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Publication Date
2018-02-01

DOI
10.1016/j.jclepro.2017.10.237

Peer reviewed

Journal of Cleaner Production 174 (2018) 413–423

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Heating energy saving potential from building envelope design and operation optimization in residential buildings: A case study in northern China

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A R T I C L E I N F O

*Article history:*
Received 10 July 2017
Received in revised form
28 August 2017
Accepted 20 October 2017
Available online 30 October 2017

*Keywords:*
Heating energy consumption
Energy saving potential
Building envelope design
Operation optimization

A B S T R A C T

Residential building heating plays a critical role in building energy conservation in China as it consumes a large proportion of the total primary energy use. Heating energy consumption in China is much larger than that in leading countries. This study investigated the energy saving potential from the building envelope design and actual operation optimization. Results showed that the heating energy consumption target specified in latest forth-step energy efficiency standard in Tianjin still leads to 30.9% higher energy consumption than German building energy efficiency standard EnEv'2009 and 49.7% higher than Passivhaus standard used in Germany. Via field measurement and questionnaire survey during operation, major findings are: (1) high indoor air temperature and window opening for ventilation are accountable for the high heating energy consumption during the operation; (2) radiator heating consumes less energy than radiant floor heating system; (3) temperature-type thermostatic valve and compartment automatic control mode have the best control performance; (4) ventilation device with purifying air unit helps to improve the indoor air quality in the terrible haze weather and to reduce the window opening demand of occupants; (5) heat metering and occupants' energy saving awareness should be encouraged.


## 1. Introduction

The building sector is one of the largest energy consumers and greenhouse gas emitters (Zhou et al., 2016; Zuo and Zhao, 2014; Sobhy et al., 2017). Buildings account for 30%–40% of the total primary energy consumption globally (Zuo et al., 2012; Zhao and Magoulès, 2012; Fumo and Biswas, 2015), in which residential buildings account for 70.4% (OECD, 2011; Yuan et al., 2013). In particular, heating accounts for a large percentage of the total energy consumption in residential buildings (Albatayneh et al., 2016), up to 40% in northern China (Yu et al., 2014; Zhou et al., 2015). Two-thirds of areas in China are located in cold and severe cold zones (most located in northern China) (Zhao et al., 2015), in which centralized heating is applied. By the end of 2012, building areas with centralized heating in severe cold and cold zones have reached 5.18 billion $m^2$, in which about 70% of the heating area attributes to residential buildings (Du et al., 2016). Moreover, with economic development, improving habitation environment and keeping comfortable indoor temperature during the winter are becoming a necessity for people (Lin and Lin, 2017). As a result, heating energy saving in residential buildings has become a key factor to analyze the building energy saving potential in China.

As a critical factor to the heating energy consumption, building envelope could contribute to the energy saving up to 22% (Stefanović and Gordić, 2016). As the building envelope is fully determined by designers according to the design standards, it is worth to investigate the relevant requirements specified in different design standards. To reduce heating energy consumption

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https://doi.org/10.1016/j.jclepro.2017.10.237

in new residential buildings, China has enacted a series of efficiency measures, starting in the 1980s. These include the 1986 “Energy-efficiency design code for heating in residential buildings” (MOHURD, 1986), which is referred to as the ‘first-step’ energy-efficiency target. This measure aimed to reduce heating energy consumption by 30% compared to levels in the early 1980s. In 1995, the target was increased to 50% less heating energy than had been consumed in the early 1980s, which is known as the ‘second-step’ energy-efficiency target (MOHURD, 1995). In 2010, the “Design standard for energy efficiency of residential buildings in severe cold and cold zones” was amended to require that heating energy consumption is reduced by 65% relative to the consumption during the early 1980s (MOHURD, 2010). This is also referred as the ‘third-step’ energy-efficiency target. Currently, most regions in China have met the second-step standard. Beijing and Tianjin met the third-step standard in 2004 and initiated an even more stringent ‘fourth-step’ energy-conservation standard in 2013 (TJURCTC, 2013; BJMOHURD, 2012). The fourth-step target requires that heating energy consumption reduce by 75% relative to consumption in the early 1980s.

Operation optimization is another key factor to reduce the heating energy consumption. In terms of this, most of existing studies focused on heating systems and its improvement potential. For instance, Martinopoulos et al. (2016) compared different heating systems via life cycle costing approach; Andrić et al. (2017) studied the environmental performance of district heating system by emergy approach; Lund et al. (2016) investigated the socioeconomic potential for introducing large-scale heat pumps in district heating system. Life cycle assessment has become a popular approach to assess the sustainability performance of buildings (Zuo et al., 2017), Abusoglu and Sedeeq (2013) combined life cycle assessment and exergy analysis together to compare various residential heating systems. Balaman and Selim (2016) proposed a fuzzy Mixed Integer Linear Programming model to optimize the district heating system. The energy consumption, emission and cost of heating systems could be investigated by empirical comparison (Papadopoulos et al., 2008) and simulation (Obyn and Van Moeseke, 2014). Similarly, demand-based model-predictive-control approach provides an effective tool to optimize the heating system operation (Bianchini et al., 2016). However, very few studies investigated the heating performance at the user side. However, there are lack of site measurement and investigation, which is very important for energy saving studies in residential buildings (Zhen et al., 2016).

The occupant behavior is also crucial to the heating energy consumption which mainly contains indoor ventilation methods and indoor temperature control. Different people have distinct sociocultural demographics (age, sex, education and wealth/income), and show differences in their physical/mental health and amounts of free time, which affect their heat-using behaviors (Wood and Newborough, 2003). A study on the energy use for space and water heating indicated that occupant behaviors significantly influence the energy consumption (Santin et al., 2009). Occupants' consciousness has significant influence on occupant behaviors, which can be improved by energy-saving education (Lam, 1998).

Despite more stringent energy efficiency standard and higher capital investment, the outcomes are far from satisfactory. Because the current design standard in China still falls behind that in developed countries, there is still great energy saving potential from the building envelope design. As shown in Fig. 1, a study of 1726 apartments in Tianjin, a critical city in northern China, showed that the heating energy consumption varies significantly in buildings even with the same function, the same location and the same energy efficiency standard (Ling et al., 2014). The heating energy consumption showed a normal distribution that nearly 70% of the users have a heating energy consumption ranging from 80 kWh/m$^2$ to 140 kWh/m$^2$ per unit area during the heating season; and 15% users have extremely high or low heating energy consumption. However, the effectiveness of the current heating system is unknown due to lack of data on heating operations and impacts of occupant behavior. It is worth to investigate critical factors that resulted in such significant differences of heating energy consumption. Therefore, this study aimed to investigate the energy saving potential from the building envelope design, to analyze the impacts of occupant behavior on heating energy consumption, and to propose ways to optimize the heating operation.

