Energy and Buildings 116 (2016) 133–140

Contents lists available at ScienceDirect

Energy and Buildings

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

Influence of outdoor temperature on the indoor environment and thermal adaptation in Chinese residential buildings during the heating season

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ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form
18 December 2015
Accepted 28 December 2015

Keywords:
Outdoor temperature
Residential buildings
Thermal comfort
Thermal adaptation
Energy saving

ABSTRACT

The relationship between the outdoor temperature and the indoor comfort temperature in naturally ventilated buildings is close to linear; this relationship is complex in heated or cooled buildings. To explore the influencing mechanism of the outdoor temperature on the indoor air temperature and thermal adaptation in winter, field studies on the thermal comfort in residential buildings with heating systems during the heating season have been conducted in three northern cities of China, with both subjective questionnaire surveys and objective on-site measurements performed simultaneously in every field survey. The results indicated that the indoor temperature is affected by the outdoor climate to some extent, even under conditions of space heating. When the outdoor temperature was below 10 °C in cold climates, the indoor temperature gradually increased with the decrease of the outdoor temperature. The outdoor temperature affected not only the adaptive behavior, but also the thermal acceptability. When the outdoor temperature experienced by the occupants in winter was lower, and the low temperature was experienced longer, the dependence on heating equipment, acceptability of a high temperature, and impatience with a low temperature environment were stronger. When the mean outdoor temperature experienced by the occupants was only slightly cold, the occupants expressed a lower thermal expectation and accepted a wider temperature range. The above climate adaptation mechanism provides a valuable reference for the design of higher efficient space heating systems.

1. Introduction

Northern China, with an area of nearly half of China's land, is cold in winter, and the heating period lasts for three to six months. It was reported that space heating consumed 23% of the total building operational energy consumption in northern China in 2008 [1], and then rose to 25% in 2011 [2]. According to a recent study on centrally heated dwellings in the UK, it was found that there was a 10% rise in the required heating temperature; for example, the thermostat settings were changed from 20 to 22 °C, which resulted in a 15% increase in energy consumption [3]. In Harbin City of China, the indoor air temperature during heating periods was approximately 17.5 °C in 1990, rising to 20.1 °C in 2000 [4,5], and then to approximately 22.8 °C in 2010 [6]. Consequently, there is an upward trend in the energy consumption for space heating in the cold climate. Therefore, the indoor thermal environment conditions and people's requirement of thermal comfort have a great impact on the energy consumption in spacing heating and on greenhouse gas emissions [7,8].

Humphreys first explored the quantitative relationship between indoor comfort temperature and outdoor temperature. The relationship for the buildings without active heating or cooling was close nearly linear. For heated and cooled buildings, the relationship is more complex [9]. Although studies on thermal comfort in heated or cooled buildings are not as common as those in naturally ventilated buildings, some remarkable results regarding the thermal environment and thermal comfort in heated buildings have been achieved in recent years. The indoor air temperature of China's urban dwellings without heating facilities was approximately 12–15 °C during the winter [10], which was far below the lower limits prescribed in ASHRAE 55 (2010) [11] and ISO 7730 (2005) [12] comfort standards. In contrast, the situation was better in the dwelling houses with district heating systems, and the mean indoor temperature of most surveyed spaces was

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http://dx.doi.org/10.1016/j.enbuild.2015.12.053
0378-7788/

approximately 22 °C in China [6,13], England [14] and Germany [15]. The living room temperature in UK homes may need to be maintained within the range of 20–22 °C for thermal satisfaction [16]. However, recently, some researchers reported that overheating situations occurred in varying degrees in the centrally heated dwelling houses, which led to thermal discomfort and energy waste during the heating period [13,14,17]. The outdoor climate had an influence on thermal adaptability, and therefore, the neutral temperature in winter was lower than that in spring [17]. Generally, people felt cold before heating but comfortable at the same cold temperature during heating periods, which might be caused by human expectations [6]. Moreover, studies have found the influences of different heating modes on the indoor environment and thermal comfort [18,19]. The occupants with individual heating accepted a lower neutral operative temperature and expressed a lower expectation of changing their current thermal conditions than those with district heating [20]. Despite the above valuable results of thermal comfort research in space-heated buildings, the effect of the outdoor temperature on the thermal environment and thermal adaptability needs to be explored in depth, as addressed by this paper. Field studies on thermal comfort were conducted during the winter heating period in three cities of China: Baotou, Yinchuan and Jiaozuo. The environmental parameters and thermal responses in the three cities were compared, the effect of the outdoor air temperature on space heating, indoor thermal environment, behavior adjustment, and thermal acceptability were analyzed, and the suitable heating temperature in cold zones and energy saving were discussed.

