition wall (150mm)	2.92
Floor	Terrazzo precast block (50mm) + mortar leveling layer (30mm) + reinforced concrete floor (100mm) + stucco (20mm)	2.72
Windows	Plastic steel hollow glass window (air layer 60mm) without internal shading	3.23
Ground	Reinforced concrete (200mm) + polyurethane extruded board (100mm)	0.47

Table 2
The information on adjacent rooms around room 13.

Adjacent room	Upstairs room 7	Downstairs room 17	West room 12	East room 14	Corridor (north)	Outside (south)
Adjacent area (m^2)	18.81	18.81	20.52	20.52	11.88	11.88

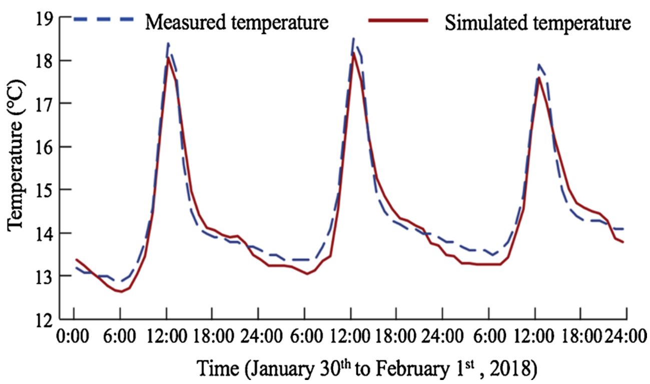

Fig. 5. Comparison of simulated and measured temperatures.

$$R_{ARHT} = \frac{Q_{ARHT}}{Q_{HL}} = \frac{Q_{ARHL} - Q_{ARHG}}{Q_{ARHL} - Q_{ARHG} + Q_{EHL}} = \frac{18.11 - 5.48}{18.11 - 5.48 + 7.44} = 62.93\% \quad (5)$$

3.2. The influence of temperature difference on heating load

The validated model is further used to calculate the ARHT to the target room and explain the influence of temperature difference on heating load. The heat transfer is assumed to occur from the target room to one adjacent room, and the temperature difference is set to 0, 3 °C, 6 °C, 9 °C, 12 °C and 15 °C respectively. Under these cases, the heating load and the ratio of ARHT are compared with heating load without the ARHT and the result is shown in Fig. 7.

It can be seen from Fig. 7 that heating load without the ARHT of the target room is 560.02 W. As the temperature difference increases, the heating load of the target room also increases significantly. With the temperature difference rises to 3 °C, the heating load will increase by around 15%, no matter in which direction. While when the temperature difference rises to 6 °C, the heating load of the target room goes up to around 30%. The ratio of ARHT even reaches to 50% if the temperature difference rises to 15 °C.

3.3. The influence of heat transfer coefficient on heating load

Building material is also a key factor for the heating load, and the heat transfer coefficient of the interior wall becomes an influencing factor for ARHT. The envelope materials of simulation - both floor and wall- were selected from the references of Practical heating and air conditioning design manual, China (Lu, 1993). Six different interior walls and floors are chosen and heat transfer coefficients are shown in Table 4. The temperature differences between two sides of interior wall and two sides of floor are both set to be stable at 10°C. The reference heat transfer coefficient of interior wall is 2.92 W/(m2*K), and energy-saving rates under different interior wall materials are calculated as shown in Fig. 8a. While, the reference heat transfer coefficient of floor is 2.72 W/(m2*K), and energy-saving rates under different floor materials are calculated as shown in Fig. 8b.

Table 3
Ratios of heat loss and the heat gain.

Heat items		Composition	Quantity of heat (kWh)	The ratio of heat (%)
The heat gain	a	The total heat gain	25.32	100
	b	Heat gain through the adjacent room	5.48	21.63
	c	Solar radiation heat gain	3.04	12.02
	d	radiator heat gain	16.80	66.35
The heat loss	e	The total heat loss	25.55	100
	f	Envelope heat loss	7.44	29.12
	g	Heat loss through the adjacent room	18.11	70.88

The reference heating load of the target room is still 560.02 W, and it can be seen from the figure that with heat transfer coefficient decreasing, the energy-saving rate increases. In Fig. 8a, with the heat transfer coefficient in A1 case, the ARHT on the same floor is 778.94 W, which takes up 58.18% of the total room heating load. While if a high-performance interior wall is selected as A6 case, the ARHT will drop to 469.50 W, which takes up 45.60% of the room heating load. The energy could be saved for 23.11% under this condition.