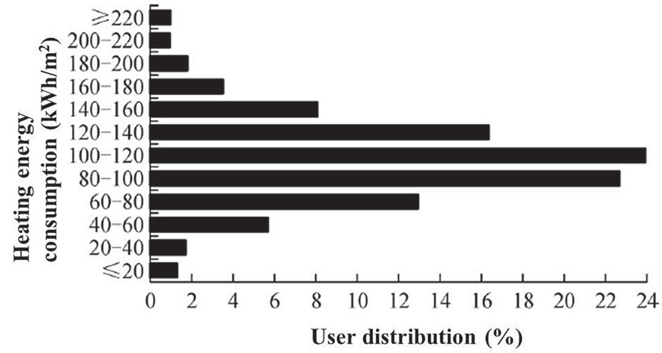


**Fig. 1.** Distribution of heating operation energy consumption (Ling et al., 2014).

The structure of this paper is as follows. First, the method section explains case buildings, data measurement and the questionnaire used in this study. Then, results section describes the indoor temperature, heating energy consumption and occupant behaviors. This is followed by a discussion for the energy saving potential of building envelopes, implications for a better understanding of heating energy consumption and its relationships with heating operation and occupant behaviors. All findings and implications are summarized in conclusions section.

## 2. Method

This study presented a comprehensive analysis on heating energy saving potential in residential buildings. In this study, “energy consumption” is referred in particular to “heating energy consumption”. The method was divided into three parts. In the first part, comparison method was used to analyze the energy saving potential from building envelope design according to different design standards. The second part investigated the control performance on the user side according to field measurement data which collected from case buildings. In the last part, a questionnaire survey was conducted to analyze the impacts of occupant behavior based on their feedback.

### 2.1. Case buildings

Five residential buildings which met the third-step energy efficiency standard in Tianjin were selected as case buildings. These buildings were named as Building 1, Building 2, Building 3, Building 4 and Building 5, respectively. All case buildings are located in the same district of Tianjin. In addition, they are all north-south oriented buildings with similar configuration of their property. Therefore, case buildings are validated to be used to analyze the heating performance in this study. One typical household was selected in each building for data collection. Two case buildings were equipped with hot-water radiators, while the other three used radiant floor heating system. Table 1 provides the general information of these buildings.

Temperature type and flow-rate type thermostatic valves were used for radiator heating control. The temperature-type thermostatic valve was used in Building 1 so that occupants only need to adjust the set point to the corresponding temperature. Consequently, the valve will adjust the flow rate automatically. Similarly, flow-rate type thermostatic valve was used in Building 2. On the valve, each scale corresponds to a specific flow rate rather than temperature. On the other hand, for radiant floor heating system, three control modes were used in case buildings as shown in Fig. 2. Mode 1 controls the flow rate of the main inlet pipe by manual thermostatic valve (MTV), Mode 2 controls the flow rate of each branch pipe by MTV, and, Mode 3 controls the flow rate of each branch pipe by automatic thermostatic valve (ATV).

### 2.2. Measurement

Both indoor temperature and heating energy consumption of case buildings were measured simultaneously in this study. The data was collected from November 2011 to March 2012.

#### 2.2.1. Indoor temperature

In residential buildings, indoor temperature varies according to the locations. Generally, there is a higher temperature around the radiator. Locations where the sunlight can reach directly and those near the electric equipment have a higher temperature. On the contrary, external walls and external windows have a lower temperature. It is difficult to measure the distribution of indoor temperature and calculate the average indoor temperature accurately.

In this study, the HOBO-data logger was used as the measuring instrument for indoor temperature. Its measuring range is from −20 °C to 50 °C, and its measuring accuracy is ±0.2 °C. All data loggers were located at the same position for all buildings, and according to the relevant national standard (BJMAQTS, 2010), the measuring point was arranged at the center of the room 1.5 m above the ground. In addition, the indoor temperature was recorded every 5 min automatically. This recorded temperature was used as the mean temperature of the room. Meanwhile, the temperature variation of the room during the entire heating period was calculated by hour.

#### 2.2.2. Heating energy consumption

The heating energy consumption was calculated and accumulated by the totalizer automatically according to Eq. (1).

$$q = Gc\rho(t_{sp} - t_m) \quad (1)$$

where.

$q$ is the power input of the heating system, W;
$G$ is the flow rate, $m^3/s$;

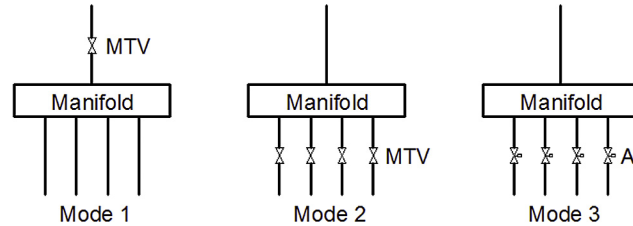


**Fig. 2.** Control modes for radiant floor heating systems.

$c$ is the specific heat of water, J/kg·°C;
$\rho$ is the density of water, $kg/m^3$;
$t_{sp}$ is the temperature of the inlet water, °C;
$t_m$ is the temperature of the outlet water, °C.

To measure the amount of water flowing into the room, ultrasonic flow meters were installed on the main outlet pipe of the heating system. In addition, temperature sensors (Pt100 platinum resistance) were used to measure the difference between inlet and outlet water temperatures. The data were as recorded every 10 s.

### 2.3. Questionnaire

Occupant behavior affects the room ventilation and air temperature (Keyvanfar et al., 2014; Lazos et al., 2014; Schakib-Ekbatan et al., 2015). This consequently has a major impact on heating energy consumption (Blight and Coley, 2013; Kamilaris et al., 2014; Ma et al., 2015). Occupants' energy consumption behavior and habit vary from household to household. A questionnaire was developed to investigate the relationship between occupant behaviors and the energy consumption in this study. The questions addressed indoor temperature control method, approaches of indoor temperature adjustment, and indoor ventilation mode (Table 2).

