

Article

Investigation of Indoor Thermal Environment and Heat-Using Behavior for Heat-Metering Households in Northern China

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Abstract: Heat-using behavior has a major impact on heating energy in heat-metering systems, and therefore, a better understanding can assist in behavior guidance to reduce energy. The objective of this paper was to investigate heat-using behavior, including adjusting heating end valves and operating windows, and identify the main factors affecting the heat-using behavior of households in heat-metering modes. Thirty households were measured and surveyed. The factors influencing heat-using behavior, including outdoor and indoor environmental parameters and time of day, were analyzed. The results are the following: (1) The indoor temperature for heat-metering households was relatively high, up to 24–25 °C (95% confidence interval). (2) The heat-using behavior of households has a lack of rationality: a low proportion of households with adjusted heating end valves, high indoor temperature settings, and more frequent window openings. Improving indoor comfort is the main reason for households to adjust heating end valves, accounting for 79% (95% confidence interval, CI: 71–87%). “Thermostat control valve does not work” is the main reason for households without adjustment, accounting for 63% (95% confidence interval, CI: 53–72%). (3) Time of day and indoor temperature affect active households’ willingness to adjust heating end valves. Time of day, indoor temperature, and outdoor temperature have impacts on opening windows during heating periods.

Keywords: heat metering; heat-using behavior; thermal comfort; heating end valve; operating window



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1. Introduction

The space-heating demand reduction has attracted growing attention in society under the background of energy shortage and global warming [1]. Buildings consume approximately 40% of the total end use, resulting in more than 35% of society’s total greenhouse gas production. Urban heating energy accounts for over 20% of buildings’ total energy demand [2]. Consequently, a reduction in the heating energy in buildings is instrumental to the efforts of reducing energy and carbon in society.

Occupant behavior has a significant impact on the space-heating energy of heat-metering systems [3]. Heat metering affects the heat-using behavior of users through heat-metering equipment, corresponding to the management and pricing policies to reduce heating energy [4]. In 1976, the Economic Commission for Europe proposed to implement heat metering for new buildings and existing buildings. Then, Germany, Denmark, Finland, France, and other countries began to implement heat metering. In recent years, the European Union has released two important instructions, including the Energy End-use Efficiency [5] and Energy Services Directive (2006/32/EC) [6]. Heat metering in China began in the 1990s. In the past decade, a series of policies, regulations, and technical standards have been launched to promote heat metering. Table 1 summarizes the main regulations and standards on heat metering, and two of them were considered to be milestones [7]. One was the Guidance on the Pilot Work of Urban Heating System Reform, issued in 2003. It marked the supervision of heating metering and charging by the Ministry of Housing

and Urban-Rural Development. The other was the Code for Acceptance of Energy Efficient Building Construction, implemented in 2007 [8], which states that indoor temperature control devices and heating meters must be installed mandatorily. With the introduction of these policies, heat metering has gained popularity in many countries.

In heat-metering systems, users can adjust indoor temperatures freely through thermostatic valves. As occupant behavior varies significantly between individuals, the heating energy consumption of buildings may vary greatly [9]. Cholewa T. et al. [10] calculated heating energy in heat metering based on long-term field data, reduction ranging from 7.1% to 23.3%. Seligman C. et al. [11] investigated energy consumption in 28 identical townhouses and found that the largest variation in energy consumption was two to one. Furthermore, the energy consumption of the houses depended significantly on the occupants. In order to understand the current situation of heating energy in heat-metering systems, many scholars have carried out research. For example, Terés-Zubiaga J. et al. concluded that heating energy could be reduced by 15–20% by implementing individual metering and charging in the building [12]. Calise F et al. found that a 64% reduction could be reached in a heat-metering system when it operated for many hours per day [13]. However, contrary to popular belief, Shipworth M et al. proposed that the use of thermostatic valves may not reduce the average maximum temperature in a living room and may shorten the duration of heating operation, resulting in the heating energy consumption not being reduced [14]. Andersen RV et al. [9] considered that if the occupants can adjust the temperature setpoints, higher heating energy consumption may result. Therefore, whether heat metering can reduce heating energy is closely related to heat-using behavior.

Table 1. Regulations and technical standards for heat metering.

Year	Content	Regulations and Technical Standards
1995	Plan for the installation of heat meters	The 9th Five-year Plan and 2010 Plan for Building Energy Conservation of the Ministry of Construction
1999	Room temperature regulation suggested during the design phase	Code for Residential Building Design GB50096-1999 [15]
1999	Implementation of temperature regulation and heat-metering devices for new buildings	Provisions on the administration of energy conservation in civil buildings
2003	Gradual implementation of charging by heat metering	Guidance on the Pilot Work of Urban Heating System Reform
2007	Indoor temperature control devices and thermal control metering devices installed mandatorily	Code for Acceptance of Energy Efficient Building Construction
2008	Requirement for the energy-saving retrofit of a heating system carried out synchronously with the retrofit of heat metering	Technical Guidelines for Heating Metering and Energy Saving Renovation of Existing Residential Buildings in Northern Heating Area
2008	Formulation of measures for the administration of heating metering in civil buildings	Measures for the Administration of Heating Metering in Civil Buildings
2009	Stipulations for the heat-metering design of new buildings and the retrofit of existing buildings	Technical Guidelines for Heating Metering [16]
2013	Heating system assessment, retrofitting on energy efficiency, installation, and acceptance	Technical code for retrofitting of heating system on energy efficiency [17]
2017	Evaluation method of energy consumption	Evaluation method of energy consumption for district heating system [18]
2018	Functional requirements, physical layer, data link layer, data security, and application layer of household metering data transmission	Technical requirements of utility meters data transmission [19]
2020	Manufacture and testing of heat meters	Heat meters [20]