For floor material in Fig. 8b, with the heat transfer coefficient in B1 case, the heat transfer to other floors' adjacent rooms is 690.70 W, which takes up 55.22% of the total room heating load. While if a high-performance interior wall is selected as B6 case, the ARHT will drop to 304.72 W, which only takes up 35.24% of the room heating load. The energy could be saved for 30.86% under this condition.

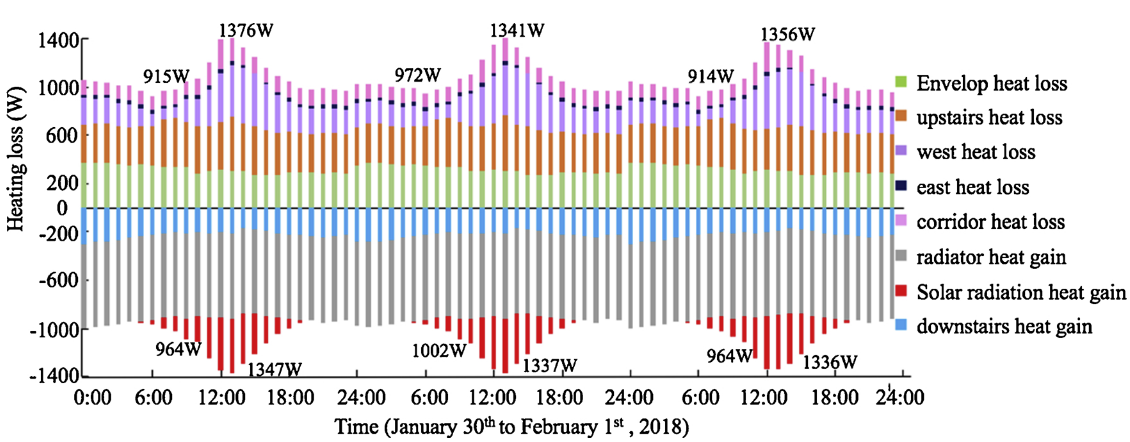

Fig. 6. The composition of heating load.

