Winter Thermal Comfort and Perceived Air Quality: A Case Study of Primary Schools in Severe Cold Regions in China

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Abstract: In Northeast China, most classrooms in primary and secondary schools still use natural ventilation during cold days in winter. This study investigated the thermal comfort and the perceived air quality of children in primary schools in severe cold regions in China. Field measurements were conducted in four typical primary classrooms in two naturally ventilated teaching buildings in the winter of 2016 in the provincial city of Shenyang. Six field surveys were distributed to 141 primary students aged 8 to 11, and 835 valid questionnaires were collected. The results showed that the indoor temperature and the daily mean CO₂ concentrations of the primary school classrooms ranged from 17.06 to 24.29 °C and from 1701 to 3959 ppm, respectively. The thermal neutral temperature of the primary school students was 18.5 °C, and the 90% thermal comfort temperature ranged from 17.3 to 20.1 °C. Children were able to respond to changes in indoor air quality, but there was no significant correlation between the children's perceptions of air quality and the carbon dioxide levels in the classroom. In general, children have a lower comfort temperature than adults. In addition, children are more sensitive to temperature changes during the heating season than adults. Due to differences in thermal sensation between children and adults, the current thermal comfort standard based on adult data is not applicable to primary school buildings and children. The air quality evaluation during heating season indicates that it is necessary to add indoor air environment monitoring instruments and purification equipment to the naturally ventilated classrooms. At present and in the future, more research based on children's data is needed to solve the indoor air environment problems in primary school buildings.

Keywords: severe cold region; natural ventilation; primary school; classroom thermal environment; perceived air quality

1. Introduction

The indoor air environment of teaching buildings is receiving unprecedented attention. As of June 2019, there are more than 160,000 primary schools in China, with more than 105 million pupils [1]. The classroom is the most important functional space in the teaching building and is also a staff-intensive space. The indoor comfort requirement is a basic requirement of the school and is more important than the energy conservation requirement [2]. The classroom should provide a comfortable and healthy indoor air environment because occupants may be in the classroom for a long time. The indoor air environment includes the thermal environment and the air quality, both of which are important aspects
of the indoor environment [3]. Research has shown that an uncomfortable classroom air environment, such as high temperatures and a low ventilation rate, has adverse effects on the study behavior of occupants [4]. Because children are less resistant to adverse environments, poor indoor air quality has a more significant impact on children than adults [5]. The indoor air environment affects not only the occupant’s experience but also the building energy consumption, especially during the heating season. Most of the energy consumption of teaching buildings in severe cold areas is used for heating in winter to ensure the stability of the indoor thermal environment.

Research on thermal comfort has primarily focused on human heat exchange and the thermal balance model. At present, there are two primary research methods for thermal comfort: the thermal balance model and the adaptive model. The thermal balance model is widely used in the study of indoor thermal comfort. The thermal neutral temperature and the comfort temperature range are crucial indices used in thermal comfort research. The predicted mean vote/predicted percentage of dissatisfied (PMV/PPD) thermal balance model was first proposed by Fanger in the 1970s and was used to predict the average thermal sensation and dissatisfaction rate of occupants. In the ASHRAE-55 standard, thermal comfort is defined as the mental state in which occupants express their satisfaction with the thermal environment [5]. The international standards ISO7730 and ASHRAE-55 and the Chinese standard GB/T 50785-2012 define the comfort zone using Fanger’s PMV/PPD method based on experimental data. However, the general adaptability of PMV models has been controversial. Field studies of thermal comfort have brought PMV models into question. Fanger [6] proposed the ePMV (i.e., the expectation factor model) to expand the application scope of the PMV model. Based on the black box theory, Yao [7] proposed the aPMV (i.e., adaptive model) applicable to free-running buildings. Humphreys et al. [8] and de Dear et al. [9] proposed several empirical equations for predicting a comfortable temperature. The human body adapts to the environment; thus, the ePMV and aPMV models have limitations for practical applications due to the diversity of building types and different climatic conditions [10]. The difference between an actual thermal sensation and a predicted thermal sensation is attributed to physiological factors of the climate and environment, as well as psychological expectations [11]. ASHRAE’s adaptive database covers four continents and focuses on European countries and the United States [12]. However, the database does not include Asian countries represented by China.