2. Method

2.1. Geography and climate characteristics

Qinling mountain and Huai River is the regional and climatic dividing line of North-south in China. Baotou, Yinchuan and Jiaozuo are located in northern China (Fig. 1(a)). The monthly mean dry-bulb temperatures, based on a typical meteorological year (TMY), for Baotou, Yinchuan and Jiaozuo [21] are shown in Fig. 1(b). Although the summer temperatures in these cities are similar, the winter temperatures are quite different. The mean daily temperature of the coldest month (January) in Baotou is −12.2 °C, which is the lowest of the three cities. The mean daily temperatures of January in Yinchuan and Jiaozuo are −6.0 °C and 1.5 °C, respectively. Then, according to the definition of China's national standard Thermal Design Code for Civil Building (GB50176-93) [22], Baotou and Yinchuan belong to the severe cold zone, while Jiaozuo falls into the cold zone. Because the cold climates of the above cities in winter last for a long period, these cities fall into the district heating zone of China. Normally, heating supply methods in China can be divided into two categories: district heating and individual heating. Occupants in apartments supplied with district heating have no direct way to control the indoor thermal environment, meaning this group of occupants had to accept their thermal environment passively [19]. During the survey period, the investigated apartments with district heating were provided 24 h heating.

2.2. Questionnaire surveys and on-site measurement

The surveys in this study were performed in the winter of January, February and December in 2010 during the middle of a heating period. A summary of the background characteristics of the surveys is given in Table 1. A total of 377 sets of valid data were obtained from surveying 133 subjects in 63 house19holds in Baotou. For 69 residential units in Yinchuan, 178 individuals provided a total of 519 sets of valid data, and 99 individuals from 44 residential units provided 891 sets of valid data in Jiaozuo. The percentage of female interviewees is slightly higher than male interviewees. All of the households were randomly selected, but no more than two households were located in the same building. Owing to the limitation of manpower, economy, and equipment, the surveys conducted in Baotou were spread over a period of a week, and spread over another week in Yinchuan. The occupants were asked to fill out the questionnaire three times a day, i.e., morning (6–8 a.m.), noon (11 a.m.–1 p.m.) and evening (7–9 p.m.). Because the investigators lived in Jiaozuo, the survey in Jiaozuo lasted about one month, and the survey of every household in Jiaozuo lasted three days. Although differences existed in the investigation span, the obtained data can reflect the local thermal environment and thermal response of each city during the middle of the heating period.

The subject houses under investigation were all apartment types situated in urban areas. A thermal comfort questionnaire was used to gather information about the subjective thermal sensation and humidity sensation with the ASHRAE seven-point scale. The questionnaire also included general background information, such as age, gender, weight and height of the occupants, as well as the activity level, thermal environmental control, space heating method, and a clothing checklist.

When the occupants of these houses were filling out the questionnaires, they were asked to sit and relax in their rooms. The field test included the measurements of air temperature and relative humidity (indoor and outdoor) by data loggers (Testo 175 H2, Germany). The accuracy of the temperature sensor and the humidity sensor is ±0.5 K and ±3% RH, respectively. The data loggers,

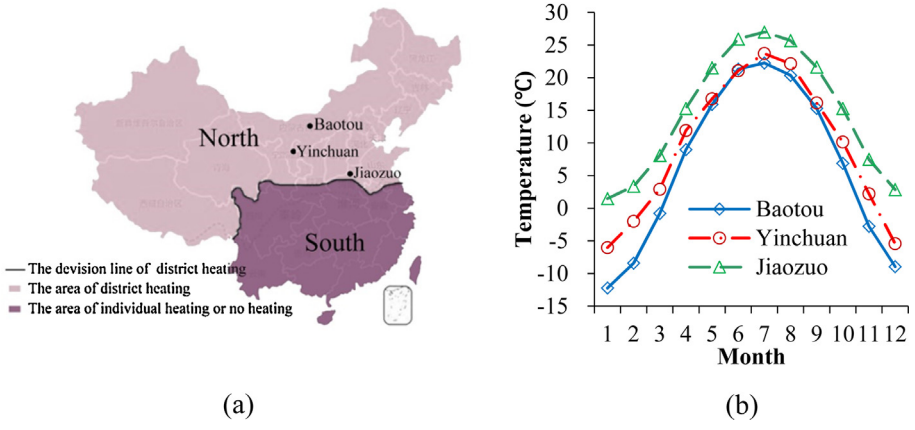

Fig. 1. (a) Location of Baotou, Yinchuan and Jiaozuo. (b). Monthly mean outdoor dry-bulb temperature (based on typical meteorological year).