## 3. Results

### 3.1. Indoor temperature

Table 3 shows the average, maximum, minimum, and standard deviation values of the indoor temperature in five case buildings during the 11/10/2011 to 3/20/2012. It can be found that radiator performed much better than radiating floor heating system in terms of temperature control. The average temperature, highest temperature, lowest temperature and standard deviation of radiator heating are all lower than those of radiant floor heating system.

For radiator heating (Building 1 and 2), two control methods have similar results on indoor temperature. The average temperature difference is 1.1 °C (4.9%). For radiant floor heating system (Building 3, 4 and 5), the results vary significantly between different control modes. The range of average temperature was up to 4 °C while the range of standard deviation was up to 3.1 °C.

**Table 1**
The general information of case buildings.

| Building | Number of floors | Building area $m^2$ | Average household area $m^2$ | Shape coefficient $m^{-1}$ | Heating equipment | Control method |
|---|---|---|---|---|---|---|
| 1 | 32 | 11,117 | 87 | 0.26 | R* | Automatic temperature control |
| 2 | 18 | 6033 | 84 | 0.25 | R | Automatic flow rate control |
| 3 | 21 | 7977 | 95 | 0.26 | FR** | Mode 1 |
| 4 | 27 | 4309 | 40 | 0.24 | FR | Mode 2 |
| 5 | 17 | 2300 | 34 | 0.26 | FR | Mode 3 |

**Note:** R* represents radiator heating.
FR** represents radiant floor heating system.

**Table 2**
Questionnaire.

| | | | | |
|---|---|---|---|---|
| Heating equipment | Radiator ☐ | Radiant floor heating system ☐ | | Others ☐ |
| Temperature control | Radiator heating | Thermostatic valve | Flow-rate type ☐ | Temperature type ☐ |
| | | Control effect | Satisfied ☐ | Unsatisfied ☐ |
| | | | If you feel unsatisfied, why | ________ |
| | Radiant floor heating system | Control mode | Mode 1 ☐ | Mode 2 ☐ |
| | | | Mode 3 ☐ | |
| | | | Others ________ | |
| | | Control effect | Satisfied ☐ | Unsatisfied ☐ |
| | | | If you feel unsatisfied, why | ________ |
| Ventilation | Do you have ventilation machine | | Yes ☐ | No ☐ |
| | If you have, how do you feel about it | | Good ☐ | General ☐ |
| | Why | | ________ | |
| | If you do not have ventilation machine, do you open windows to ventilate | | Yes ☐ | No ☐ |
| | How many times do you open windows a day | | ________(times) | |
| | How long does it last each time | | ________(minutes) | |
| Temperature adjustment | When the indoor temperature is too high | | | |
| | Adjust the thermostatic valve ☐ | | Open windows ☐ | Both ☐ |

**Table 3**
The indoor temperature results of five case buildings (°C).

| Building | Average temperature | Highest temperature | Lowest temperature | Standard deviation |
|---|---|---|---|---|
| 1 | 21.5 | 24.8 | 18.4 | 1.2 |
| 2 | 22.6 | 25.8 | 18.0 | 1.4 |
| 3 | 25.8 | 30.6 | 17.9 | 3.5 |
| 4 | 23.7 | 28.8 | 18.5 | 2.2 |
| 5 | 21.8 | 28.7 | 17.7 | 0.4 |

### 3.2. Heating energy consumption

Heating energy consumption, $\Sigma Q$, and heating energy consumption per unit of floor area, $Q_a$, of case buildings obtained during the measurement period are shown in Table 4. The average $Q_a$ is 85.3 kWh/m$^2$·a. The $Q_a$ of Building 4 (91.7 kWh/m$^2$·a) is significantly larger than that of Building 1 (77.3 kWh/m$^2$·a). Radiator heating (Building 1 and 2) leads to lower heating energy consumption than radiating floor heating system (Building 3, 4 and 5). In addition, during the testing period, the average daily outdoor temperature and the average wind velocity in Tianjin was −0.2 °C and 3.1 m/s, respectively.

### 3.3. Questionnaire

To investigate the relationship between occupant behaviors and the energy consumption, 80 questionnaires were distributed and 54 were returned. Among the respondents, 23 households used radiator for heating, and 31 households used radiant floor heating system. The results are shown in Table 5.

**Table 4**
The heating energy consumption results of five case buildings.

| Building | $\Sigma Q$ kWh | $Q_a$ kWh/m$^2$·a |
|---|---|---|
| 1 | 859,344 | 77.3 |
| 2 | 506,772 | 84.0 |
| 3 | 709,155 | 88.9 |
| 4 | 395,135 | 91.7 |
| 5 | 194,580 | 84.6 |
| Average | | 85.3 |

## 4. Discussion

### 4.1. Design standards

#### 4.1.1. Tianjin and German building energy efficiency standards

China has made significant achievements in building energy conservation since implementing the building energy saving strategies 30 years ago. The requirements specified in different steps of Tianjin building energy efficiency standards had increased from 30% in 1987's first-step target to 75% in latest fourth-step target.

Germany has successfully reduced energy use in new buildings by more than 75% through the implement of building energy efficiency standards during the past three decades. Three standards have been went through in Germany, i.e. WSVO′1995, EnEV′2002 and EnEV′2009 (Galvin and Sunikka-Blank, 2013). Recently, the forth standard EnEV′2014 has been implemented in Germany. In addition, Passivhaus standard is used in those Passivhaus projects in Germany which provide comfortable indoor conditions at an extremely low heating and cooling load (Schnieders et al., 2015). U-value limits of external wall and external window specified in different standards are shown in Table 6.

