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Full Length Article

Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China

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ABSTRACT

Seasonal variation of thermal comfort demands directly affects the energy needs for heating or cooling purpose. In previous studies, the differences of neutral temperatures between summer and winter were revealed, but the studies on the difference of human thermal adaption in transitional seasons are insufficient. To clarify this, this paper presents a year-long survey which was carried out in 505 residential buildings in six cities located in the Hot Summer and Cold Winter (HSCW) zone of China involving 11,524 subjects. Results show a significant difference of adaptive responses in different seasons, and a lag of behavioral responses behind climate change in transitional seasons is observed. Occupants not only adjust clothing insulation according to air temperature in different seasons, but also actively control indoor air movement, including closing/opening windows and using fans. The seasonal, monthly and daily neutral temperatures are studied, implying that occupants' thermal experience has significant effect on their thermal comfort by behavioral, physiological and psychological paths. According to the comparative study, the running mean air temperature method and aPMV model are recommended in free-running space. The findings provide scientific evidence to the concept that dynamic thermal comfort temperature range should be considered in evaluation of indoor thermal environment.

1. Introduction

The existing building stock in cities in China's Hot Summer and Cold Winter (HSCW) climate zone covers some 9 billion m^2 of which residential buildings accounted for 66% in 2012 [1]. The HSCW zone has unique climate characteristics, i.e. hot long summers, cold wet winters, a rainy climate with monsoon, and so on, as described in reference [2]. Due to economic growth, there has been a continued and growing demand for the improvement of the indoor thermal environment and consequently the growth of energy demand for both heating and cooling [1,3]. Such situations have a considerable adverse impact on the nation's energy reduction target [4].

In residential buildings, besides the building design [5], occupants' behavioral habits, varieties of thermal sensation and comfort requirements [6] significantly impact on energy consumption. There would be a potential waste of energy [7] to maintain the indoor thermal environment within the thermal comfort thresholds using the thermal comfort standards if there is not a full understanding of the different thermal sensation characteristics in different seasons in free-running buildings. Our previous study in naturally ventilated classrooms demonstrates that occupants' thermal sensations dynamically respond to the outdoor climate [8]. Because of adaptions to the natural climate using available facilities, occupants have a wider acceptable temperature range in NV (Naturally ventilated) buildings than that in AC (Air-conditioned) buildings [9–11]. Many studies [12–20] also conclude that differences exist in occupants' thermal sensations between summer and winter, due to the obvious differences in outdoor climates between these two seasons.

China has a diverse climate and consequently is divided into five climate zones for building thermal design purposes [21]. Among the five zones, the HSCW zone has unique climatic characteristics and the residents have diverse adaptations for ensuring thermal comfort [22–26] in free-running space. This has attracted many scholars to engage in this research. Some previous studies were concentrated in a specific city for year-long study [26,27], whilst

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Nomenclature

PMV	Predicted Mean Vote
TSV	Thermal sensation vote
AMV	Actual mean vote (of thermal sensation)
aPMV	Adaptive model of PMV
ePMV	Extended model of PMV
MTU	Monthly Temperature Up (winter → spring → summer)
MTD	Monthly Temperature Down (summer → autumn → winter)
V_a	Indoor air velocity, m/s
V_{out}	Outdoor air velocity, m/s
RH_a	Indoor relative humidity, %
RH_{out}	Outdoor relative humidity, %
T_a	Indoor air temperature, °C
T_{out}	Outdoor air temperature, °C
$T_{out, m}$	Monthly mean outdoor air temperature, °C
T_n	Neutral temperature, °C
$T_{n, s}$	Seasonal neutral temperature, °C
$T_{n, m}$	Monthly neutral temperature, °C
$T_{n,d}$	Daily neutral temperature, °C
T_{od-i}	the 24-h daily mean temperatures of i days ago, °C
T_{rm}	Ddaily running mean outdoor air temperature, °C
AC	Air-conditioned
NV	Naturally ventilated
SD	Standard deviation
HSCW	Hot summer and cold winter
P	Probability
R^2	Determination coefficient
I_{cl}	Ensemble clothing insulation
PFU	Proportion of fan use
PWO	Proportion of windows opened
N	Number of samples

some studies focused on a specific season (e.g. summer) in this area [28,29]. However, most studies [30–33] were only conducted during a specific season in one city/province.