The factors influencing heat-using behavior consist of metering devices, environmental factors [21–23], building and system characteristics (local, age, size of dwelling, room type, and so on) [24–26], occupant characteristics (age, gender [27], income, education level of occupant [27–30]), and other factors (awareness and energy price) [31]. For example, low flow rates of heating water in pipes and inaccurate installations of heating meters led to a doubtful energy bill, which reduced the enthusiasm of residents to save heat [32,33]. Andersen R.V. et al. suggested a strong correlation between heating and outdoor temperature [9]. For building characteristics, Hansen A.R. et al. proposed that the heat transfer coefficient of the envelope affects the heating indoor temperature setpoint [34]. Buildings with higher heat transfer coefficients had lower indoor temperature setpoints because of the warmer clothes of the occupants. Oreszczyn T. et al. found that there was a correlation between heat-using behavior and room type [26]. The mean temperature of living rooms was determined to be higher than in kitchens and bedrooms [35]. The required indoor temperature in winter was found to correlate with the age, gender, culture/race, and education level of the user. Children and elderly persons seemed to prefer higher indoor temperature setpoints in [27,28]. Karjalainen S et al. proposed that men were more active in adjusting thermostatic valves than women. In addition, Bao Xu et al. proposed that the users' attitudes toward heat metering were key to the successful retrofit of heat metering [36].

Great achievements have been made in the application effects of heat metering and factors influencing heat-using behavior for heat-metering households. However, the following research gaps still exist. Firstly, the application effect of heat metering is closely related to indoor temperature. However, there are few studies on indoor thermal environments with heat-metering systems. Secondly, heating is charged according to the quantity of heat, but researchers rarely study whether the cost of heating affects the residents' thermal comfort temperature. Thirdly, there is a lack of research on the effect of indoor thermal environment parameters on heat-using behavior. This study aims to survey heat-using behavior (including adjusting heating end valves and operating windows) and indoor thermal environments and identify the main factors affecting heat-using behavior in heat-metering households. It is of great significance to improve the thermal comfort of indoor environments for heat-metering systems and promote the development of heat metering–assisted heating in China.

2. Research Methodology

In order to measure and survey indoor thermal environments, heat-using behavior, and thermal comfort of heat-metering households, a methodology combining field measurements and surveys is adopted in this paper. The purpose of the survey is to understand the thermal comfort of heat-metering households by determining the states and times of heating end valve adjustments and the times of window operations. When households adjust heating valves and operate windows, indoor parameters can be obtained through a field measurement window, which is supplemented with the survey. Figure 1 shows the flowchart of the methodology. The participants included 20 heat-metering households in China-Singapore Tianjin Eco-City and 10 households in Qinhuangdao, and the measurements were carried out from 11 December 2020 to 11 January 2021 and 1 December 2022 to 16 December 2022, respectively. China-Singapore Tianjin Eco-city and Qinhuangdao are coastal cities with maritime climates. The seasons are distinctive. The annual average temperature of the two regions is about 11 °C.

2.1. Field Measurement

The field measurement parameters mainly included outdoor environmental parameters (outdoor temperature and relative humidity), indoor environmental parameters (indoor temperature and relative humidity), and window state. The measurement instruments included a magnetic switching recorder, temperature recorder, and temperature and humidity recorder. The specific parameters of the instruments are shown in Table 2.

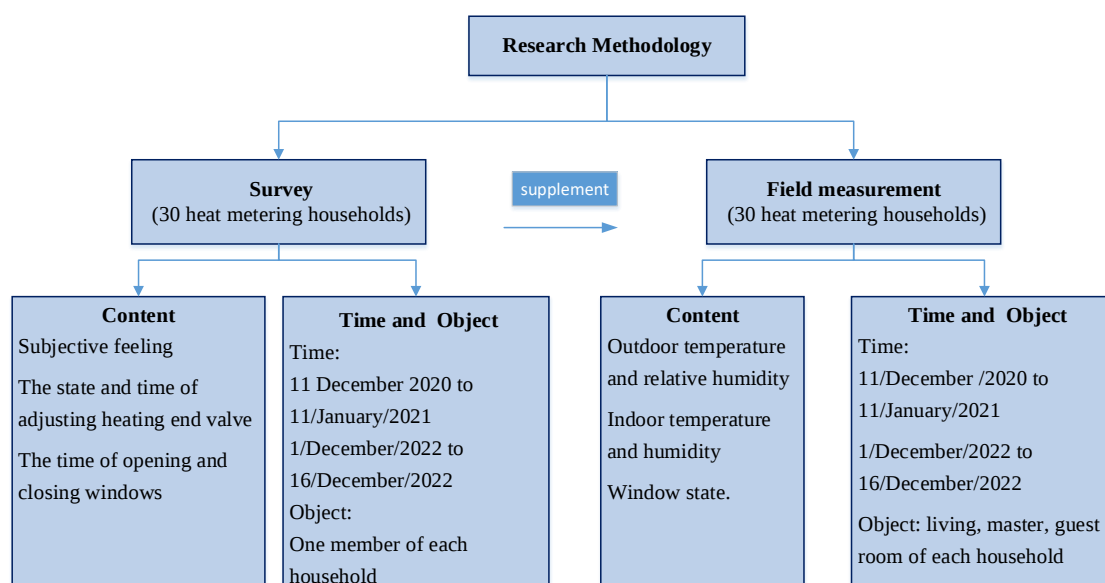


Figure 1. The flowchart of the methodology.

Table 2. Parameter of measurement instrument.

