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Study on adaptive thermal comfort in Japanese offices under various operation modes

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ABSTRACT

This research focuses on determining thermal comfort and analysing adaptive opportunities in Japanese office buildings under various operation modes including free running (FR) mode. There are very limited studies on office buildings linking occupant's adaptive actions and various modes of operation, compared to studies on houses and air-conditioned buildings in Japan. Large data on Japanese lifestyle, socio-cultural setup and climate are required in order to construct the adaptive model that can be used for the design of indoor thermal environments of Japanese offices.

We conducted questionnaire based field surveys to record thermal comfort responses of occupants and measured environmental variables simultaneously, in all the seasons in Tokyo and Kanagawa, Japan. The comfort temperature is evaluated with SET^* (Standard effective temperature) in order to incorporate the effect of humidity and air velocity on thermal comfort. Nonlinear regression analysis is used to analyse the lower and upper limit of the optimum comfort temperature. Authors also examine adaptive models that can be used to design indoor thermal environment of Japanese office buildings under different operation modes. The limit of the optimum comfort temperature is shown at very low and high outdoor air temperature. The lower and upper limits of the optimum comfort temperature is approximately 23.5 °C and 26.6 °C in mixed-mode. In addition, it is seen that the optimum comfort temperature tends to increase and decrease at very low and high outdoor air temperatures respectively. We find behavioural adaptation related to clothing and window-opening leading to variation in the comfort temperature across different seasons.

1. Introduction

Thermal comfort is a complex design problem involving various parameters. In an air conditioned environment, the response of occupants towards comfort temperature and preference were found to be similar in spite of variations in race, gender and age of occupants and climates [1]. Thus *PMV-PPD* model is widely accepted as an index for thermal comfort [1]. However, field surveys especially in naturally ventilated (NV) buildings and buildings in free running (FR) mode (i.e. air-conditioning is not in use) around the world prove that comfort temperature varies with outdoor air temperature. This indicates a strong influence of prevailing outdoor environmental conditions on comfort temperature [2,3]. Variation in prevailing outdoor environmental conditions provides opportunities for occupants to adapt based on their past experiences, and it also influences the comfort temperature [4].

Adaptation is a continuous process and is influenced by prevailing environmental conditions, past experiences and expectations of the occupant. It also assumes that subjects are active towards change in the surrounding thermal environment and always act on personal factors or initiate actions that work towards restoring comfort. Imperative, if occupants get adaptive opportunities to take various actions, it leads to their satisfaction. It is well established that occupant's comfort preferences and feelings are different in air-conditioned environments compared to the non-air-conditioned environments [5,6].

Research also suggests that offices ventilated naturally by open-

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windows not only improves the thermal comfort for occupants but also saves energy [5]. In the context of global warming much more attention has been given to building energy savings as this sector is second largest consumer of primary energy in Japan [7]. A method to promote energy saving is to relax the air-conditioning set temperature and the introduction of natural ventilation. Study of built thermal environment based on adaptive thermal comfort model is being promoted around the world because it considers the adaptive opportunity, natural ventilation and a range of comfort temperature [5,8–11]. Based on adaptive thermal comfort field study results from across the world, ASHRAE standard 55 [2] and European Standard EN 15251 [3], in their latest editions incorporated adaptive thermal comfort models in defining indoor thermal environment. However, this database does not include data from Japanese buildings. In Japan *PMV* is widely used as thermal comfort index and is yet to have an adaptive comfort model covering a wide range of buildings.

In general, indoor temperature setting for air-conditioning systems in the offices of Japan in summer and winter is 26 °C and 22 °C respectively. With an aim to reduce the energy consumption in the offices of Japan, Government of Japan introduced cool biz and warm biz initiatives in 2005 where office occupants are allowed to wear flexible clothing in summer and winter [12]. In same year, Government of Japan also recommended new set temperatures of 28 °C and 20 °C [12] for summer and winter respectively. Cool biz and warm biz initiatives make it easier for office occupants to take adaptive actions to be comfortable based on outdoor thermal environments.

Just by shifting the set point temperatures and by allowing occupants to change clothing level may not achieve the target of improving comfort and reducing energy consumption. Instead it is required that the thermal environment should be designed considering adaptive model so that better adaptive opportunities are available to the occupants to feel more comfortable. Office buildings whose thermal environment is designed based on the adaptive model can also reduce the energy consumption, because temperature setting can be relaxed and period air-conditioning usage can be shortened.

