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Student responses to classroom thermal environments in rural primary and secondary schools in winter

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ABSTRACT

A comfortable classroom environment is conducive to the growth and education of young students. The goal of this study was to investigate the thermal environments in rural primary and secondary school classrooms in Northwest China and identify suitable values for the design parameters of heating systems to ensure the thermal comfort of the students. Surveys were conducted and field measurements were obtained from November 2014 to December 2015. The measurements included indoor and outdoor environmental parameters, such as the dry-bulb temperature, the relative humidity, the indoor air-flow speed, the globe temperature and the CO2 concentration. Data were collected in a total of 36 classrooms in 13 primary and secondary schools. The perceptions of 1126 students regarding the indoor environment were collected through questionnaires. Both the thermal sensation vote (TSV) and the predicted mean vote (PMV) were evaluated. The slope of the TSV curve was noticeably less than that of the PMV curve, which indicates that the students are less sensitive to temperature changes than predicted. The adaptive predicted mean vote (aPMV) model was also used to evaluate the students' mean thermal sensation and was more suitable for this research. The neutral temperature, the preferred temperature and the comfortable temperature range of students were obtained by analyzing the actual predicted percentage dissatisfied (PPD*) and the students' thermal comfort expectations. The findings can serve as a guideline for the design and evaluation of heating systems in primary and secondary schools in rural areas.

1. Introduction

Young students spend approximately 30% of their lives in school classrooms [1]. Therefore, appropriate indoor conditions are necessary, including the thermal environment and air conditioning. There are complicated relationships between a building's physical environment and various psychological and physiological factors exhibited by the occupants. The climate, the economic conditions, the design of the building and the students' ages affect the thermal environments of primary and secondary school classrooms and the students' perceptions of them. The perceptions of students in rural Northwest China are different from those in urban areas. Hence, the design parameters in the current building design standard [2] may not be suitable for rural schools in Northwest China. The specification does not consider the differences between urban and rural areas and differences in climate.

Many studies [3,4] have examined the thermal comfort of children, and the results have shown that the actual thermal comfort levels differ from those given in the international thermal comfort standard, ISO 7730 [5], and the U.S. standard, ASHRAE 55-2013 [6]. These studies used a steady-state predicted mean vote (PMV) model, which assumes a steady state condition.

The values of the main environmental variables related to thermal comfort are different for adults and children. Pupils aged 7 to 11 in England were more sensitive than adults to higher temperatures, and comfortable temperatures were lower than those given by the PMV and the EN 15251 adaptive comfort model by approximately 4.0 and 2.0 °C, respectively [7]. In a recent study in Australia, the neutral and preferred temperatures of students were found to be generally lower than those for adults under the same thermal environmental conditions [8]. A study conducted in the UK that obtained the thermal sensation responses of 2693 pupils and measured classroom temperatures found that schoolchildren have lower comfort temperatures than adults [9]. Children have a higher metabolism than adults; therefore, the requirements for the indoor

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thermal environment are different, and comfort standards for adults may be not adequate for children. Further research on the thermal comfort requirements of schoolchildren is necessary.

Several studies have examined gender differences in the thermal comfort levels of children in primary and secondary schools. Nam et al. [10] conducted research on the thermal comfort perceptions of preschool children and kindergarteners aged 4–6 years old in Korea and examined the influence of gender on thermal comfort. Katafygiotou and Serghides [11] studied a typical classroom and a laboratory in a secondary school building in Cyprus over several seasons and found differences in the thermal sensations of girls and boys.

Primary and secondary school classroom are often naturally ventilated. Mishra et al. [12] conducted a study of naturally ventilated (NV) classrooms at the Indian Institute of Technology at Kharagpur. The students exhibited broad comfort zones and a significant level of adaptation to the environments of NV classrooms. Thermal comfort in ventilated classrooms has also been studied in England [13,14], Chile [15] and the Netherlands [16]. Zeiler [17] evaluated the performance of thermo-active building heating systems in schools in the Netherlands during the winter.

Several representative models from thermal adaptation theory have been developed. Fanger and Toftum proposed the expectation factor as an extension to the PMV model [18]. Auliciems, Humphreys, Nicol, de Dear and others have presented various empirical equations for predicting comfortable temperatures, which various studies have shown are a function of the outdoor air temperature [19–21]. Based on a black box approach, Yao [22] developed the adaptive predicted mean vote (aPMV), which considers factors such as culture, climate, and social, psychological and behavioral adaptations. Yao's model involves the heat balance and uses an adaptive approach to predict thermal sensation votes. Basic information for the present research was obtained from Ref. [23].