Instrument Name	Measurement Accuracy	Measurement Range	Measurement Frequency
Magnetic switching recorder	---	Maximum magnetic sensing distance 30 mm	2 min
Temperature recorder	$\pm 0.3\text{ }^{\circ}\text{C}$	$-20\text{ }^{\circ}\text{C}$ – $+80\text{ }^{\circ}\text{C}$	2 min
Temperature and humidity recorder	Temperature $0.1\text{ }^{\circ}\text{C}$ Humidity $0.1\%\text{ RH}$	Temperature -40 – $100\text{ }^{\circ}\text{C}$ Humidity 0 – $100\%\text{ RH}$	5 min

A magnetic switching recorder and magnet were placed at each window to monitor the open/closed status with a 2 min data collection interval (Figure 2a). The status was recorded as “1” by magnetic switching recorder when the distance between the two devices exceeded 30 mm, indicating the window was open. On the contrary, when the window was considered closed, “0” was recorded when the distance between the two devices was less than 30 mm. Therefore, two devices were installed under the closed state of the window to accurately measure the window state, and their distance was set within 30 mm. Every window in the master bedrooms, guest bedrooms, and living rooms for the dwellings was measured.

The sensor probes of the temperature recorders were also placed at the windows to monitor windows open/closed statuses (Figure 2b). The sampling frequency was also set at 2 min. Unlike the magnetic switching recorders, the temperature recorders did not directly record the opening or closing state of the window but recorded the temperature near the window. The window state was manually determined. When the temperature suddenly dropped $2\text{ }^{\circ}\text{C}$ or more, the window was considered to be open. On the contrary, when the temperature suddenly rose by $2\text{ }^{\circ}\text{C}$ or more, the window was considered to be closed.

Indoor environmental parameters (indoor temperature and humidity) were recorded using temperature and humidity recorders at 5 min intervals (Figure 2c). The recorders were placed in living rooms at a height of 1.2 m and more than 1 m away from any window.

For outdoor environmental parameters, hourly observation data of Chinese surface weather stations of the National Meteorological Science Data Center Network were adopted, and the nearest Meteorological Station Tianjin Tanggu station (platform number: 54,623) and Qinhuangdao station (platform number: 54,449) were selected. The extracted climatic elements included hourly outdoor temperature and relative humidity.

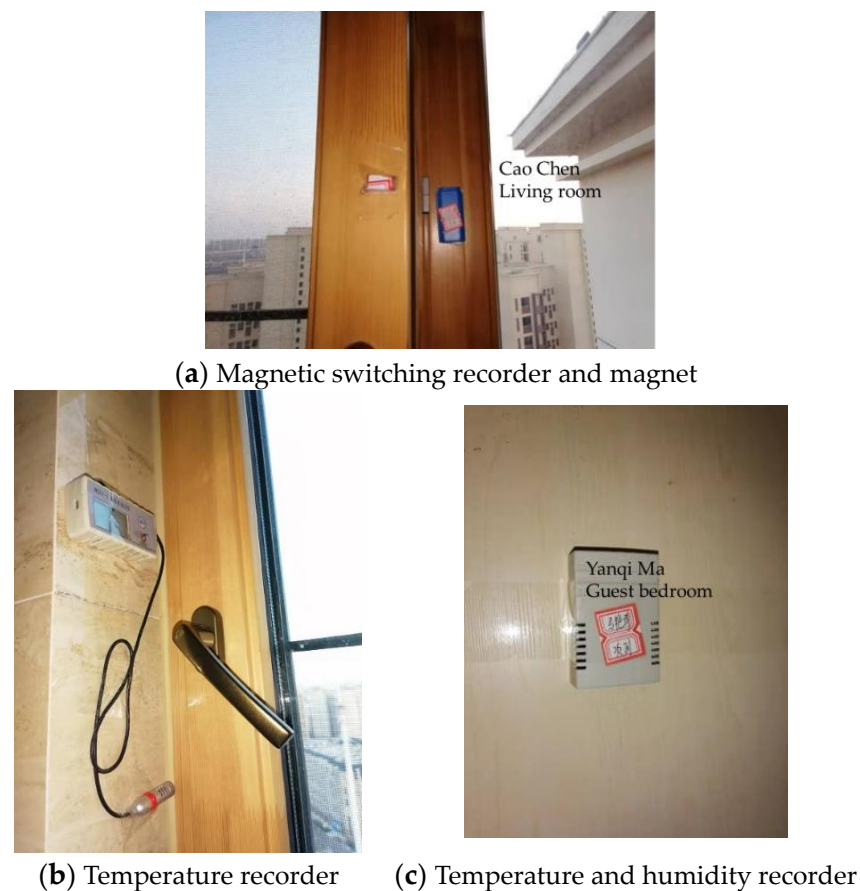


Figure 2. Layout of the measurement instrument.

2.2. Survey

The questionnaire included three aspects: (1) the behavior regarding heating end valve adjustment, (2) the behavior regarding window operation, and (3) thermal comfort. Table 2 provides a description of the questionnaire variables. The first two aspects of the questionnaire adopted an open approach without providing the answer options. The respondents filled in the questionnaire according to their own heat-using behaviors. For example, the question “When do you adjust heating end valve today?” was developed in the first aspect of the questionnaire. The third aspect, including thermal comfort, thermal sensation, and environment acceptance, adopted a closed approach by providing the answer options. For thermal comfort, 5-level thermal comfort indexes in ASHRAE were adopted. The thermal sensation was evaluated using seven indicators that represented the respondents’ thermal response (cold and thermal sensation). Relevant scales are shown in Table 3. In addition, since thermal comfort and thermal sensation are related to respondents’ clothing at the moment, the question “What are you dressing now?” was also set in the questionnaire. Plain language was used to pose questions as much as possible, and professional terms were avoided as much as possible to ensure the validity of the questionnaire on the quantity and quality. In addition, 15 questionnaires were tested in a residential community in Beijing, and preliminary feedback was obtained to form the final questionnaire.

