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Adaptation-based indoor environment control in a hot-humid area

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ABSTRACT

Human thermal adaptation has received more and more attentions since 1990s as its capability to explain and predict human thermal comfort in buildings. The present study aimed to propose a new indoor environment control based on human thermal adaptation (named as adaptation-based control), and test its performance in the hot-humid area. The adaptation-based control was defined as the united control of operable windows, electric fans and air-conditioners by sensing indoor and outdoor environment parameters with an aim to creating a healthy, comfortable and energy efficient indoor environment. The adaptation-based control system was set up and the field tests were conducted in an office building in the typical summer days. The tests confirmed that all the expected targets on indoor environment were well achieved by the control system. Compared to the conventional control (air temperature set point at 26 °C), the adaptation-based control increased the indoor air temperature, mean radiant temperature, moisture content and air speed while decreased the indoor CO_2 concentration. The occupants perceived the indoor environment more close to neutral in thermal and humid aspects, and the same or more comfortable and acceptable in terms of thermal environment and air quality. The sick building syndrome incidence was decreased by 40%. The daily mean energy consumption on indoor air conditioning was saved by 31% on the sunny days and by 40% on the overcast days. The adaptation-based control is strongly recommended to apply in the hot-humid area as its great advantages on human comfort and energy saving.

1. Introduction

The hot-humid area in South China includes Guangdong, Guangxi, Fujian, Hainan, Hong Kong, Macao and Taiwan. The summer is very long, hot and humid, and the winter is short and temperate. The economy is rapidly developed, the building stock is large and the air-conditioners are widely used in buildings in this area. For instance, the ownership of air-conditioners has reached to 1.09 units per household at the end of 2014 [1] in the Guangdong province. It is of great importance and practical significance to study the controls of air-conditioner and indoor environment for both human thermal comfort and building energy saving in the hot-humid area.

The return-air temperature of an air-conditioner is usually set by users (e.g. 26 °C) and automatically controlled by the air-conditioner system. This is mostly widely used in the hot-humid area and referred to as conventional control in this study. Under the conventional control, the indoor air temperature is under control, while other parameters, such as humidity and air speed, are not well controlled, and the personal factors (e.g. clothing insulation) are not considered by the control system, resulting in an indoor environment that human thermal comfort may not be fully guaranteed.

Fanger [2] proposed the predicted mean vote (PMV) model in 1970 based on the human heat balance equations. The PMV model took a more comprehensive perspective by including four environmental and two personal factors and provided a solid foundation for predicting human thermal comfort. Since then, the new indoor environment control that based on the PMV model, namely, the PMV-based control, occurred. The PMV-based control uses sensors to collect indoor environment parameters of air temperature, humidity, speed and mean radiant temperature (MRT), applies the PMV model [3–5], the artificial neural networks [6–9], or the fuzzy logic algorithms [10,11] to predict the actual PMV value, and drives the actuators triggered by the PMV difference between the

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actual and the preset, so as to achieve a constant PMV and a better thermal comfort.

Compared with the conventional control, the PMV-based control takes more factors into consideration, guarantees a better comfort and provides more potentials on energy saving. However, as proved by many field studies in the recent 30 years, the PMV model cannot well predict the human thermal sensation and the neutral temperatures in real buildings, particularly in the natural ventilated (NV) buildings in warm climates. Meanwhile, the PMV-based control is mainly focused on the air conditioning system. Other environmental conditioning measures, such as electric fans and operable windows, are not included, and therefore, the total efficiency and the energy saving potentials still have rooms for improvement.

Human thermal adaptation has received more and more attentions since 1990s. In 1998, Brager and de Dear [12] proposed a conceptual model for thermal adaptation, based on the premise that the person is no longer a passive recipient of the given thermal environment, but instead is an active agent interacting with the person-environment system via multiple feedback loops. Thermal adaptation was attributed to three processes of behavioral adjustment, physiological acclimatization and psychological adaptation, and the expectation was proposed as the most likely explanation for the poor predictive capabilities of the PMV model in the NV buildings. By collecting the field data in the NV buildings around the world, de Dear et al. [13] established an adaptive comfort model in forms of linear relationship between the monthly mean outdoor air temperature and the indoor neutral operative temperature, and introduced it into the ASHRAE 55 standard [14] as an optional method for determining the acceptable thermal conditions in the NV spaces. The adaptive comfort model has a better capability to explain and predict human thermal comfort in real buildings compared to the PMV model.