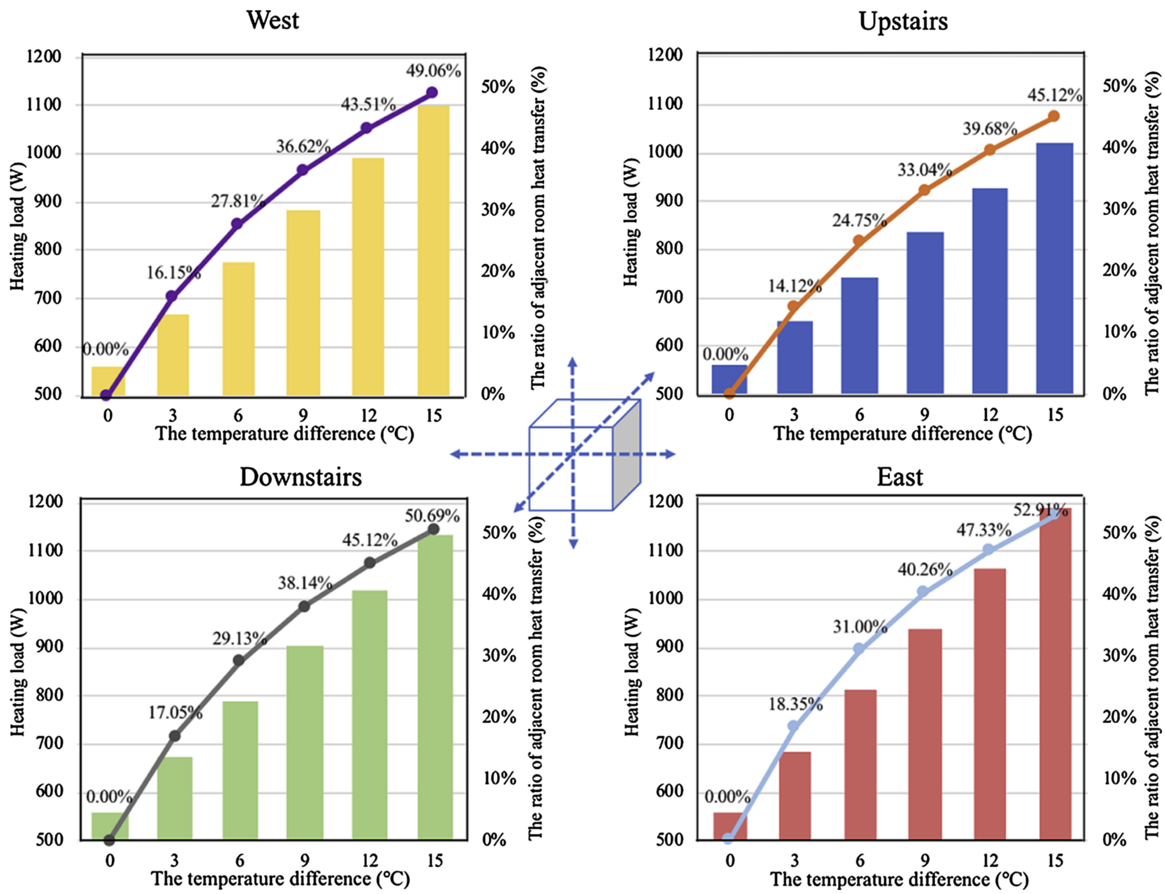

Fig. 7. Ratios of ARHT under different temperature difference in four directions.

3.4. The influence of the number of vacant rooms on heating load

Except for the outdoor environment and corridor, four adjacent rooms around the target rooms are the possible heat loss source. The number of vacant rooms is decided by the occupancy rate of a single building. A typical building model is firstly selected as a research object to study the relationship between occupancy rate and the number of vacant rooms.

A 5-Unit/Block building is considered as a two-dimensional model with 10 storeys, and each story has 2 households. With this total 100 households, the occupancy rate is entered with computer programming and the maximum possible number of vacant rooms can be output. For example, the occupancy rate is set to be 30%, and the number of vacant rooms around each room for these 30 households are calculated with 30 results. This result gets a stable number of maximum possible vacant rooms by repeating several times. The relation between the occupancy rate and the number of vacant rooms is given in Table 5.

With this computer programming, the relation between occupancy rate and number of vacant rooms of residential buildings with different building type could be easily confirmed. With the result from Table 5, ARHT with different occupancy rate can be obtained with different number of vacant rooms from 0 to 4. The temperature difference between target room and vacant room is set at 10 °C, and heating load and its possible range under different conditions are shown in Fig. 9.

As seen in Fig. 9, the heating load increases dramatically with the increasing of the adjacent vacant room number. With only one adjacent vacant room, the ARHT for the target room will range from 306.98 W to 419.43 W, which takes up 35.41% to 42.82% of the total heating load. While with two or three adjacent vacant rooms, the ratios of ARHT for the target room will be 54.34%–58.92% and 65.22%–67.49%. When

Table 4
Envelope materials and heat transfer coefficients.

Envelop	The envelope material		Heat transfer coefficient W/(m^2*K)
Interior wall	A1	Concrete partition (150mm)	2.92
	A2	Concrete partition (180mm)	2.70
	A3	Concrete partition (200mm)	2.59
	A4	Brick wall (120mm)	2.37
	A5	Brick wall (180mm)	2.01
	A6	Brick wall (240mm)	1.76
Floor	B1	Layer (30mm) + Reinforced concrete floor (100mm) + Stucco (20mm)	2.72
	B2	Surface layer (25mm) + Reinforced concrete floor (80mm) + Wood board (25mm)	2.21
	B3	Surface layer (25mm) + Reinforced concrete floor (400mm) + Steel mesh plastering (25mm)	1.82
	B4	Surface layer (25mm) + Reinforced concrete floor (80mm) + Wood board (50mm)	1.65
	B5	Surface layer (25mm) + Reinforced concrete floor (80mm) + Stucco (20mm) + Wool carpet	1.44
	B6	Terrazzo precast block (50mm) + Mortar Leveling Surface layer (25mm) + Reinforced concrete floor (80mm) + Styrofoam (25mm)	1.20