Questionnaires were sent through the questionnaire star at 9 p.m. every day (11 December 2020 to 11 January 2021 and 1 December 2022 to 16 December 2022). A total of 413 questionnaires were collected, and 386 of them were valid.

Table 3. The description of the questionnaire.

No.	Variable	Descriptive	Scales
1	Behavior regarding heating end valve adjustment	The indoor temperature setpoint this morning	
2		The time for adjusting heating end valve	
3		Indoor temperature after adjusting heating end valve	
4	Behavior regarding window operation	Time of opening window in master bedroom	
5		Time of opening window in living room	
6		Time of opening window in guest bedroom	
7	Thermal comfort		
8	Thermal sensation	Very cold	−3
9		Cold	−2
10		Slightly cold	−1
11		Moderate	0
12		Slightly hot	1
13		Hot	2
14		Very hot	3
15	Thermal comfort	Comfortable	0
16		Slightly uncomfortable	1
17		Uncomfortable	2
18		Very uncomfortable	3
19	Thermal environment acceptance	Intolerable	4
20		Very unreceptive	−3
21		Unreceptive	−2
22		Slightly unreceptive	−1
23		Moderate	0
24		Just acceptive	1
		acceptive	2
		Very acceptive	3

2.3. Data Analysis Methodology

Data were analyzed using SPSS 17.0 and Origin 2019b 64Bit; a 95% confidence interval was given in the results. In addition, the stepwise regression method was used to establish the relation between variables. The variable selection process of the stepwise regression method consists of two steps: one is to remove insignificant variables from the regression model, and the other is to introduce new variables into the regression model. The specific steps are as follows:

At first, the unitary regression model between n regressive independent variables, $X_1, X_2, \dots, X_n$, and the dependent variable Y are established, as follows:

$$Y = w_0 + w_i X_i + \psi \quad I = 1, 2, \dots, n \quad (1)$$

The F-test statistic value of the regression coefficient for variables X_i are calculated, written as $F_1^{(1)}, \dots, F_n^{(1)}$. The highest value is

$$F^{(1)} = \max\{F_1^{(1)}, \dots, F_i^{(1)}\} \quad (2)$$

For a given significance level, the corresponding critical value $F^{(1)}$ is marked. If $F_i^{(1)} > F^{(1)}$, X_i is introduced into the regression model.

Second, the binary regression model between dependent variables Y and independent variables $\{X_{i1}, X_{i1}\}, \{X_{i1}, X_{i1-1}\}, \{X_{i1}, X_{i1+1}\}$, and $\{X_{i1}, X_n\}$ are established. The F-test statistic values of the regression coefficient for variables X_i are calculated and written as $F_1^{(2)}, \dots, F_i^{(2)}, F_k^{(2)} (k \notin I_1)$. The highest value is

$$F^{(2)} = \max\{F_1^{(2)}, \dots, F_i^{(2)}\} \quad (3)$$

For a given significance level, the corresponding critical value is marked as $F^{(2)}$. If $F^{(2)} > F^{(2)}$, X_{i2} is introduced into the regression model. Otherwise, the process of the variable introduction is terminated.

Considering the regression model between dependent variables and independent variables $\{X_{i1}, X_{i2}, X_{ik}\}$, the above steps are carried out repeatedly. One of the independent variables that has not been introduced into the model is selected each time; it is terminated until no variables are introduced.

3. Results and Analysis

3.1. Indoor Thermal Environment

3.1.1. Indoor Thermal Environment Distribution

The statistical results of the indoor temperature for 30 households during the measurement period are shown in Figure 3. The indoor temperature is concentrated in the range of 23–28 °C, accounting for 80%. The 95% confidence interval for the indoor temperature is 24–25 °C. Figure 4 shows the curve of indoor temperature for a household from 14 December 2020 to 17 December 2020. It was found that indoor temperature fluctuated with the fluctuation of outdoor temperature, and it had a certain delay. The indoor temperature was above 25 °C, and even the highest temperature reached 27.4 °C without opening a window all four days. It was higher than the design temperature of 20 °C specified in the Design Standard for Heating, Ventilation and Air Conditioning of Civil Buildings [37]. This indicates that heat metering did not make households reduce their indoor temperatures.

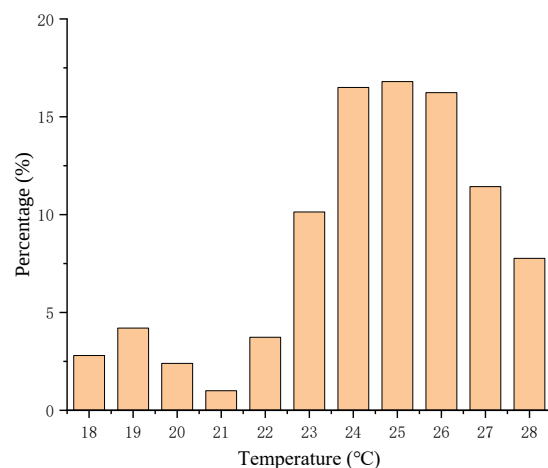


Figure 3. The distribution of thermal environment.

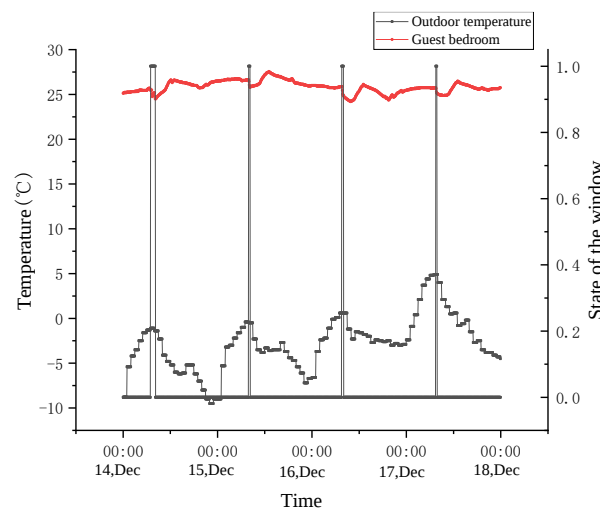


Figure 4. The profile of indoor temperature.