In primary school classrooms that still use natural ventilation in winter, a poor indoor thermal environment is usually accompanied by poor indoor air quality due to closed classroom doors and windows and thermal insulation. The assessment of indoor air quality, which consists of the perceived air quality (PAQ) and indoor CO\(_2\) concentration, is an important part of the assessment of the indoor air environment. In the ASHRAE-62 standard, acceptable indoor air quality is defined as the absence of known pollutants whose concentrations are determined by authoritative institutions. The majority of people (80% and more) express no dissatisfaction [13]. It is important to understand the occupants’ views on indoor air quality to ensure that natural ventilation is used rationally and energy is saved while ensuring human health. Stazi et al. [14] showed that a high indoor CO\(_2\) concentration led to declines in the students’ attention [15], memory ability [16], and overall performance [17]. Artificial ventilation in a naturally ventilated classroom does not guarantee the minimum CO\(_2\) concentration required by current specifications [18]. The average CO\(_2\) concentration level in naturally ventilated classrooms is generally higher than that in mechanically ventilated classrooms [19]. Indoor CO\(_2\) concentration in classrooms is significantly higher in winter than in other seasons [20]. The characteristics of China’s monsoon climate result in longer and colder winters in cold regions than in other regions at the same latitude. As a result, the air environment in primary school classrooms in cold regions is worse than in comparable regions, and there are more occupants that experience a wider range of impacts. Existing research has rarely focused on the compound problem of the thermal environment and indoor air quality in a low-temperature environment in primary and middle schools, and comparative analyses of subjective and objective data are lacking.
Research on naturally ventilated classrooms has shown that children and adults have different thermal comfort temperatures [12]. There are few studies on indoor air environment focused on children, and the research scope is limited to warm areas in Europe and the United States [21]. The difference in thermal comfort between children and adults is attributed to the physiological characteristics of the occupants, as well as to the environmental characteristics of naturally ventilated primary school classrooms. The thermal balance and thermal adaptation models used in the current specifications, such as ISO7730 EN15251 and GB/T50785-2012, recommend a design value of the classroom temperature that is derived from the model calculation or adaptive database [10]. However, children and adults have different metabolic rates, activity levels, and living habits. Therefore, models and data based on thermal comfort research focused on adults are not applicable to children. Moreover, the thermal comfort of students in a crowded primary school classroom cannot be accurately predicted based on a study of a university classroom in the climate-controlled room. Research on classroom thermal comfort worldwide has shown that children have different thermal comfort temperatures in different seasons and different climatic conditions [22]. In England’s temperate climate, the comfort temperature for children aged 11–16 years is 16.5 °C in winter [23] and 19.1 °C in summer [24]. In addition, the comfort temperature for children aged 7–11 years was found to be 20.5 °C [25] in spring. In South Korea’s temperate climate, the comfort temperature for children aged 4–6 is 22.1 °C [26]. In the Australian subtropics, the comfort temperature [27] is 24.5 °C in winter and 22.5 °C [28] in summer for primary and secondary school students, respectively.

At present, there are a large number of primary and secondary schools in cold areas, but there is a lack of investigation and evaluation of classroom thermal environment. In order to have a positive impact on the thermal environment design of primary and secondary schools in winter conditions and to improve the energy efficiency and relevant standards of classroom design, this study conducted a primary school site thermal environment survey and evaluations of the PAQ. Based on the above analysis and the relevant studies on the indoor environment of primary and secondary school classrooms in the severe cold region of Northeast China [21,29], the research focus of this study is as follows. A continuous monitoring of four classrooms in a primary school in Shenyang is conducted to obtain measurements of the indoor thermal environment and air quality of classrooms in cold regions in winter. Children’s feeling and satisfaction degree with thermal environment and air quality are investigated. The actual neutral temperature is calculated based on thermal sensing voting (TSV) and compared with the predicted neutral temperature based on PMV. In addition, the influence of the personnel density on the PAQ of the thermal environment is discussed, and the linear relationship between clothing insulation, and the neutral temperature is analyzed. The research results will provide reference value for the indoor thermal comfort temperature design of primary school classrooms in severe cold areas.