Large data from field surveys in Japan and analysis are required for adaptive model which can be used in Japan, because extent of adaptation varies according to climate, socio-cultural setup and the occupants' experience. In Japan, adaptive thermal comfort in houses [13–15], offices [11,16–20] has been widely investigated for comfortable range incorporating seasonal difference and outdoor air temperature. It is also reported that high temperature and humidity are some of the characteristics of Japanese climate, which affects the thermal comfort [21].

However, there are very limited studies done on adaptive thermal comfort in office buildings linking various modes of operation of buildings and window-opening compared to houses and air-conditioned buildings. In addition, the effect of humidity on present adaptive model is not explained. The outdoor temperature varies greatly with season in the geographical area, like in Japan. Therefore, it can be predicted that the limit of optimum comfort temperature is found due to limitation of clothing and human's physiology when outdoor temperature is very high or low. Previous studies also specify a limit of the optimum comfort temperature, and conclude that optimum comfort temperature becomes constant when the outdoor air temperature is lower than or higher than a certain temperature [22–25]. It is required to explore new analytical methods because adaptive model in previous studies using linear regression cannot explain the limit of optimum comfort temperature at higher and lower outdoor temperature.

In aforesaid context, this research focuses on the thermal comfort and adaptive opportunities in office buildings of Japan under various operation modes. In addition, we discuss two new analytical methods of the adaptive model suitable for Japanese climate. First, SET^* (Standard effective temperature [1,2,26]; i.e. the temperature of an imaginary environment at 50% relative humidity, <0.1 m/s (20 fpm) average air speed, and mean radiant temperature is equal to air average temperature, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level [2]) is used for evaluating comfort temperature in order to consider the effect of humidity and air velocity that we cannot ignore in hot and humid climate. Second, we propose the adaptive model by nonlinear regression analysis in order to describe the lower and upper limit of optimum comfort temperature. In addition, we discuss the relationship between the change of comfort temperature and adaptive actions. This study is conducted to develop an adaptive model which can be used for designing the thermal environment in office buildings of Japan that will operate under different modes.

2. Methodology

2.1. Field survey

We conducted 49 rounds of a questionnaire based field survey from 2012 to 2016 in five office buildings in Tokyo and Kanagawa in Japan [27–29] (Fig. 1, Table 1). These buildings were selected based on availability, accessibility and mode of operation (openable windows, operation of the heating, cooling and electric fan). 503 subjects in the age group of 20–70 years participated in the surveys (Table 2). Total 2722 data sets were collected. We used the data collected in the field surveys and the calculation formula of ASHRAE standard [2] when calculating SET^* and *PMV*. The outdoor environmental parameters were obtained from Tokyo meteorological station (Fig. 2) [30]. It is the nearest from the investigated buildings in Tokyo and Kanagawa. The mean outdoor temperature varied from approximately 3 to 32 °C, the mean wind speed varied from approximately 2 to 7 m/s, and the mean relative humidity varied from approximately 30 to 100% from July 2012 to September 2012 and from October 2015 to September 2016.

2.2. The environmental measurements

The indoor air temperature (T_a), the globe temperature (T_g), the relative humidity and the air velocity at 1.1 m above floor were measured (Fig. 3 (a)). Table 3 shows the measuring instruments that were used in the field survey. Mean air velocity over 10 s is considered for analysis. The instrument setup was placed close to the group of about five occupants sitting close to each other (Fig. 3 (b)). We measured the environmental variables of each group before moving to the next group at 15–20 min intervals (Fig. 4).

In order to record the use of environmental controls in office, use of heating, cooling and electric fan and the proportion of open windows were noted down against each group.

2.3. The survey questionnaires

During the field surveys occupants were given questionnaires translated in Japanese to record their thermal responses and preferences. Table 4 lists some of the parameters that were collected in surveys, and Fig. 5 shows clothing items written in questionnaire [31].

In this research, the ASHRAE thermal sensation scale is translated in two types. First is ASHRAE thermal sensation scale and second is modified thermal sensation scale (Table 4). It is difficult to