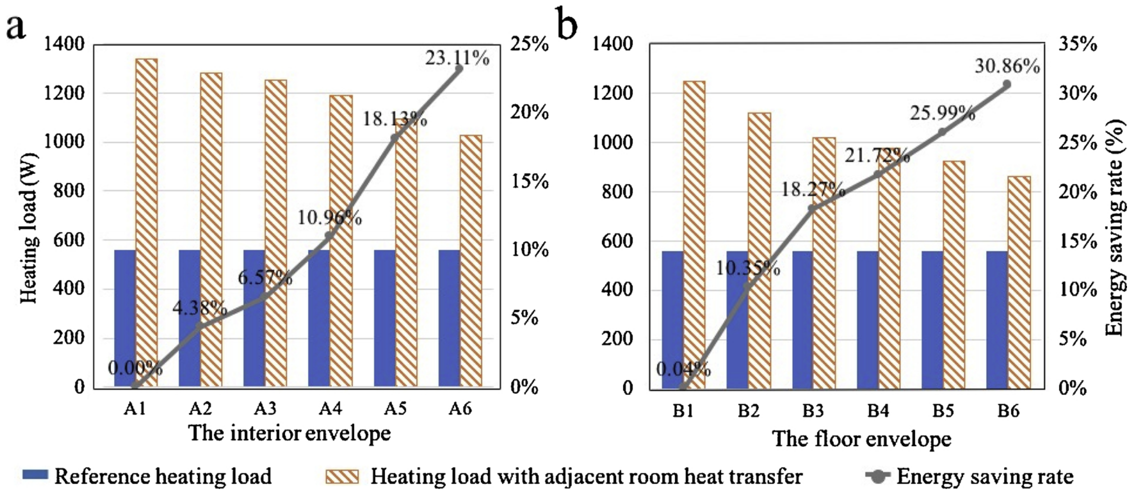

Fig. 8. Energy-saving rates: a) with different interior wall materials; b) with different floor materials.

Table 5
The relationship between the occupancy rate and number of vacant rooms.

Maximum possible number of vacant rooms	4	3	2	1	0
Occupancy rate	0-3%	3%-30%	31%-58%	59%-86%	87%-100%

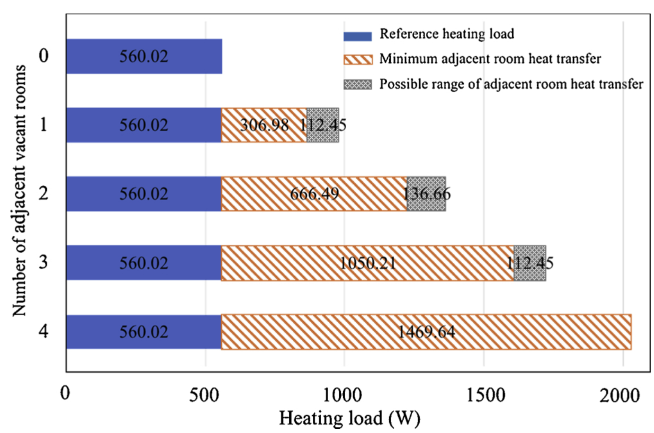

Fig. 9. Heating load of a target room with different number of adjacent vacant rooms.

the occupancy rate drops below 3%, nearly all the households will have heat loss in all four directions, and the ratio of ARHT could reach to 72.41%. This result echoes the findings in Section 3.1, which indicates the ARHT maybe twice more than the basic heating load of an ordinary room.

3.5. Questions proposed and future study

The ratios of ARHT in various conditions are calculated based on a validated model, and the corresponding results are found based on the real office building. However, the heat metering heating mainly occurs in residential building, and more work will be done in residential building to reveal the weight of ARHT for real household condition in the future.

From this study, ARHT is studied in three-dimensional space, namely through upstairs, downstairs, outdoor, corridor, left and right rooms. However, the heating fee in China is still charged by the area. This conflict may push the heat fee policy to be further improved, and more economic methods should be introduced into this problem for fair heating charging as heat has already become a valuable goods.

4. Conclusion

In this study, ARHT is investigated within a real building and the modeling is validated based on the measured data. The results indicate three factors, namely temperature difference between target and adjacent rooms, heat transfer coefficient of interior envelope structure and the number of vacant rooms around target room, all have significant impacts on the heat transfer capacity of adjacent room and specific results are concluded as follows:

In a real condition of a measured room, ARHT in one day accounts for near 70% of the total heating load.

The heat transfer capacity of adjacent rooms increases significantly with the increase of the temperature difference between adjacent rooms. With heat transfer only occurs to one adjacent room, ARHT could take up around 50% of the total heating load with the temperature difference of 15 degrees.

The heat transfer capacity of adjacent rooms decreases with decreasing heat transfer coefficient of the interior wall and floor structure. The heating load could be saved around 30% if high-performance material could be utilized in interior wall and floor structures.

The heat transfer capacity of adjacent rooms increases dramatically with the increasing of vacant room numbers. With a rather low occupancy rate, the heat loss will possibly happen in all four directions and the ratio of ARHT could reach to 72.41%, which indicates the ARHT is twice of the basic heating load of an ordinary room.

The result of this research shows an unexpected amount of ARHT, as it could take up 70% of the total heating load. To remove the barrier of the uncertainty of ARHT and push the heat fee policy towards fair heat metering, this quantitative research provides a case study and basic data for further fair allocation of heat charges, which is vital to the implementation of household heat metering in China. The economic model or game theory could be thereafter adopted to help solve this quantitative problem in the future.

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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