2. Method

The study measured the indoor environment of the sample classrooms, conducted a questionnaire survey on occupants, and established a research method combining subjective and objective approaches. The indoor environmental parameters and occupants’ adaptive behaviors were evaluated by combining subjective and objective methods. The research methods mainly included the following three task areas: (1) Taking the outdoor air temperature and relative humidity as the main indicators, the winter climate of the severe cold region was analyzed, and the target buildings were determined. (2) In the field measurement part, the measurement parameters and instruments involved in the research were defined, as well as the arrangement mode of the instruments. (3) In the questionnaire design part, a corresponding indoor environment questionnaire was designed centering on underage occupants. The subjective evaluation and satisfaction degree of indoor thermal environment and air quality were obtained through questionnaires.
2.1. Climate Condition and Target Building

Field measurements and questionnaire surveys were carried out simultaneously in two teaching buildings (Figure 1) of a typical primary school in Shenyang city during 19th to 26th December, 2016. Shenyang city in Northeast China is located at north latitude 41°48′ and east longitude 123°25′. The average outdoor temperature in the coldest month is below −5 °C. According to the regional division of China’s building climate, Shenyang belongs to Zone C of the severe cold region, as shown in Figure 2. The heating period in Shenyang lasts 150 days from November 1 to March 31 [30]. The outdoor meteorological data were obtained from the China Meteorological Data Network [31]. The outdoor ambient temperature and relative humidity were measured at a climatic measurement point that was located 1500 m from the measurement buildings. The variation of the outdoor temperature and relative humidity during the measurement period is shown in Figure 3. The average outdoor temperature was −5.3 °C, the lowest temperature was −21 °C, and the highest temperature was 3 °C. The outdoor relative humidity ranged from 44% to 98%, and the average relative humidity was 77%.

Figure 1. Map of the primary school site.

Figure 2. Location of Shenyang.
The selection of sample classrooms should be as representative as possible, considering the impact of the building envelope, room orientation, and thermal insulation type in the classroom environment. Four classrooms of the primary school were selected to determine the indoor air environment in winter. The sample classrooms are ordinary classrooms with natural ventilation, and there is no ventilation in the teaching building. Figure 4 shows photos of the sample classrooms selected in the study. The details of the four sample classrooms are listed in Table 1. The layout of the classrooms is the same. The classrooms were closed most of the time during the heating period, and the doors and windows remained closed during classes. The staff density of classrooms is about 1.5 seat/m². Due to the high occupant density of the classroom, the influence of the body heat of the students on the indoor thermal environment cannot be ignored.

![Figure 3](image-url)  
**Figure 3.** Outdoor air temperature and humidity during the measurement period.

![Figure 4](image-url)  
**Figure 4.** Classrooms selected for the measurements (a) Vacant classroom; (b) Occupied classroom.
The measured indoor environmental parameters in this study included indoor air temperature, black global temperature, and carbon dioxide concentration. Thus, according to the GB/T 50785-2012, top is calculated using Equations (1) and (2) [33]:

\[
t_{\text{op}} = \frac{10}{5000} \pm 0.21 \degree C
\]

\[
RH = 50\% \pm 3\%
\]

The measured heights of the indoor air temperature, black global temperature, and carbon dioxide concentration were 0.6, 1.1, and 0.9 m, respectively. The technical specifications of the instruments are shown in Figure 5.

Table 1. Information on the selected classrooms.

| General Information          | Building A | Building B |
|------------------------------|------------|------------|
| Classroom                    | A1         | A2         |
| Number of students           | Boys       | Girls      |
|                             | 33         | 18         | 19         |
|                             | 15         | 41         | 22         |
| Staff density (seat/m²)      | 1.51       | 1.21       | 1.63       |
| Student age(y)               | 10–11      | 9–10       | 10–11      |
| Size (m) L *W *H             | 8.6 * 5.8 * 3.2 | 8.7 * 6.4 * 3.2 |
| Door (m) W *H *number        | 2.1 * 0.9 * 2 | 2.1 * 0.9 * 2 |
| Exterior window (m) W *H *number | 1.7 * 2.0 * 3 | 2.4 * 2.0 * 3 |
| Interior window (m) W *H *number | 1.5 * 0.9 * 1 | 1.5 * 0.9 * 1 |
| Insulation type              | No         | External wall insulation |
| Ventilation type             | Natural ventilation |
| Ventilation installation     | No         | No         |
| Heating system               | Electric radiant heating |
| Floor                        | 4th        | 4th        | 4th        |
| Orientation                  | East       | West       | South      | North      |

*L: length; W: width; H: height.