High indoor temperature leads to households wearing lighter clothes in winter. The thermal resistance of different clothes is shown in Table 4 [38]. According to Table 4, the distribution characteristics of clothing thermal resistance for respondents during the heating period could be obtained, as shown in Figure 5. It was found that the clothing thermal resistance of respondents ranged from 0.36 clo to 1.37 clo. Clothing thermal resistance less than 0.75 accounted for 51%. The 95% confidence interval of the clothing thermal resistance is 0.71–0.81 in northern China. It is less than the standard clothing thermal resistance in ASHRAE Standard 55-2017 [39].

Table 4. The thermal resistance of different clothes.

Clothing	Thermal Resistance (clo)	Clothing	Thermal Resistance (clo)
Pants, short-sleeved shirts, socks, shoes	0.57	Shorts, short-sleeved shirts, shoes, and socks	0.36
Pants, long-sleeved shirts, shoes, and socks	0.61	Long-sleeved overalls, T-shirts, shoes, and socks	0.72
Jackets, pants, long-sleeved shirts, and socks	0.96	Long-sleeved overalls, long-sleeved shirts, shoes, and socks	0.89
Jackets, vests, trousers, long-sleeved shirts, and socks	1.14	Insulated work clothes, long Johns, shoes, and socks	1.37
Trousers, long-sleeved shirts, long-sleeved sweaters, shoes, and socks	1.30	Long-sleeved sweatshirts, sweatpants, shoes, and socks	0.74
Knee-length skirt, short-sleeved shirt, and sandals	0.54	Full pajamas, slippers, and no socks	0.96
Long skirts, long-sleeved shirts, and jackets	1.1		

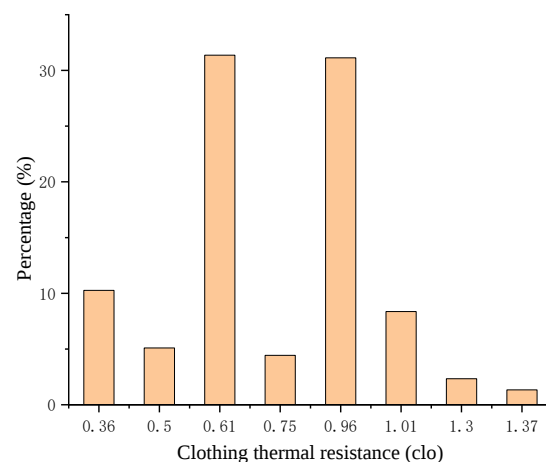


Figure 5. The distribution of clothing thermal resistance.

3.1.2. Satisfaction with Thermal Comfort

Subjective sensation voting reflects the real feelings of the respondents for the indoor thermal environment. The voting results of subjective sensation, including thermal comfort, thermal sensation, and acceptability of the indoor environment, are shown in Figure 6. The samples with thermal comfort voting values of 0 account for 83% (95% confidence interval, CI: 81–85%). The samples with thermal sensation voting values of −1, 0, and 1 accounted for 17%, 74%, and 8%, respectively, accounting for 99% of the total number of samples. Thermal sensation voting values −1, 0, and 1 indicate that households were satisfied with the indoor thermal environment. Thus, it could be obtained that a 95% confidence interval for households with thermal sensation satisfaction is 97–100%. The samples with voting values of acceptability of the indoor environment 0 (moderate), 1 (just acceptable), 2 (acceptable), and 3 (very acceptable) accounted for 46%, 12%, 29%, and 6%, respectively, accounting for 92% of the total samples. A 95% confidence interval for

households with acceptable indoor environments is 86–97%. It shows that most households could accept the indoor thermal environment.

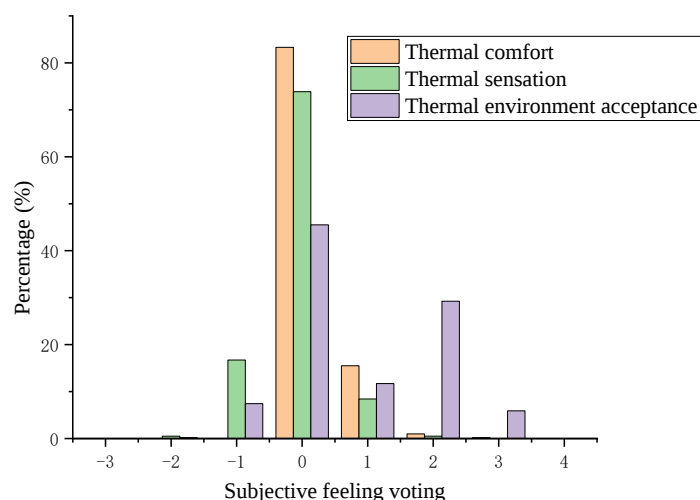


Figure 6. Subjective sensation voting of thermal metering households.

3.1.3. Acceptable Temperature Range

MTSV (Mean Thermal Sensation Vote) was adopted to describe the respondents' thermal sensations. Mean thermal sensation was obtained based on temperature frequency. The specific steps were as follows: According to the distribution range of the indoor temperature (18–30 °C), the MTSVs of all the respondents were calculated by taking ± 0.5 °C of the operating temperature as the range. The operating temperature and the corresponding average thermal sensation votes are shown in Figure 7. The relationship between MTSV and operating temperature was regressed using Origin 2019b 64Bit (Figure 7). The result is shown using Equation (1). The determination coefficient R^2 is 0.75, indicating that the regression equation has a high fitting degree. The result shows that MTSV is positively related with the indoor temperature. A similar equation was derived in the reference [40].