#### 4.1.2. Heating energy consumption targets comparison between Tianjin and German design standards

The heating energy consumption targets specified in different

**Table 5**
Questionnaire results of occupant behaviors.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Heating equipment | Radiator | 23/54 | Radiant floor heating system | 31/54 | Others | 0 | |
| Temperature control | Radiator heating | Thermostatic valve | Flow-rate type | 13/23 | | | |
| | | | Temperature type | 10/23 | | | |
| | | Control performance | Flow-rate type | Satisfied | 11/13 | Unsatisfied | 2/13 |
| | | | Temperature type | Satisfied | 9/10 | Unsatisfied | 1/10 |
| | Radiant floor heating system | Control mode | Mode 1 | 5/31 | Mode 2 | 17/31 | |
| | | | Mode 3 | 9/31 | | | |
| | | Control performance | Mode 1 | Satisfied | 4/5 | Unsatisfied | 1/5 |
| | | | Mode 2 | Satisfied | 16/17 | Unsatisfied | 1/17 |
| | | | Mode 3 | Satisfied | 9/9 | Unsatisfied | 0/9 |
| Ventilation | No household uses machine to ventilate | | | | | | |
| | Open window | 2 times/day | 48/54 | 1 time/day | 6/54 | | |
| | | >20 minutes/time | 45/54 | <20 minutes/time | 9/54 | | |
| Temperature adjustment | When the indoor temperature is too high | | | | | | |
| | Adjust the thermostatic valve | 12/54 | Open window | 28/54 | Both | 14/54 | |

**Table 6**
U-value limits of external wall and external window (W/(m$^2$·K)) specified in different building efficiency standards.

| Standard | | External Wall | External Window | | | |
|---|---|---|---|---|---|---|
| | | | WWR≤0.2 | 0.2 < WWR≤0.3 | 0.3 < WWR≤0.4 | 0.4 < WWR≤0.5 |
| Third-Step | ≤3 Floors | 0.35 | 2.8 | 2.5 | 2.0 | 1.8 |
| | 4-8 Floors | 0.40 | 3.1 | 2.8 | 2.5 | 2.0 |
| | ≥9 Floors | 0.45 | 3.1 | 2.8 | 2.5 | 2.3 |
| Fourth-step | ≤3 Floors | 0.35 | 1.8 | 1.8 | 1.5 | 1.5 |
| | 4-8 Floors | 0.40 | 2.0 | 1.8 | 1.8 | 1.5 |
| | ≥9 Floors | 0.45 | 2.0 | 2.0 | 1.8 | 1.8 |
| WSVO′1995 | | 0.40 | 1.8 | 1.8 | 1.8 | 1.8 |
| EnEV′2002 | | 0.35 | 1.7 | | | |
| EnEV′2009 | | 0.28 | 1.3 | | | |
| Passivhaus | | 0.15 | 0.8 | | | |

standards need to be normalized due to different calculation conditions in Tianjin and German standards. First, heating degree days (HDDs) of Tianjin and German standards are different. The indoor temperature is 18 °C in Tianjin standards for calculation, while it is 20 °C in German standards. As a result, the final heating degree days in Tianjin and in Germany are 2743 d °C and 3043 d °C respectively (Long et al., 2008). Second, the definition of room area is different during the calculation. Gross area is used in Tianjin standards while net area is used in German standards. Consequently, the Germany heating energy consumption targets can be converted into counterpart targets in China according to Eq. (2). Nevertheless, due to the requirements specified in Passivhaus standard are the same for all locations and do not depend on the climate conditions, its heating energy consumption target does not need to convert. Tianjin heating energy consumption targets and normalized Germany targets under the same shape coefficient are shown in Table 7.

**Table 7**
The comparison of normalized heating energy consumption target (kWh/(m$^2$·a)) specified in Tianjin and German standards.

| Standards | Shape Coefficient | | | | Average |
|---|---|---|---|---|---|
| | 0.52 | 0.33 | 0.30 | 0.26 | |
| Third-step | 48.4 | 45.3 | 40.5 | 36.0 | 42.6 |
| Fourth-step | 34.0 | 31.7 | 28.3 | 25.2 | 29.8 |
| WSVO′1995 | 48.1 | 41.2 | 40.1 | 38.6 | 42.0 |
| EnEv'2002 | 33.7 | 28.8 | 28.1 | 27.0 | 29.4 |
| EnEv'2009 | 23.6 | 20.2 | 19.6 | 18.9 | 20.6 |
| Passivhaus | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 |

$$q_G' = \frac{HDD_C}{HDD_G} q_G \phi \qquad (2)$$

where.

$q_G'$ is normalized German heating energy consumption target, kWh/(m$^2$·a);
$q_G$ is the German heating energy consumption target, kWh/(m$^2$·a);
$HDD_C$ is the HDDs of Tianjin based on actual weather, $HDD_C = 2743$ d °C (Long et al., 2008);
$HDD_G$ is the HDDs of Germany, based on actual weather, $HDD_G = 3043$ d °C (Long et al., 2008);
$\phi$ is the ratio of net area and gross area of the room, $\phi = 0.75$.

According to Table 7, Tianjin building energy efficiency standards still lag far behind the Germany standards. It can be found that there is great energy saving potential for residential buildings if the heating energy consumption targets are set more stringent in Tianjin standards. The heating energy consumption target specified in the Tianjin third-step standard is almost equivalent to that in WSVO′1995. It is 1.4 times as much as that in EnEV′2002, 2.1 times as that in EnEV′2009, and 2.8 times as that in Passivhaus standard. Similarly, the heating energy consumption target specified in Tianjin latest fourth-step standard is almost equivalent to that in EnEV′2002, 1.4 times as much as that in EnEv'2009, and 2.0 times as that in Passivhaus standard.

In Tianjin, all new buildings must be constructed according to fourth-step standard since 2013. If the heating energy consumption target specified in fourth-step standard is improved to that in

EnEv'2009, the annual heating energy consumption will be reduced by 30.9%. Moreover, if new buildings can be constructed according to the Passivhaus standard, the annual heating energy consumption will be significantly reduced by 49.7%.

#### 4.1.3. Energy saving potential from building envelope

Building envelope design plays a critical role on the final building heating energy consumption. Building envelopes are the interface between indoor and outdoor environment which affect the indoor heat gain and heat loss in the design of sustainable buildings (Yu et al., 2013). The control of thermal performance of the building envelope is an important part of the overall scheme for heating energy saving. According to energy efficiency standard, the heat loss index of building heating, defined as $q_L$, W/m$^2$, can be calculated using Eq. (3) (BJMOHURD, 2012).

$$q_L = \frac{Q_{en} - Q_{sun} + Q_{ina}}{A} - q_{ih} \quad (3)$$

where.