2.2. Field Measurement

The primary school students typically arrived at school at 7:30 am and left school at 16:30. In this study, the period between 7:30 and 16:30 was defined as the school period, whereas the other periods were defined as the nonschool period. The field measurements of the thermal environment in the primary school classrooms in winter were conducted during the school period and the nonschool period. The measured indoor environmental parameters in this study included indoor air temperature, relative humidity, black global temperature, air velocity, and carbon dioxide concentration. An RR002 temperature and humidity sensor, an Onset HOBO CO₂ sensor, and a JT2020-1 multifunctional temperature sensor were used to measure the parameters continuously. The technical specifications of the instruments are listed in Table 2. The measuring heights of the indoor air temperature, black global temperature, and carbon dioxide concentration were 0.6, 1.1, and 0.9 m, respectively. The number and location of the instruments are shown in Figure 5.

Table 2. Technical specifications of the instruments.

| Model          | Photo | Parameter | Range         | Accuracy  |
|----------------|-------|-----------|---------------|-----------|
| RR002          |       | $t_a$ (°C) | −40–85 °C     | ± 0.6 °C  |
|                |       | RH (%)     | 0–100%        | ±3%       |
| HOBO MX1102 CO₂|       | $t_a$ (°C) | 0–50 °C       | ±0.21 °C  |
|                |       | RH (%)     | 1–99%         | ±0.01%    |
|                |       | CO₂ (ppm)  | 0–5000 ppm    | ±50 ppm   |
|                |       | $t_a$ (°C) | −20–120 °C    | ±3%       |
|                |       | RH (%)     | 10–95% RH     | ±3%       |
| JT2020-1       |       | $t_a$ (°C) | 0–50 °C       | ±0.5 °C   |
|                |       | $v_a$ (m/s)| 0–5 m/s       | ±0.03 m/s |

$t_a$: air temperature; RH: relative humidity; $v_a$: air velocity.
Humphreys et al. [32] suggested the use of the operative temperature ($t_{op}$) to reflect the thermal environment. Thus, $t_{op}$ was used to compare the observed thermal comfort values in the current study with those of other studies. According to the GB/T 50785-2012, $t_{op}$ is calculated using Equations (1) and (2) [33]:

$$t_{op} = \frac{h_t t_{mr} + h_c t_a}{h_t + h_c}$$  \hspace{1cm} (1)$$

$$t_{mr} = \left[ \left( t_g + 273 \right)^4 + \frac{1.1 \times 10^8 v_a 0.6}{\varepsilon D_k^{0.4}} (t_g - t_a) \right]^{0.25} - 273 \hspace{1cm} (2)$$

where $h_c$ is 4.0 W/(m$^2$·K) and $h_t$ is 4.7 W/(m$^2$·K); $t_{mr}$ represents the average radiation temperature; $t_a$ represents the indoor air temperature; and $t_g$ represents the black global temperature (°C). $D_k$ is the diameter of the ball (m); $\varepsilon$ is the emissivity; and $v_a$ is the velocity of air (m/s).

### 2.3. Occupants and Questionnaire

Pupils in the 4 selected classrooms were invited to complete the subjective questionnaires. A total of 141 students participated in this study as classroom occupants, and 835 valid questionnaires (6 times) were collected from the on-site survey. Participants ranged in age from 9 to 11 years, with an average age of 10. There were 71 male students (50.4%) and 70 female students (49.6%), with a male–female ratio of 1:1. The distribution of gender and the number of occupants are listed in Table 1. The occupants were primary school students, and they lacked knowledge of the thermal environment and air quality perception. The teachers instructed the students before the questionnaire was distributed to ensure the participation of the occupants and the validity of the questionnaires. The students could not adjust doors or windows or change clothes during school hours. According to the recommended value of clothing insulation, the average clothing insulation of the primary school students in the four classrooms was determined to be 1.2 clo. All students were sitting or writing while filling out the questionnaire during a self-study period. According to the Chinese Thermal Environment Assessment Standard (GB/T50785-2012) [33], the children’s metabolism was determined as 1.2 met. The age of primary school students in China ranges from 6 to 11 years, and research on thermal comfort in this age group is limited. Primary school clothing is characterized by limited variability. During most of the school days in the cold regions, the students’ indoor clothing is almost the same as the outdoor clothing. Research has shown that students are capable and sensible enough to determine hot and cold conditions as well as the circumstances under which they are comfortable or uncomfortable. The indoor–outdoor temperature difference is significant in severe cold regions in China in winter. Students participate in many outdoor activities. The thermal resistance of the students’ clothing is primarily based on the outdoor temperature. Therefore, wearing coats (as shown in Figure 4) is often not required under indoor temperature conditions.
The content of the questionnaire included the occupant’s thermal sensation and thermal satisfaction to the classrooms thermal environment. The questionnaire included three parts. The first part was information on the students, including age, gender, and clothing, which was used to estimate the occupants’ clothing insulation and metabolic rate. The second part focused on thermal comfort, including voting on thermal satisfaction and thermal sensation. The third part was the perception of indoor air quality, including the odor intensity and the acceptability of the indoor air quality. The questions and voting scales used in the questionnaire are listed in Table 3. The vocabulary of the questionnaire was adjusted to match the age and comprehension of the occupants. The design of the students’ questionnaire was completed after communication with teachers to ensure that the students made true and accurate choices on the questionnaire. The primary school students were willing to listen to the teachers and answered the questionnaire contents carefully. During the questionnaire survey, no negative emotions were observed among the students.