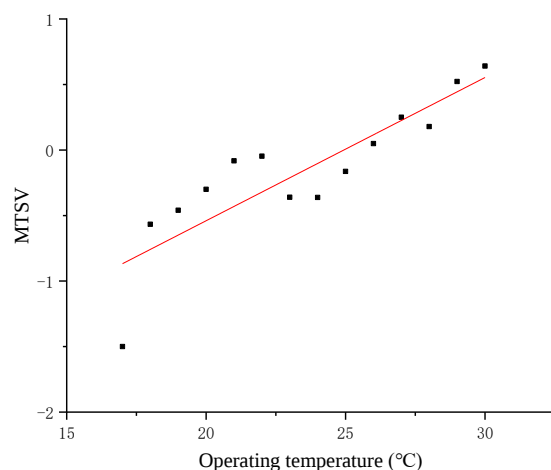


Figure 7. Regression curve of MTSV and operating temperature.

When the average thermal sensation index is 0, the operating temperature is considered the thermal neutral operating temperature, which indicates that occupants feel neither cold nor hot. Therefore, assuming MHSV = 0, the thermal neutral operating temperature could be calculated using Equation (1), which is 24.8 °C, which is higher than the indoor design temperature of 20 °C with central heating in China. Based on PMV, the acceptable temperature range for 90% heat-metering households could be obtained

by assuming $MHSV = [-0.5, 0.5]$, that is, $[20.3\text{ }^{\circ}\text{C}, 29.4\text{ }^{\circ}\text{C}]$. The acceptable temperature range for households is wide, but the lowest temperature and highest temperature are relatively high. Relevant studies have shown that the thermal neutral temperature of non-heat-metering households in Beijing is $23.1\text{ }^{\circ}\text{C}$, and the acceptable temperature range is $[18.9\text{ }^{\circ}\text{C}, 27.3\text{ }^{\circ}\text{C}]$. The thermal neutral temperature of residential buildings in Harbin was measured as $21.5\text{ }^{\circ}\text{C}$, and the acceptable lowest operating temperature for 80% of residents was found to be $18\text{ }^{\circ}\text{C}$ [41]. Therefore, compared to non-heat-metering households, the thermal neutral operating temperature of heat-metering households was not reduced as heat-metering changed. On the contrary, the indoor thermal comfort temperature increased, which indicates that residents pay more attention to comfort with the improvement of people's living standards.

$$MTSV = 0.11t_0 - 2.73 \quad (4)$$

3.2. Adjusting Heating End Valve

The statistical results of heating end valve adjustment show that the proportion of days adjusting heating end valves was low. Among 386 valid questionnaires collected, only 119 adjusted heating end valves, accounting for 31% (95% confidence interval, CI: 21–40%). According to the statistics of 30 households, it was found that only 14 households adjusted the heating end valves, accounting for 47% (95% confidence interval, CI: 37–57%). The proportion of households adjusting heating end valves was relatively low. Among the 14 households with adjustment, 9 households adjusted heating end valves frequently and adjusted the indoor thermostatic valves, and the number of adjustments was greater than 12. The others adjusted the valves in the pipe in the stairwell only once during the measurement period. Improving indoor comfort was the main reason for households to adjust heating end valves, accounting for 79% (95% confidence interval, CI: 71–87%) (Figure 8a), and a lower percentage of households considered the economic benefits brought by adjusting the valve. A total of 53% (95% confidence interval, CI: 43–63%) of households did not adjust heating valves; “Poor thermostat valve” was the main reason for not adjusting heating end valves for heated households, accounting for 63% (95% confidence interval, CI: 53–72%). In addition, 19% (95% confidence interval, CI: 11–27%) of households did not know how to adjust them (Figure 8b).

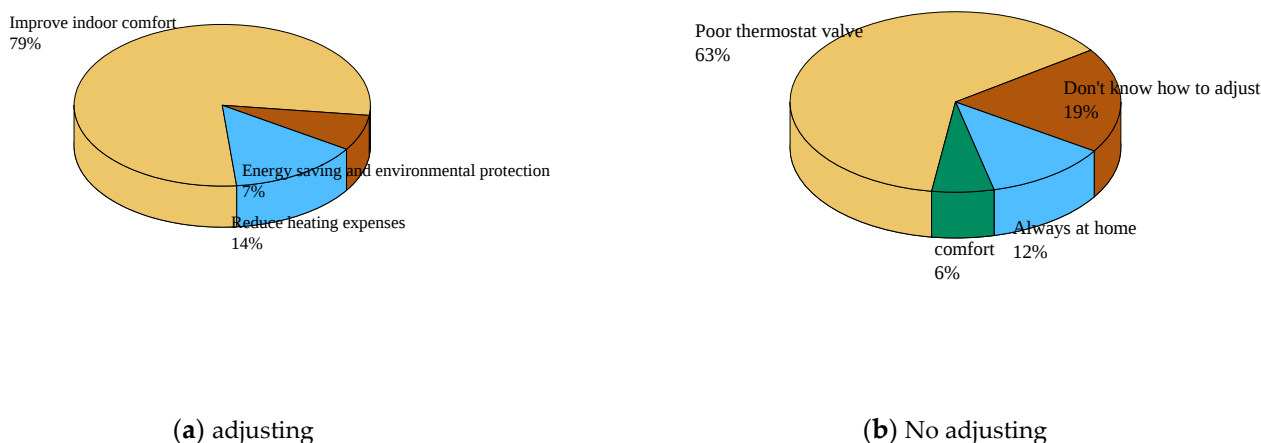


Figure 8. The reason for adjusting end valve and not adjusting.