$Q_{en}$ is the total heat transfer through building envelope, W, and it can be calculated via Eq. (4);
$Q_{sun}$ is the solar radiation heat gain through non-opaque parts of the building envelope, W, and it can be calculated via Eq. (5);
$Q_{ina}$ is air infiltration heat loss, W, and it can be calculated via Eq. (6);
$q_{ih}$ is building internal heat gain, W/m$^2$, and it is 3.8 W/m$^2$ specified in the standard (BJMOHURD, 2012);
$A$ is building's floor area, m$^2$.

$$Q_{en} = \sum \varepsilon_i U_i F_i \zeta_i (t_n - t_e) \quad (4)$$

where.

$\varepsilon_i$ is correction factor of average heat-transfer coefficient with regard to solar radiation heat gain;
$U_i$ is heat-transfer coefficient of the building envelope, W/m$^2$·K;
$F_i$ is building envelope area, m$^2$;
$\zeta_i$ is temperature variation correction factor;
$t_n$ is indoor temperature, and it is 18 °C specified in Tianjin standard (BJMOHURD, 2012);
$t_e$ is outside average temperature, and it is −0.2 °C in Tianjin.

$$Q_{sun} = \sum I_{suni} C_{mci} F_{mci} + \sum I_{suni} C'_{mci} F'_{mci} \quad (5)$$

where.

$I_{suni}$ is average solar radiation intensity through non-opaque fenestration, W/m$^2$;
$F_{mci}$ is the area of non-opaque fenestration, except for the fenestration in the middle of balconies and rooms, m$^2$;
$F'_{mci}$ is the area of the fenestration in the middle of balconies and rooms, m$^2$;
$C_{mci}$ is solar radiation correction coefficient for fenestration;
$C'_{mci}$ is solar radiation correction coefficient for enclosed balconies.

$$Q_{ina} = (t_n - t_e) C_{air} \rho N V \quad (6)$$

where.

$C_{air}$ is specific heat of air, kJ/kg·K;
$\rho$ is air density, kg/m$^3$;
$N$ is air exchange rate, and it is 0.5 ACH specified in the fourth-step building efficiency standard (BJMOHURD, 2012);
$V$ is net volume of the room, m$^3$.

According to these equations, the heat loss index ($q_L$) of each Tianjin energy efficiency standard and Germany standard is calculated and shown in Fig. 3.

As shown in Fig. 3, the heat loss index calculated by Tianjin fourth-step standard is almost equivalent to that calculated by WSVO′1995. From this perspective, if the U-value limits of existing buildings specified in the third-step standard can be improved to that specified in WSVO′1995, EnEV′2002, EnEV′2009 or Passivhaus standard, the annual heating energy consumption will be reduced by 14.9%, 21.9%, 36.1%, and 58.3%, respectively.

### 4.2. Operation

#### 4.2.1. Indoor temperature

Tianjin building energy efficiency standard requires the indoor temperature should be controlled at 18 ± 2 °C. According to Table 3, all the lowest temperatures of case buildings reached 18 °C. However, the highest temperatures were much higher than 20 °C, as high as 30.6 °C. All the average temperatures of five case buildings

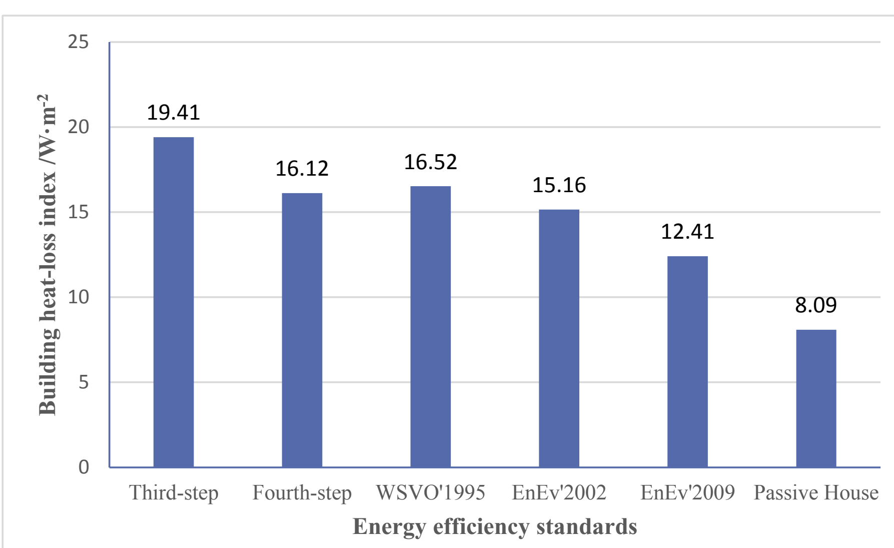


**Fig. 3.** Heat loss index calculated by Tianjin and Germany energy efficiency standards.

were higher than 20 °C, the lowest one is 21.5 °C and the highest one is 25.8 °C. However, when the indoor temperature is relatively high, occupants will try to cool down the room by means of adjusting the thermostatic valve or opening the window. Consequently, the maximum and average indoor temperature without occupants' cooling behavior will be even higher than the recorded indoor temperature which will make occupants feel uncomfortable.

The case buildings with radiator heating have lower average temperatures than those with radiant floor heating system. In terms of temperature control, the control performance varies using different control methods. The features of different control method are discussed as following.

*4.2.1.1. Control methods for radiator heating.* Temperature-type thermostatic valves were installed for each radiator in Building 1. Occupants only need to adjust the temperature set point to the value they need and, consequently, the valve will adjust the flow rate automatically. When the indoor temperature was 2 °C higher than the set point, the thermostatic valve will automatically slow down the flow rate. While, when it was 2 °C lower than the set point, the thermostatic valve automatically will turn up the flow rate. However, during the actual operation, the variation of the indoor temperature was as large as 6.4 °C. The average indoor temperature was 21.5 °C with a standard deviation of 1.2 °C. This is mainly attributed to the fact that the thermostatic valve was installed near the radiator, and the temperature was tested around the radiator. In addition, solar radiation and window opening have significant impacts on the indoor temperature (Liu et al., 2011; Quesada et al., 2012; Tian, 2013; D'Oca and Hong, 2014). The thermostatic valve cannot fast response to temperature changes due to solar radiation and window opening. Therefore, the temperature control was not as effective as designed.