Table 3. Scales used in the questionnaire survey.

1. **How do you feel about the temperature in the classroom?**

|        | Very hot (3) | Hot (2) | Warm (1) | OK (0) | Cool (−1) | Cold (−2) | Very cold (−3) |
|--------|--------------|---------|----------|--------|-----------|-----------|----------------|

2. **How do you feel about the humidity in the classroom?**

|        | Very dry (3) | Dry (2) | Somewhat dry (1) | OK (0) | Little humid (−1) | Humid (−2) | Very humid (−3) |
|--------|--------------|---------|------------------|--------|-------------------|------------|----------------|

3. **Are you satisfied with the temperature in the classroom?**

|        | Very Satisfied (5) | Satisfied (4) | Neutral (3) | Dissatisfied (2) | Very Dissatisfied (1) |
|--------|---------------------|---------------|-------------|-----------------|----------------------|

4. **Are you satisfied with the humidity in the classroom?**

|        | Very Satisfied (5) | Satisfied (4) | Neutral (3) | Dissatisfied (2) | Very Dissatisfied (1) |
|--------|---------------------|---------------|-------------|-----------------|----------------------|

5. **How do you feel about the air freshness of your classroom at this moment?**

|        | Fresh | Stale | Stale with Occasional Odor | Stale with Odor |
|--------|-------|-------|---------------------------|----------------|

6. **How do you perceive the indoor air quality in the classroom?**

|        | Very Satisfied (5) | Satisfied (4) | Neutral (3) | Dissatisfied (2) | Very Dissatisfied (1) |
|--------|---------------------|---------------|-------------|-----------------|----------------------|

During the measurement period from 19th to 26th December, 6 questionnaires were conducted with students in 4 sample classrooms. Students in each class were surveyed for two days. Questionnaires were distributed at three different time periods every day, at 8:40 (after the first class), 10:45 (after the second class), and 15:40 (after the seventh class). It takes students 5 minutes to answer the questionnaire. Students’ activity level during school time affects their thermal sensation [3,34]; therefore, students were required to be in the classroom for at least 30 minutes when filling out the questionnaire.

3. Results

3.1. Environmental Parameters

The maximum, minimum, and average values of the indoor and outdoor environmental parameters during the school period and the calculated values of the $t_{op}$ are summarized in Table 4. The average air temperature in the classrooms was 21.5 °C, which is higher than 18 °C, thus meeting the requirements of the specification GB 50099-2011 [35]. According to Formulas (1) and (2) the indoor $t_{op}$ of the classrooms ranged from 17.06 to 24.29 °C, with an average of 21.77 °C.
Table 4. Values of the outdoor and indoor environmental parameters.

| Site   | Parameters | Maximum | Minimum | Average | St. Deviation |
|--------|------------|---------|---------|---------|---------------|
| Outdoor | $t_a$ ($^\circ$C) | 3       | −21     | −5.9    | 6.5           |
|        | RH (%)     | 98      | 44      | 77.1    | 13.8          |
|         | $t_{op}$ ($^\circ$C) | 24.29   | 17.06   | 21.77   | 1.53          |
|         | RH (%)     | 64.47   | 27.26   | 44.42   | 8.88          |
| Indoor  | $v_a$ (m/s) | 0.25    | 0       | 0.07    | 0.03          |
|         | CO$_2$ (ppm) | 5000    | 677     | 2451    | 1007          |

$t_a$: air temperature; RH: relative humidity; $t_{op}$: operative temperature; $v_a$: air velocity.