Because of the lower economic development in rural regions, advanced heating systems are generally lacking, and the thermal environment in classrooms in Northwest China is uncomfortable in winter. To improve the conditions in primary and secondary school classrooms, the following tasks were undertaken:

- Data on the indoor thermal environment in rural primary and secondary schools including the dry-bulb temperature, the relative humidity, the air speed, the globe temperature and the CO2 concentration were collected.
- Surveys of the pupils were conducted concurrently with the collection of the measured environmental data.
- The measured data and the survey results were analyzed to obtain the neutral temperature, the preferred temperature, and the comfortable temperature range.
- The results obtained from the PMV, MTS and aPMV models were compared, and the local conditions that affect the adaptation in the aPMV model were analyzed.

The results of this study can provide guidelines for achieving a satisfactory indoor thermal environment and for evaluating the indoor thermal environments of primary and secondary schools in Northwest China.

2. Methodology

Measurements of the classroom thermal environments were collected, and surveys of the thermal sensations of primary and secondary school students were conducted. The data were collected in the period November 15–22, 2014, in Shaanxi Province, December 21–31, 2014, in Gansu Province, and December 5–13, 2015, in Qinghai Province. The data were collected from 13 schools and included a total of 36 classrooms and 1126 pupils. The thermal sensation vote (TSV) was obtained from questionnaires, the PMV value was calculated based on ISO 7730 [5], and estimates of metabolic rates were obtained from Havenith [24]. Estimates of clothing insulation values were calculated based on ASHRAE Standard 55-2013 [6]. The variation in clothing insulation as a function of the indoor temperature was included. Neutral temperatures, preferred temperatures, and comfortable temperature ranges in the classrooms were obtained through an analysis of the measurements and the survey results.

2.1. Geographical and climatic conditions and school building parameters

The survey was conducted in rural areas of Shaanxi, Gansu and Qinghai Provinces in Northwest China, where the mean temperatures in the coldest months are −0.9 °C, −6.7 °C and −8.2 °C, respectively, and the number of days on which heating is required are 82,126, and 161 days, respectively. The locations of the provinces and the primary and secondary schools included in the study are shown in Fig. 1. The numbers of schools, classrooms and students in each province were as follows: 4 schools, 14 classrooms and 421 students in Qinghai Province, 4 schools, 10 classrooms and 345 students in Shaanxi Province, and 5 schools, 12 classrooms and 360 students in Gansu Province. A total of 1206 questionnaires were distributed and 1126 were returned, giving a return rate of 93%. The respondents included 514 male students (45.6%) and 612 female students (54.4%), all between the ages of 9 and 16, with an average age of 12.6 years. Table 1 lists the numbers of stories and the ages of the school buildings, the types of external walls and windows, the heating system types, and the gender ratios of the students.

2.2. Survey questionnaires

To ensure that younger students could easily understand the questions (see Fig. 2), the surveys were designed in cooperation with the teachers. Additionally, each item in the questionnaire was explained by the teachers before the students completed the questionnaires. The survey included the following information: (1) basic information about the students such as gender, age, and clothing; (2) perceptions of the temperature and the humidity, the air quality, and thermal comfort levels using the 7-point ASHRAE scale for the TSV and a 5-point scale for the thermal comfort rating; (3) the thermal preference, the thermal acceptance (acceptability of the thermal environment for a thermal sensation vote ranging from −1 to 1). The main contents of the questionnaire are shown in Fig. 2.

The total clothing insulation value, or thermal resistance, for an individual can be calculated using Equation (1) [25] (the thermal resistance of the wooden seats in the classrooms was disregarded [26]):

$$I_{\mathrm{cl}} = 0.835 \sum_{i} I_{clu,i} + 0.161 \quad (1)$$

where I_{cl} is the total clothing thermal resistance and $I_{clu,i}$ is the thermal resistance for each piece of clothing in units of clo (1 clo = 0.155 (°C•m^2)/W).

2.3. Environmental measurements

The arrangement of the instrumentation at the No. 1 school in Qinghai province is shown in Fig. 3. The indoor environmental conditions (i.e., the air temperature, the relative humidity, the