Flow-rate type thermostatic valves were installed for each radiator in Building 2. The variation of the indoor temperature was as large as 7.8 °C. The average indoor temperature was 22.6 °C with a standard deviation of 1.4 °C. The average temperature in Building 2 was 1.1 °C higher than that in Building 1, and the standard deviation was 0.2 °C larger. The temperature control performance of flow-rate type thermostatic valves was not effective as that of temperature-type ones. Because the working principle of flow-rate type thermostatic valve is to control the temperature through matching a certain inlet flow rate corresponding to a certain indoor temperature. However, in actual operation, the inlet temperature varies according to the outdoor temperature. It will be low when outdoor temperature is high and vice versa. As a result, the correspondence between the inlet flow rate and indoor temperature is not the same as the original setting in actual operation.

*4.2.1.2. Control methods for radiant floor heating system.* The temperature control methods of buildings 3, 4 and 5 are Mode 1, 2, and 3, respectively, which are shown in Fig. 2(a) and (b), and 2(c). The average indoor temperature was 25.8 °C, 23.7 °C and 21.8 °C with a standard deviation of 3.5 °C, 2.2 °C and 0.4 °C, respectively. The most effective control method is Mode 3, followed by Mode 2, and the worst is Mode 1. This is due to the fact that the valves were installed on the main pipe in Mode 1. As a consequence, the occupants cannot control the flow rate in each room individually, and they can only adjust the total inlet-water flow rate. Mode 2 required occupants to adjust the valve for each room manually. However, the valves were centralized installed on the corner part of the building, which was inconvenient for the manually control. Moreover, there is a large variation of temperatures between daytime and nighttime. It is impractical to such frequently adjust the valves whenever it is necessary. For Mode 3, occupants only need to set up the valves to a certain temperature, and then the valves can be controlled automatically based on the set point. The standard deviation for three control modes has great differences. Mode 1 and 2 have large standard deviations of 3.5 °C and 2.2 °C which means the indoor temperature of households varied significantly. On the contrary, the standard deviation of Mode 3 is as small as 0.4 °C which indicates the indoor temperature was controlled stably for all households.

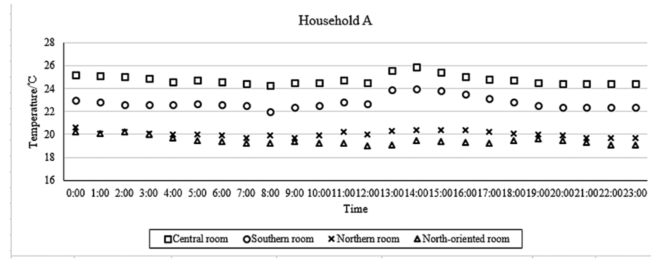


**Fig. 4.** Temperature variation of Household A on 1/15/2012.

Two households, A and B, were selected for analyzing the temperature variation in detail. Two households have the same location and configuration of the property. They are located in Building 3 and Building 5 which have the worst and best temperature control performance.

Household A is located in Building 3 with control Mode 1. Fig. 4 shows its temperature fluctuation on 1/15/2012. The highest and lowest temperature of Household A was 25.9 °C and 19 °C respectively. The daily average temperature of household A, its central room, southern room, northern room, and north-oriented room was 21.4 °C, 23.6 °C, 22.2 °C, 20.1 °C, and 19.5 °C, respectively. All room temperatures were higher than the 18 °C which is the heating temperature requirement specified in Tianjin energy efficiency standard. Especially for the central room and southern room, the temperature was consistently higher than 22 °C during the whole day. At 12:00 to 15:00, there was an about 2 °C temperature rise so that overheating most likely occurs in these two rooms. Consequently, occupants maybe lower the indoor temperature by opening the window which leads to huge amount of energy waste.

Household B is located in Building 5 with control Mode 3. Fig. 5 shows its temperature fluctuation on 1/15/2012. Its daily average temperature was 20 °C which is 1.8 °C lower than that of Household A. The highest and lowest temperatures were 22.4 °C and 17.9 °C respectively, both of them are lower than those of Household A and the latter is very close to 18 °C. The average temperature of the central room, southern room, northern room, and north-oriented room was 20.9 °C, 20.4 °C, 19.7 °C, and 19.2 °C, respectively. The temperature differences among rooms are not significant. This indicated that, according to indoor temperature control performance, control Mode 3 is much more effective than control Mode 1. The indoor temperature began to increase gradually since 6:00

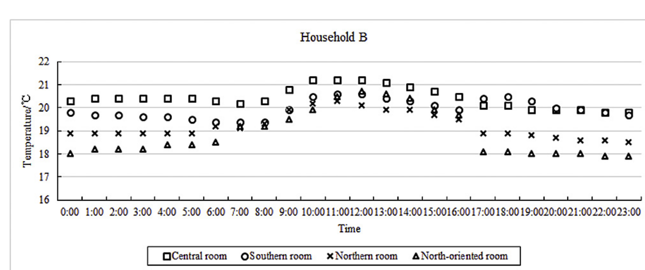


**Fig. 5.** Temperature variation of Household B on 1/15/2012.

when the sun rises. However, there is no significant temperature variation as shown in Fig. 4. This is because the temperature in Household A was consistently maintained at about 20 °C which is the highest temperature in Household B. After 16:00, the temperature sharply decreased about 2 °C in Fig. 5. This was caused by the window opening behavior after occupant returning home.

In summary, for radiant floor heating system, main pipe control has a relative poor temperature control performance. Compartment control method is preferred for the design of indoor temperature control, especially control Mode 3 with ATVs which provide an easy and more effective control method for occupants.

#### 4.2.2. Heating energy consumption

According to Table 4, heating energy consumption of radiator heating (Building 1 and 2) is lower than that of radiant floor heating system (Building 3, 4 and 5). The average heating energy consumption of radiator heating and radiant floor heating system is 79.7 kWh/$m^2$ and 89.0 kWh/$m^2$ respectively, and the difference is 10.4%. From Table 4, it can be observed that temperature-type thermostatic valves can save more 8% energy than flow-rate type ones. This result is consistent with the result of indoor temperature analysis. However, two results are inconsistent for radiant floor heating system. Table 4 shows that control Mode 3 has the best control performance, followed by Mode 1, and the Mode 2 is the worst. In terms of indoor temperature, results show that control Mode 2 has a better control performance than Mode 1, while heating energy consumption results are opposite. Nevertheless, in both two kinds of result, control Mode 3 has the best control performance and there is no large difference between control Mode 1 and Mode 2. One reason for different results of Mode 1 and Mode 2 is that the number of research households for Mode 1 is relatively large and the heating energy consumption varies significantly between different households (standard deviation is 3.5). Therefore, the heating energy consumption of Mode 1 is slightly lower than Mode 2, but their difference is only 3.1%. Moreover, the heating energy consumption will also be influenced by window opening behaviors during the operation.