The indoor relative humidity in the classroom ranged from 27.26% to 64.47%, with an average of 44.42%. A total of 91.9% of the relative humidity values in the school period were in the range of 30%–60%, which meets the standard of classroom humidity [35]. The research results showed that the four classrooms had few open windows during the class period, and the window opening frequency during the break period was also relatively low. The average wind speed in the classroom was low, with an average wind speed of 0.07 m/s. During the class time, the indoor wind speed ranged from 0 to 0.1 m/s due to opening doors and teachers and students walking in the classroom. When a window was opened for ventilation after class, the wind speed reached a maximum of 0.25 m/s. During the school period, the daily mean value of the CO$_2$ concentration in the classroom ranged from 1701 to 3959 ppm. The average daily CO$_2$ concentration was well above the recommended level of 1000 ppm [36], and the highest CO$_2$ concentration was 5000 ppm.

3.2. Thermal Sensation and Satisfaction Votes

In the process of on-the-spot measurement, six questionnaires were conducted in four classes. In each sample classroom, votes on thermal sensation, humidity feeling, and satisfaction were collected. The temperature and humidity of the four sample classrooms are shown in Figure 6 during the six questionnaires.

Figure 7 shows the results of the thermal sensation vote, with 19.28% votes for moderate temperature. The percentages of the votes for “warm”, “hot”, and “very hot” were 41.8%, 16.65%, and 15.33%, respectively. The results show that most students felt that the classroom environment was too hot, and only a small number of students believed that the classroom was “cool”, “cold”, or “very cold”. The combined percentage of “very hot” (+3) and “very cold” (−3) was 15.45%, representing the proportion of students that expressed dissatisfaction with the temperature. The students’ vote on the satisfaction with the indoor thermal environment is shown in Figure 8. The proportion of votes for “dissatisfied” and “very dissatisfied” with the classroom temperature was 5.04%, whereas that for “satisfied” and “very satisfied” was 86.33%. The result of the satisfaction vote indicates that children were satisfied with the indoor temperature. Although students thought the indoor environment was too hot, they still had a high acceptance of classroom temperature. Students thought that the warm temperature in the classroom might be caused by the clothing or the activity levels. Some students may have felt a little hot but were still “satisfied” with the temperature. These results are similar to those of Teil [3]. The comparative results of the thermal sensation and satisfaction votes indicate that the investigation of the students’ thermal sensation is useful for managing the indoor temperature environment. During the field measurements, the average thermal resistance of the students’ clothing changed little and remained high. High clothing insulation results in low sensitivity of the students to indoor temperature changes at low temperatures, which is consistent with the findings of Ref. [12]. It is difficult for students to adjust their thermal comfort during class, except for putting on or removing a coat. The opening of doors and windows is mostly performed by teachers or the students close to the doors and windows.
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Figure 6. Operative temperature and relative humidity in the 4 selected classrooms during the questionnaire survey.

Figure 7. Thermal sensation vote.

Figure 8. Thermal satisfaction vote.

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The results of the humidity perception and humidity satisfaction votes are shown in Figure 9 and 10, respectively; 69.7% of students thought that the humidity in the classroom was "OK". The proportion of students that felt that conditions were "somewhat dry" and "dry" were 15.21% and 9.22%, respectively. The total votes for "somewhat humid" and "humid" were only about 5%. The votes for "very dry" and "very humid" were 0.6%. Students had relatively high satisfaction with the indoor relative humidity. The combined percentage of "satisfied" and "very satisfied" votes was 82.7%. The relative humidity on 94.6% of the school days met the specification requirements. However, physiological studies have shown that the range of relative humidity that the human body feels comfortable with ranges from 45% to 65% [37]. Some of the occupants were uncomfortable.
The results of the humidity perception and humidity satisfaction votes are shown in Figures 9 and 10, respectively: 69.7% of students thought that the humidity in the classroom was “OK”. The proportion of students that felt that conditions were “somewhat dry” and “dry” were 15.21% and 9.22%, respectively. The total votes for “somewhat humid” and “humid” were only about 5%. The votes for “very dry” and “very humid” were 0.6%. Students had relatively high satisfaction with the indoor relative humidity. The combined percentage of “satisfied” and “very satisfied” votes was 82.7%. The relative humidity on 94.6% of the school days met the specification requirements. However, physiological studies have shown that the range of relative humidity that the human body feels comfortable with ranges from 45% to 65% [37]. Some of the occupants were uncomfortable in the humid environment. During field measurements, the humidity was lower during the nonschool period than during the school period. The results show that the respiration and activities of the students are the main reasons for changes in the relative humidity in the closed classrooms.

Figure 8. Thermal satisfaction vote.