According to the frequency of adjusting heating end valves, households in northern China can be classed into three categories: (I) negative households (no adjustment of heating end valve in the heating season), (II) general households (once to two times during the heating period); and (III) active households (twelve times or more during the heating period). For 30 households being measured, the proportions of negative, general, and active households were 53%, 17%, and 30%, respectively. There was a low proportion of active households.

Variations in heating end valve adjustment depended on many factors, including socioeconomic attributes, environmental factors, residential characteristics, and so on. It became more important to further investigate which factors affected heat end valve adjustment in active households. The stepwise regression method was adopted to establish this fact. The measurement parameters, including time of day, outdoor temperature, outdoor wind speed, indoor temperature, and relative humidity, were analyzed. Since time is not a numerical variable, one day is divided into four stages, that is, $T = 1$ (6:00–8:30), $T = 2$ (8:30–17:00), $T = 3$ (17:00–23:00), and $T = 4$ (23:00–6:00). The results of the stepwise regression are shown in Table 5. B is the regression coefficient, and its absolute value directly reflects the influence of the independent variable on the dependent variable. That is, $B > 0$ means that the independent variable has a positive impact on the adjustment of heating end valves, while $B < 0$ means that it has a negative impact. Beta is the standardized regression coefficient; t is the result of hypothesis testing on B/Beta ; Sig is the significant level. When $\text{Sig} < 0.05$, the predictive variable is considered to be significant.

Table 5. The results of the stepwise regression for adjusting heating end valve.

Factors	B	Beta	t	Sig.
Constant	−4.46		−7.34	0.00
Indoor temperature before adjustment	0.19	0.61	7.06	0.00
Time period	0.13	0.26	2.97	0.00
Outdoor temperature	−	0.05	0.43	0.67
Outdoor wind speed	−	0.11	1.08	0.28
Indoor relative humidity	−	−0.10	−1.24	0.22

Note: B is the regression coefficient; Beta is standardized regression coefficient; t is the result of hypothesis testing on B/Beta ; Sig is the significant level.

The significance of the four stages of the day and indoor temperature on adjusting the heating end valve for active households is less than 0.05, and the significance values of the others are all greater than 0.05. These indicate that the stage of the day and indoor temperature have a significant influence on heating end valve adjustment for active households, while the other three parameters have no significant influence on active households' heating end valve adjustment. As the indoor temperature increases, active households have a greater possibility of adjusting the heating end valve. The maximum probability time adjusting the valve for active households is the fourth stage of the day (6:00–8:30). Active households have the lowest possibility to adjust heating end valve at the time 23:00–6:00.

The correlation between adjusting temperature amplitude Δt and two variables (stage of the day T and indoor temperature before adjustment t) was linearly regressed using SPSS. The results are calculated based on Equation (2). It was obtained that the critical temperature of adjusting heating end valve for active households is 24.5 °C, 23.7 °C, 22.9 °C, and 22.1 °C in day stages 1, 2, 3, and 4, respectively. When the indoor temperature was higher than the critical temperature, the households turned down the heating end valve and the indoor temperature could be reduced. On the contrary, the households turned up heating end valves when the indoor temperature was lower than the critical temperature. For example, assuming the indoor temperature is 26 °C at the fourth stage of the day, the temperature can be reduced by 1.64 °C.

$$\Delta t = 10.64 - 0.34 T - 0.42 t \quad (5)$$

3.3. Operating Windows

The statistical results of opening windows for households show that 75% (95% confidence interval, CI: 66–83%) of households opened windows in the measurement period. The proportion of window openings was higher. Figure 9 shows the number of households with different average durations of opening windows every day. It shows that the number of households with an average opening window duration every day of more than 3.5 h was

six, accounting for 20% (95% confidence interval, CI: 12–27%). The duration of window opening for some households was long.

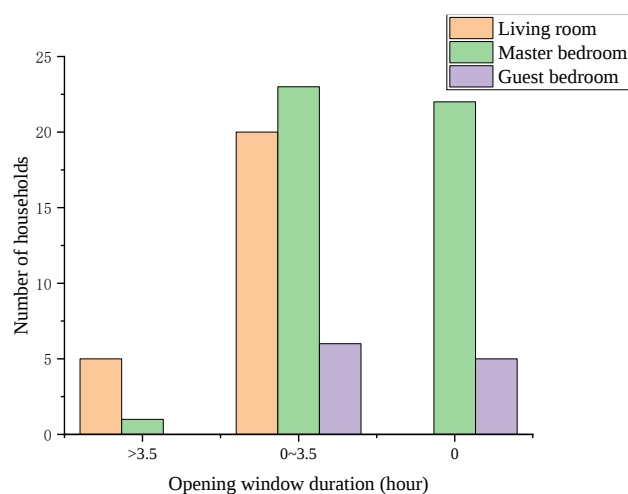


Figure 9. The number of households with different opening window durations.

In addition, the duration of window opening for living rooms was the longest, the duration for the master bedroom was the second longest, and the shortest duration of the window opening was in the guest bedroom. This shows that the function of the room is an important factor affecting window operation. The window opening states of living rooms for ten households are shown in Figure 10. The durations of window openings are different for different households during the heating period in winter. The figure shows that households' preference was an important factor affecting the window operation. Yang J et al. also proposed that residents' window opening was closely related to their personal preferences [34].