The aim of this study is to obtain a sophisticated understanding of residents' thermal sensations and their dynamic responses to the variation in outdoor climates for different seasons in free-running space. This will provide a fundamental knowledge of the thermal comfort demand for residential buildings in this region. Consequently, a dynamic solution to achieve indoor thermal comfort in residential buildings will possibly be developed to meet the requirements for both thermal comfort and energy efficiency.

2. Methods

Onsite field measurements and a questionnaire survey have been conducted in this research. Statistical regression methods are used for the analysis of data.

2.1. Brief of the field study

A large-scale, nationwide, thermal comfort survey was conducted in the five climate zones of China during the period 2008–2011 [34]. The field study in each city lasted for more than twelve months. The data were collected in daytime from 8:30 to 20:30 by visiting selected typical buildings in a city on three to five occasions in each month. During the field study, thermal comfort questionnaire surveys were conducted, while the indoor and outdoor thermal environmental parameters, such as air temperature, relative humidity, and air velocity were measured.

This paper presents the study of 505 residential buildings involving 11,524 subjects in the six cities located in the Hot Summer and Cold Winter zone covering Chongqing, Chengdu, Wuhan, Nanjing, Hangzhou and Changsha as illustrated in Fig. 1.

2.2. Subjective questionnaire

The questionnaire was written in Chinese, and designed to obtain comprehensive information on human responses to the thermal environment. Subjects' thermal sensation vote uses the ASHRAE seven-point thermal sensation scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot).

Occupants' clothing insulation uses the clo-checklist method, which was explained clearly in the questionnaire. Occupants can check their own types of clothing ensembles according to a list of clothes types provided in the Chinese code *'GB/T50785-2012: Appendix C: Clothing Insulation'* [35], which was translated from *'ISO7730: Annex C: Estimation of thermal insulation of clothing ensembles'* [36]. The values of different clothes types' insulation were obtained according to this code. Meanwhile, the status of windows (opened/closed) and fans (used/not used) was recorded during the survey.

2.3. Environmental parameters measurements

Indoor and outdoor environmental parameters including air temperature, relative humidity and air velocity were simultaneously measured during the survey. Because there were no obvious sources of heat radiation indoors, the indoor black globe temperature was not measured and assumed to equal the indoor air temperature in this study. Table 1 shows the instruments used to measure these environmental parameters, their accuracy and measuring ranges. According to ASHRAE 55 [37], the indoor measurement point was located at the height of the occupants' abdomen, i.e. at 0.6 m level above the floor for the seated occupants and 1.1 m level above the floor for the standing occupants respectively. The outdoor measurement points were placed in an open area near the buildings at the height of 1.1m.

2.4. Buildings

Among the buildings accommodating the apartments involved in the survey, most of them are located in downtowns of which 32.3% are along a main street and 54.7% are located inside residential communities, and other 13.0% are located in the suburbs. 60.1% of the surveyed buildings are reinforced concrete structures and the others are brick-concrete structures. Most buildings were less than 30 years old at the time of the survey. The buildings surveyed had one-, two-, three- and four-bedroom apartments usually with one dining and one living room. The average area of a room within the apartment was about 22.64 m^2; all the surveyed rooms have operable outside windows.

2.5. Subjects

The subjects were 47.4% male and 52.6% female, and mostly aged between 20 and 60. More than 95% of subjects weighed between 40 and 80 kg, and most of their heights were between 150 and 180 cm. Most of them had lived in the surveyed cities for between 8 and 42 years. The daily occupancy time in the apartment was mostly between 6 and 17 h.