In addition, as mentioned before, the average heating energy consumption target for buildings meet third-step energy efficiency target is 42.6 kWh/($m^2$•a). Based on the results, only 3.2% of the households in case buildings can meet the requirement in actual operation. Many households even consumed more than twice as much energy as the target value. According to Eq. (3), heat-transfer coefficient of the building envelope is the critical factor for the heating energy consumption. To investigate the reason of high heating energy consumption, this study further measured the heat-transfer coefficient $U$ of walls and roofs in case buildings. We found that although case buildings reached all standard requirements in the design stage, the $U$ of walls and roofs in Building 3 and 5 were 20%–25% greater than the requirements after construction. This indicated that an extra amount of heat will be consumed during the operation stage due to the higher heat-transfer coefficient is not corresponded to the designed value. Additionally, another key factor for excessive heating energy consumption is the high indoor temperature. As aforementioned, the indoor temperature of case buildings is much higher than 18 °C which is the requirement specified in the energy efficiency standard. Every 1 °C increase of indoor temperature will lead to 6% heating energy consumption. Therefore, the indoor temperature should be effectively controlled in a reasonable range, otherwise it will cause excessive heating energy consumption.

#### 4.2.3. Occupants' satisfaction

Among the 23 surveyed households with radiator heating, 13 households used flow-rate type thermostatic valve and the other 10 households were equipped with temperature type thermostatic valve. For flow-rate type thermostatic valve, 11 of 13 households reported that they were satisfied with the temperature control. For temperature type thermostatic valve, 9 of 10 households felt that the temperature control functioned well. Only 1 household reported that the indoor temperature was a little bit low. However, all respondents felt that the temperature was still relatively high in the south-oriented room when there was sufficient sunlight, even if the set point was turned down to the minimum. Among these 23 households, only 5 households turned down the set point when they were not at home. Respondents living on the western top floor were unsatisfied with the performance of temperature control. Because these apartments have a large ratio of the external building envelope area and the total building envelope area, so that the heat loss from building envelope is higher than other apartments. Similarly, these apartments are located at the end of the heat supply system so that the total systematic flow rate has dropped significantly in these apartments and the heat supply received in these apartments was lower than other apartments. As a result, their indoor temperature becomes relatively low, especially in days with cold weather.

Among the 31 households using radiant floor heating system, 5 households used control Mode 1, 17 households used Mode 2, and 9 households used Mode 3.4 of 5 households using control Mode 1 felt satisfied with the control performance. For control Mode 2, 16 of them felt that the temperature control functioned well. Despite the average indoor temperature in the 17 households with control Mode 2 was higher than 22 °C for most of the time, they seldom adjusted the set point (only 1 or 2 times during a heating season) even if they went to work during the day. However, the other one respondent reported that they were unsatisfied for the low indoor temperature, especially in the northern room. This is a family with senior occupants who stay at home all the day. They also seldom adjusted the control valve and felt that adjustments had little effect. Therefore, during sunny days, rooms which can well receive solar radiation usually exhibited a high indoor temperature while the temperature of other rooms is relatively low. This led to a relatively large temperature differential within the entire apartment. 9 households with control Mode 3 alll felt satisfied with the control performance.

In 54 returned questionnaires, 49 respondents which accounts for 90.7% reported they are satisfied with indoor temperature control performance. Such a high level of satisfaction is mainly caused by high indoor temperature which is much higher than the required temperature 18 °C. The lowest average temperature of five case buildings is as high as 21.5 °C, and the highest one is 25.8 °C. High indoor temperature will access to good user satisfaction and significantly increase the heating energy consumption.

### 4.3. Human behavior

As aforementioned, only 5 out of 23 households with thermostatic valve installed on the radiator adjusted the valve frequently. None of 31 households using radiant floor heating system manually adjusted the valve. According to them, the only criterion for heating satisfaction is the indoor temperature, i.e. satisfied for high indoor temperature and unsatisfied for low indoor temperature. However, most of the respondents stated that the temperature of the south-oriented room was relatively high and it was difficult to cool it down during sunny days. Therefore, it is imperative to investigate what methods occupants used to cool the room when the indoor temperature is too high.

Questionnaire results indicated that, only about 20% of the households adjusted the thermostatic valve to cool down the indoor temperature. To be more specifically, when the indoor temperature was high, only 12 households adjusted the thermostatic valve; 28 households opened windows (including 13 households with radiator heating and 15 households with radiant floor heating system); and the remaining 14 households used both valve adjustments and window opening.

Although results showed that most of occupants were satisfied with the control methods, occupants with radiant floor heating system suggested that it was difficult to cool their apartments down by adjusting the valve when the temperature was high. Because radiant floor heating system has huge thermal inertia so that the indoor temperature will rise and fall very slowly after the system is adjusted. Even at the beginning of the heating, it will take about three days for radiant floor heating system to warm up the room. Due to the huge thermal inertial, radiant floor heating system has good response to the heating accident during operation. For instance, there was a pipeline supply failure of the entire heating system which lasted for three days. Occupants using radiant floor heating system did not realize until the third day, and they only felt a slight decrease of the indoor temperature. Nevertheless, in another branch of the heating system which used radiator heating, occupants felt significant temperature drop within half a day. Moreover, 24 h later, occupants had already hardly stood for the low temperature.

Ventilation methods were also investigated in the questionnaire. It was found that no household used mechanical ventilation to introduce fresh air. 48 households opened windows at least twice a day, one in the morning, and the other in the afternoon after them returning home. Only six households opened windows once a day. Moreover, all of them opened windows during the morning when the outdoor air was cold.

In terms of the window-opening period, 40 households opened for more than 20 min a day. Only 14 households opened for less than 20 min. Occupants generally opened window in the morning after they got up and in the afternoon after they came back from work. However, during both of these two periods, the outdoor temperature was relatively low. According to Eq. (6), the larger the temperature difference between indoors and outdoors, the larger the infiltration heat loss. In addition, the infiltration is related to the amount of air coming into the room. The longer the window-opening period and the larger the windows, the larger infiltration heat loss. Design standard stipulated that the infiltration rate should not exceed 0.5ACH in residential buildings. This amount of air is mainly infiltrated into the building via doors and windows. However, window opening will significantly increase the actual infiltration rate and result in the increase of heating energy consumption. Thus, window opening for ventilation should be minimized during operation and it is a key factor for the increase of heating energy consumption.