Figure 9. Relative humidity sensation vote.
3.3. Thermal Neutral Temperature

SPSS was used for regression analysis of the indoor air temperature and TSV. The linear regression relationship between the TSV and the $t_{op}$ is as follows.

Figure 11 and Equation (3) show that the indoor air temperature is highly and linearly correlated with the $t_{op}$, indicating that the $t_{op}$ has a strong influence on the thermal sensation of the occupants. When TSV = 0 and PMV = 0, the measured and predicted thermal neutral temperatures are 18.05 °C and 19.2 °C, respectively, and the predicted thermal neutral temperature is slightly higher than the measured thermal neutral temperature. In addition, the TSV is higher than 0, indicating that children feel that the classroom environment is relatively hot during the measurement period.

$$TSV = 0.2907t_{op} - 5.2495$$
$$R^2 = 0.7723$$

(3)

where TSV represents the thermal sensation vote, and $t_{op}$ represents the indoor operative temperature.
The PPD was calculated based on the PMV. The actual percentage of the thermal dissatisfaction rate (denoted as PPD*) was based on the TSV of the primary school students. Figure 12 shows the relationship between the PPD and PPD* and the operative temperature. A regression analysis was conducted to obtain the regression equation. When the PPD is 80% (90%), the comfort temperature range of the primary school students is 16.7 to 20.8 °C (17.7 to 19.8 °C). When the PPD* is 90%, the comfort temperature range of the primary school students is 17.3 to 20.1 °C. When the temperature exceeds 19.5 °C, the fit of the relationship between PPD and PPD* and the indoor air temperature improves.

Figure 12. Regression relationship between the thermal dissatisfaction rate and the indoor temperature.

3.4. Perceived Air Quality

Questions 5 and 6 in Table 2 are aimed at a subjective assessment of the air quality of the classroom by the occupants based on their satisfaction with the indoor air quality. The results in Figures 13 and 14 indicate that 62.5% of occupants voted for “fresh air”, 12.5% of occupants voted for “stale”, 18.3% of occupants voted for “stale air with occasional odor”, and 6.3% of occupants voted for “stale with odor”. Figure 13 also shows the results for the different classrooms. The results for the students in Classrooms A1 and A2 were similar, and most of the students voted “stale with occasional odor”, while 63.64% of the students in B2 voted for “fresh air”. Figure 14 shows the relationship between CO₂ concentration and the dissatisfaction rate. The results show that classrooms with high CO₂ concentrations also had high dissatisfaction rates. The CO₂ concentration and dissatisfaction rate had similar trends. However, there was no linear correlation between the occupants’ dissatisfaction with the air quality and the CO₂ concentration. As shown in Figure 14, the average indoor CO₂ concentration was highest in Classroom A2, with the average daily CO₂ concentration exceeding 2600 ppm. Students in the A2 classroom also had the highest dissatisfaction with indoor air quality. However, the student’s dissatisfaction was not correlated with the CO₂ concentration in the classroom. There was little difference in the average daily CO₂ concentration between Classroom B1 and Classroom B2, but the dissatisfaction rate for Classroom B1 was much higher than that for Classroom B2.
Figure 13. The percentage of the votes for the air freshness categories in different classrooms.

Figure 14. The dissatisfaction rates and CO2 concentration during the measurement period.

4. Discussion

4.1. Comparison with Previous Research Results

Field research results of thermal comfort in winter (Table 5) show that different occupants have different levels of adaptability to and perception of the thermal environment. The predicted thermal neutral temperature of occupants is generally higher than the actual thermal neutral temperature. The reason is that the occupants have certain adaptability to the environment.
As shown in Table 5, the thermal neutral temperature of minors is generally lower than that of adults, and in Ref. [27] similar results were obtained. In the study by Li et al. [41], in the heating season and under similar conditions of clothing insulation (1.15 clo and 1.2 clo), the thermal neutral temperature of minors (17.7 °C) was significantly lower than that of adults (22.9 °C), and the difference between the two was close to 5 °C. In Refs. [42], similar results were obtained. The difference in the thermal neutral temperature between minors and adults can be explained by physical and physiological differences [25,26]. Physical differences mean that children have a higher surface area to weight ratio [44,45]; thus, their heat absorption rate and heat dissipation rate are higher than those of adults. Physiological differences mean that children have a higher heart rate [44] and a higher metabolic rate than adults [25]. Therefore, in an environment with similar physical parameters, the thermal neutral temperature of children is lower and the reaction to high temperatures is stronger than that of adults.