In summary, the conventional and PMV-based indoor environment controls both have some deficiencies in ensuring human comfort and improving building energy saving. The present study is aimed to propose a new indoor environment control based on human thermal adaptation (named as adaptation-based control), and test its performances in human comfort and energy saving in an office building in the hot-humid area of China.

Our specific goals are: 1) to propose the adaptation-based control and its logic based on previous studies on human thermal adaptation in the hot-humid area of China; 2) to develop an adaptation-based control system in an office building in the hot-humid area of China; 3) to conduct the comparative field tests on the adaptation-based control and the conventional control in the typical summer days; and 4) to determine the performance of the adaptation-based control in terms of indoor environment, subjective responses and energy efficiency. This study moves forwards the human thermal adaptation from fundamentals and standards to engineering techniques, and provides valuable references for the innovations and applications of the advanced indoor environment control in the hot-humid area.

2. Adaptation-based control

2.1. Literature review

The previous studies on human thermal adaptation in the hot-humid area in China were briefly reviewed as follows.

A climate chamber study was conducted on the thermal comfort of sixty subjects who were born and raised in the hot-humid area. Seasonal and climatic heat acclimatization was confirmed, and the indoor thermal history was found to play a key role in shaping the subjects' sensations by showing that a warmer indoor thermal history in warm seasons produced a higher neutral temperature, a lower thermal sensitivity, and lower thermal sensations in warm conditions [15].

The thermal comfort field studies were carried out for a whole year both in the NV buildings and the buildings with split air-conditioners in the hot-humid area in China. The adaptive behaviors of clothing adjustment, opening windows, using fans and using air-conditioners were identified, and the functions relating the behaviors and indoor environment were provided [16,17].

A large thermal comfort database that consists of 3894 sets of raw data from 32 urban and 270 rural buildings was established by Zhang [18]. Based on the database, the acceptable range was determined and the design criteria were proposed for the built environments of naturally ventilation, using fans and using air-conditioners. The acceptable range of indoor air temperature by opening windows and doors was 18.0–28.5 °C for urban buildings and ≤28.5 °C for rural buildings under the conditions that indoor air speed of 0.3 m/s could be achieved. The upper limit of indoor air temperature was raised from 28.5 °C to 29.5 °C by using fans under the conditions that a maximum indoor air speed of 0.9 m/s could be achieved. Air-conditioners were turned on with setting points range of 24–28 °C when indoor air temperature was higher than 29.5 °C.

Airflow utilization is an effective and low-cost way of local people in the hot-humid area to maintain comfort in summer. A summer-long field study conducted on nine NV buildings showed that opening windows and doors were driven by both indoor air quality and thermal comfort motivations, while using fans were driven by thermal comfort motivations [19]. Zhai et al. [20] and Zhai et al. [21] studied the effects of using fans in warm and humid environments in climate chambers. The results showed that the upper limit of the 80% acceptable range could be raised up to 30 °C and 60%, and 30 °C and 80%, respectively, when the fans with and without personal controls were provided. The indoor air speeds that required for maintaining thermal comfort were also provided.

2.2. Control logic

A new indoor environment control was proposed based on the previous studies on human thermal adaptation in the hot-humid area. The adaptation-based control was defined as the united control of operable windows, electric fans and air-conditioners by sensing indoor and outdoor environment parameters with an aim to creating a healthy, comfortable and energy efficient indoor environment. The logic of the control is shown in Fig. 1.

The temperature settings for opening windows and using fans were determined according to Refs. [16–19]. The temperature settings for running both air-conditioners and fans were determined according to Refs. [20,21]. In addition, two logics were developed for opening windows. One was triggered by the indoor CO_2 concentration, aiming to guarantee the healthy indoor air quality, and the other was triggered by the indoor-outdoor air temperature difference, aiming to make full use of the outdoor climate resources. The CO_2 control target was set as below 1100 ppm according to the national indoor environment standard.

3. Research methods

3.1. Office and equipment

Guangzhou is located at latitude 23°08′N and longitude 113°19′E and is a typical city in the hot-humid area of China. The monthly mean air temperature is 28.4 °C and the relative humidity is 83% in July, and 13.3 °C and 74% in January, respectively. Two adjacent offices on the second floor of an office building in Guangzhou were