### 4.4. Heating tariffs

Since the implementation of China's building energy-efficiency standards, many energy-efficient buildings have been constructed. Nonetheless, heating energy consumption in residential buildings remains high. Data show that the residential heating energy consumption intensity in northern China is about 1–1.5 times greater than that in areas of northern Europe where climate conditions are similar (BECCTU, 2007). In this study, the heating energy consumption is about 2 times larger than that specified in design standards. This is arguably because of the heating tariff system. Traditionally, occupants are charged for heating based on a fixed tariff per floor area in China. This tariff structure was originally implemented as a form of social welfare because the government or employers cover a large portion of occupants' heating costs. Due to occupants' heating bills under this tariff are not based on actual heating energy consumption, there is little incentive to conserve heat. However, heat metering is a mandatory component of German energy efficiency policy (Zhao et al., 2009), and occupants have a strong awareness of energy conservation (Thollander et al., 2013). Therefore, the practical heating energy saving performance in Germany is much better than that in China.

The “State Council's August 2006 decision on strengthening energy efficiency” (NDRC, 2006) aims tie heating bills to actual consumption by requiring heat metering in buildings. Heat metering in buildings can significantly reduce the heating energy consumption by 15%–35% (Yuan and Xu, 2015). Tianjin has made significant efforts to improve building energy efficiency, including research and pilot studies of heat metering since 2000. “Heat metering management measures” were released in 2011 to facilitate meter installations, and heat meters are mandatory in all new and retrofitted buildings. The latest heat metering policy suggests occupants charging the heating bill 30% by floor area and 70% by heat metering. However, an energy-consumption-based heating tariff is not mandatory. As a result, heat meters are not utilized in most residential buildings even though they have been installed.

### 4.5. Operation optimization

According to the results, we found the design energy consumption has large difference with actual operation energy consumption. The main reasons are that the occupant behavior is inconsistent with the design scenario and the heat energy consumption is inconsistent with occupants' actual heating demand. There are a number of standards for building energy efficiency. However, these standards only aim at building developers and designers rather than occupants. Therefore, heating energy saving is completely voluntary for occupants. In addition, improper operation design will lead to poor control performance, e.g. occupant do not know how to control the indoor temperature. There is huge energy saving potential if the difference between the heating energy consumption and actual heating demand can be effectively reduced.

The results showed that both radiator heating and radiant floor heating system have their distinct advantages. Radiator heating has lower energy consumption than radiant floor heating system, while radiant floor heating system has high thermal comfort level (Rhee et al., 2017). Additionally, due to radiant floor heating system has huge thermal inertia, it has good response to the heating accident during operation. Therefore, heating mode selection should take well-consideration according to actual ‘native’ features of the project in the design stage. Radiator heating is more energy efficient, so we recommend using radiator heating if both two modes are acceptable. In addition to heating mode, designers also should select appropriate heating control modes and control strategies, which are helpful for occupant controlling indoor temperature and saving energy, such as temperature-type thermostatic valve and compartment automatic control mode.

Furthermore, the government should enforce the implementation of heat metering. Meanwhile, occupants' energy saving awareness should be enhanced. Although the current 30%/70% heating metering policy is conducive to energy saving, it is difficult to draw occupants' attention due to it is not mandatory. Occupants' awareness and motivation are particularly crucial factors for the heating energy saving. It is helpful to avoid excessive indoor temperature and reduce window opening behavior, which are two critical factors of high heating energy consumption. Currently, the outdoor air quality is poor and the haze weather is very serious in China. Residential building heating is directly related to outdoor PM2.5 concentration. Therefore, the government must vigorously promote the awareness of energy saving, especially for heating energy saving, and make occupants aware of the importance of heating energy saving and emission reduction. In addition, in order to respond to the sever haze weather in China, ventilation device with air purifying could be installed in the buildings to improve indoor air quality and reduce the window opening demand.

## 5. Conclusions

Last three decades have witnessed noticeable achievements in China in terms of energy efficiency in residential buildings. However, there is still a large gap between practices in China and those in leading countries, which is not only reflected in the design standard, but also in actual operation.

In terms of energy conservation, China falls much behind to Germany. By comparison analysis of different design standards, the heating energy consumption target specified in latest forth-step energy efficiency standard in Tianjin still leads to 30.9% higher energy consumption than EnEv'2009 and 49.7% higher than Passivhaus standard used in Germany. On the other hand, by heat loss index comparison, if the U-value limits of existing buildings which satisfied third-step standard are improved to that specified in WSVO′1995, EnEV′2002, EnEV′2009 or Passivhaus standard, the annual heating energy consumption will be reduced by 14.9%, 21.9%, 36.1%, and 58.3%, respectively.

Indeed, more efforts are required on not only the stringent energy efficiency design standard but also the improvement of operation strategies. By evaluating the heating energy consumption in residential buildings in Tianjin, this study highlights two critical factors responsible for high heating energy consumption in operation stage, i.e. high indoor air temperature and window opening for ventilation. The major findings are:

(1) Radiator heating consumes less energy than radiant floor heating system. It has more effective temperature control performance than radiant floor heating system. To be more specific, temperature-type thermostatic valves are more effective than flow-rate-type thermostatic valves for radiator heating. For radiant floor heating system, the compartment automatic control mode is most effective, followed by compartment manual control mode and main pipe control mode is not recommended.
(2) Window opening is the main approach for ventilation in China at present. It is an important method to introduce fresh air into the room for increasing indoor $CO_2$ concentration and reducing indoor $CO_2$ concentration. However, simultaneously, it leads to heating energy consumption increase.
(3) Ventilation device with purifying air unit could installed to significantly improve the indoor air quality in the terrible haze weather and to reduce the window opening demand of occupants.
(4) The government should enforce implementation of heat metering and enhance occupants' energy saving awareness.

## Acknowledgments

This work was supported by Tianjin Municipal Science and Technology Commission (Contract No. 17JCZDJC39800 and 14ZCDGGX00795). The authors are thankful to anonymous reviewers for their valuable comments and feedback.

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