Rural primary school students in Gansu and Shaanxi provinces [12,43] were of similar age as the occupants in this study. However, the indoor thermal environment has high variability, and the temperature of rural classrooms is far lower than that of urban classrooms in the winter. The differences in clothing insulation, psychological expectations, and adaptability lead to significant differences in the thermal comfort results between urban and rural children of a similar age. Due to the relatively harsh weather conditions in rural areas in winter, the occupants have developed adaptive behaviors. Therefore, the thermal comfort temperature of rural children was 5 °C lower than that of urban children.

### 4.2. Clothing Insulation and Thermal Neutral Temperature

As shown in Figure 11, the slope of the curve that describes the relationship between the TSV and the indoor temperature in the comfort model in this study is 0.2907. The results indicate that primary school students in this area are highly sensitive to the temperature. Although the average indoor temperature is higher than 18 °C, children still maintain high thermal resistance by using warm clothing. High clothing insulation and a high metabolic rate cause high sensitivity to a high-temperature environment. An analysis of the results of previous studies (Table 5) indicates a linear relationship between the neutral temperature and the thermal resistance of clothing.

Figure 15 shows that the occupant’s neutral temperature decreases as the thermal resistance increases. Although clothing insulation is the main means for children to adjust their thermal...
comfort, high thermal resistance of clothing will also affect the occupants’ indoor activities and performance. As shown in Figure 15, in the winter in severe cold and cold regions, the occupants’ clothing insulation ranges from 1.2 to 1.8 clo (purple area in Figure 15). These values are much higher than the recommended value of clothing insulation in ASHRAE-55.

![Figure 15. The relationship between the neutral temperature and the clothing insulation.](image)

4.3. Prospects and Deficiencies

The comparison results in Table 5 show that compared with adults, students have different thermal sensation in the classroom under a similar thermal environment. Current thermal comfort models and indoor thermal environment standards are based on adult data and do not apply to children. Special thermal comfort standards should be set for children, and more child-centered thermal comfort research needs to be explored.

In Figure 15, the relationship between clothing thermal resistance and thermal neutral temperature indicates that a lower temperature (purple area in Figure 15) seems to further reduce the room temperature in order to facilitate energy saving. However, it is worth noting that the lower thermal neutral temperature comes at the expense of high clothing insulation. High clothing insulation will affect students’ activities and is not conducive to learning and thinking.

The heating season in the severe cold region is long; December and the next March belong to the heating period, but the outdoor temperature in December and March has an obvious difference. Further comparative analysis of long-term field measurements and questionnaires covering the entire heating season will be the focus of the next phase of the study.

5. Conclusions

In this study, the indoor air environment of classrooms was investigated, as well as the thermal comfort and PAQ of primary school students in a severe cold region in Shenyang. The following conclusions can be drawn.

The indoor temperature ranged from 17.06 to 24.29 °C during school hours, with an average of 21.77 °C. The actual and predicted thermal neutral temperatures were 18.05 and 19.2 °C, respectively. The regression relationship between the TSV and indoor temperature showed that the acceptable temperature range for 80% of primary school students was 16.0 to 21.4 °C, and that of 90% of primary school students was 17.3 to 20.1 °C. This shows that the indoor temperature can be adjusted down to adapt to the students’ feelings and save energy.
The results of the TSV showed that most children thought that the classroom temperature was relatively hot; 41.80% thought it was “warm”, 16.65% thought it was “hot”, and 15.33% thought it was “very hot”. Although 57% of the indoor relative humidity values in the school period were less than 45%, most of the primary school students felt that the indoor humidity was moderate. Only 25.03% of the students voted that the classroom environment was dry, indicating that the sensitivity of children to temperature is higher than that of humidity.

The children in severe cold regions, whose actual neutral heat temperature was lower than the predicted value, were sensitive to high temperature and prefer a colder environment than adults in winter, all of which were due to significant clothing insulation and higher metabolism. At present and in the future, more research based on children’s data is needed to solve indoor air environment problems in primary school buildings.

In order to maintain the thermal environment, reducing ventilation in the winter classroom in severe cold areas will easily lead to indoor CO$_2$ concentration exceeding the standard value. Moreover, the air quality evaluation results indicated that students in naturally ventilated classrooms were unable to judge indoor air quality accurately. Therefore, it is necessary to add indoor air environment monitoring instruments and purification equipment to primary school classrooms during the heating season.

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