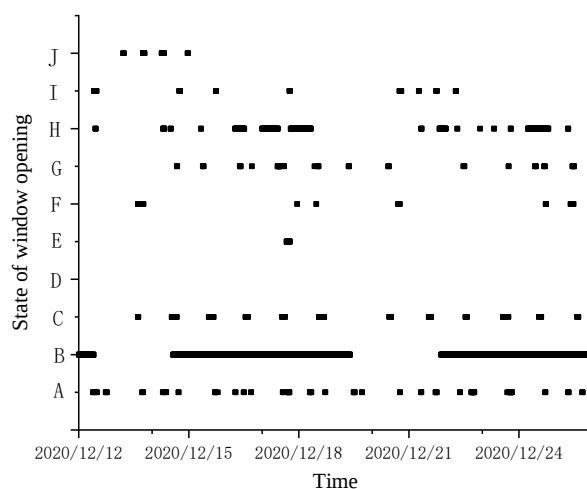


Figure 10. State of the window opening for living bedroom.

The stepwise regression method was adopted to analyze the influence of measurement parameters on window operation, including the stage of the day, outdoor temperature, indoor temperature, and relative humidity before opening the window. The results are shown in Table 6. The table shows that the stage of the day, outdoor temperature, and indoor temperature before opening the window have a significant influence on households opening windows. Outdoor temperature and indoor temperature are positively correlated with window opening. That is to say, the probability of opening windows for households increases as the outdoor and indoor temperatures increase. The maximum probability of

opening windows is in the fourth stage of the day (6:00–8:30). Households have the lowest possibility of window openings from 23:00–6:00.

Table 6. The results of the stepwise regression for operating windows.

Variable	B	Beta	t	Sig.
Constant	0.03		3.41	0.00
Outdoor temperature	0.02	0.15	14.08	0.00
Time period	0.19	0.39	35.70	0.00
Indoor temperature before opening window	0.03		3.41	0.00
Indoor relative humidity	-	−0.01	−0.76	0.34

4. Discussion

4.1. Indoor Thermal Environment

According to the results of the survey and measurements, the 95% confidence interval of the indoor temperature for heat-metering households is 24–25 °C. This is higher than the design temperature of 20 °C [37]; even the highest temperature reaches 27.4 °C (Section 3.1). One of the main reasons for higher indoor temperatures may be excessive heating load. According to [37], the additional load generated by the heat transferring between rooms should be considered for heat-metering rooms, but the additional amount should not exceed 50%. However, it was found that some households could not adjust heating end valves in the field, resulting in less heat transfer between rooms. Therefore, the design heat load was excessive, and the indoor temperature was higher than the design temperature. The second reason may be a high comfort requirement. With the improvement in people's living standards, residents pay more attention to comfort. Residents wear less clothing, of which the thermal resistance is less than that in ASHRAE55-2017 standard 1 [39]. A high thermal neutral temperature is required, up to 24.8 °C according to Section 3.1.3.

4.2. Heat-Using Behavior

Only 47% (95% confidence interval, CI: 37–57%) of the households measured adjusted heating end valves. The proportion of households is low. This may be related to the fact that the households had formed certain heat usage habits under the traditional heating system. Indoor temperature was set high for active households, according to Section 3.1.1. The purpose of implementing heat metering is to reduce heating energy by lowering the indoor temperature setpoint or downsizing or closing the heating end valve. However, it is difficult to achieve the aim because of the low proportion of households adjusting heating end valves and the higher indoor temperature setpoints. In addition, according to the results from the measurements, 75% (95% confidence interval, CI: 66–83%) households opened the windows in winter, and the duration of window opening for some households was long (more than 3.5 h), which led to a serious waste of heating energy. High indoor temperature is one reason for residents to open windows, according to Section 3.3. Therefore, it is very necessary to improve the scientific and rational heat-using behavior, closing the window in winter, reducing the indoor temperature, and shortening the time of heating (when no one is home). Only this can highlight the advantages of energy saving for heat metering.

4.3. Heating Meters Propaganda

Heat metering in China has been implemented for more than a decade. Lots of policies and regulations of the state have been implemented, and most of the northern cities have also introduced methods for prices and charging for heat metering. However, according to the survey results, 19% (95% confidence interval, CI: 11–27%) of heated households do not know how to adjust the heat, which is also one of the main reasons that residents do not adjust the heating end valve. This indicates that the influence and radiation of propaganda for heating departments and social mass media are far from enough. Improving the understanding of heat metering can improve the willingness to adjust heating end valves for residents [42]. Therefore, it is necessary to strengthen publicity and guidance

on information related to heat metering. This helps to improve the understanding of heat metering and increase the enthusiasm of households to adjust the heating end valve.

4.4. Thermostat Valve

Most households measured could not adjust indoor temperature freely because of the dated facility, where 63% (95% confidence interval, CI: 53–72%) of households expressed that the thermostat valves had poor adjustment function in the extensive survey. The main reason might be the non-standard installation of the thermostat valves and the quality of heating water, resulting in the blockage of the thermostat valves. This makes the policies and regulations issued by the state become paper articles. Therefore, it is necessary to strengthen the supervision of the relevant department and set up specific and operable rules to ensure the actual availability of heating meters.

5. Conclusions

The field measurement and survey were carried out to study heat-using behaviors in residential buildings in northern China. A total of 30 households were selected as a case study in this research. The following conclusions are drawn:

- (1) The 95% confidence interval of the indoor temperature for heat-metering households is 24–25 °C. This is higher than the design temperature of 20 °C. The thermal neutral temperature for heat-metering households was high, up to 24.8 °C. The acceptable temperature range was 20.3–29.4 °C.
- (2) The heat-using behavior had a lack of rationality. The proportion of adjusted heating end valves for households was low. Indoor temperature was set high for active households. The window-opening phenomenon of households was obvious during the heating period; 75% (95% confidence interval, CI: 66–83%) of households measured opened their windows.
- (3) Active households with high indoor temperatures have a high probability of adjusting end valves. At times between 6:00 and 8:30, active households were willing to adjust the valve. High indoor and outdoor temperatures caused window-opening behavior in households. The probability of window opening is high between 6:00 and 8:30.

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