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Human health and thermal comfort of office workers in Singapore

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A R T I C L E I N F O

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A B S T R A C T

Poorly operated air conditioning and mechanical ventilation (ACMV) system might cause significant Sick Building Syndrome (SBS) symptoms and thermal discomfort in the hot and humid climate. This study presents our investigations on the prevalence of SBS symptoms and thermal comfort in offices in Singapore via two approaches including: (1) the onsite objective monitoring and questionnaire-based investigation under normal ACMV practices, and (2) the online survey with occupants in controlled indoor temperatures. The results indicate that the prevalence of individual SBS symptoms is lower than the similar studies in other geographic regions. Overcooling seems to be the domineering complaint in the local context and the occupants seem to prefer higher indoor temperature. As such, human behavioral adjustments such as adding clothing happen quite frequently. Moreover, the data also suggests that cultural traits might skew the survey results, especially in certain subjective aspects regarding the satisfactory level and comfort. To sum up, the prevalence of SBS symptoms are generally acceptable in current local context. However, due to the hot and humid ambient environment, traditional ACMV system with vapor compression refrigerant tends to trigger the overcooling issue in relation to the sensible and latent heat. It is invaluable to advance our understanding of the relationships between the ACMV system, human behavioral adjustments, and building energy consumptions in the tropical region.

1. Introduction

Singapore is a city-state located in the hot and humid tropical region. The outdoor air temperature varies from 23 to 34 °C with a mean relative humidity around 90% in the morning and 60% in the afternoon. In such a climate, the air-conditioning and mechanical ventilation (ACMV) systems serve close to all local commercial and institutional buildings. With a high building density in the urban environment, the Sick Building Syndrome (SBS) symptoms and thermal comfort level have become important concerns, from both the building operation and occupants' health/productivity points of view.

Chamber experiment, modeling simulation, and field investigation are the three typical approaches to study both the prevalence of SBS symptom and thermal comfort. Chamber experiments are traditionally carried out in climate-controlled environment, with stringently controlled conditions and human behaviors to exam the impacts of targeted variables [1–3]. Previously established numerical methods form the basis of the modeling studies, with less attention to the uniqueness of specific environmental conditions and/or individual subjects [3–5]. Filed investigation is the most challenging approach, because of the uncontrollable and unquantifiable variables in the actual industry practices [1,6,7]. However, this method may render the most convincing results as it provides the direct feedbacks from the occupants.

There are limited numbers of field studies relating to SBS symptoms and thermal comfort in ACMV offices in Singapore, and a number of issues are still unresolved given the uniqueness of local indoor/outdoor climates. For example, Ooi et al. [8–10] investigated the occurrence of SBS symptoms among 2856 office workers in 56 buildings; the results showed that the SBS frequencies were lower than those reported in temperate regions. SBS symptoms were found to be associated with a group of factors, such as stress level and indoor air quality (IAQ). However, the study did not explore the factors that contributed to the lower SBS frequencies. In addition, local office environments and worker's desire/perception might have varied over the last two decades. Therefore, to understand the current state of the SBS symptoms, more studies are needed.

Though local field studies have reported the phenomenon of overcooling in ACMV offices for decades, little is known about the occupants' reactions to overcooling and the potential energy efficiency impact. Foo and Poon [11] found that 60% of the occupants worked in ACMV offices with air temperatures less than 24 °C, and they suggested that an air temperature of 27 °C might be good enough to satisfy more than 80% of the occupants. de Dear et al. [12] studied 235 respondents' thermal comfort levels in ACMV offices. Their results indicated that the mean thermal comfort vote

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was −0.34, which deviated slightly from neutrality in the cool side. Cheong et al. [13] investigated thermal comfort of college students in an ACMV lecture theater. The results revealed that the occupants were slightly uncomfortable and dissatisfied with overcooling. All these studies mainly aimed to understand human thermal comfort states assuming that the subjects were 'passive sensors' of the thermal conditions. However, the fact is, as indicated by Nicol and Humphreys, that people are active adaptors to environmental stimuli [3].

To fill up the missing gaps mentioned above, the main objectives of the study are: (1) to investigate the current prevalence of SBS symptoms in local ACMV office building and evaluate the potential associations between ventilation, energy consumption and these symptoms; (2) to study the human adaptive behaviors and the associated impacts on thermal comfort level in ACMV buildings.

2. Materials and methods

There were two major field investigations in this study. The first one involved onsite indoor environmental monitoring and occupants filling in a one-time paper-based survey regarding thermal comfort and SBS symptoms. For the onsite investigation and monitoring, the procedure is similar to the previous field studies by de Dear et al. and Cheong et al. in Singapore [12,13], and by Chan et al. in Hong Kong [14]. Based on the measured environmental parameters and collected personal variables, the predicted mean vote (PMV) value for the individual occupants was calculated by the on-line calculator by de Dear and Brager [15]. The second field investigation was a three-week online survey where the variations of indoor temperature were intentionally controlled but un-disclosed to the occupants. The questionnaire was designed based on the ISO standard 7730. All the data and questionnaire results were analyzed using SPSS 18.0 (IBM Inc.) with a significant level of 0.05.

2.1. Basic information

The onsite investigations and monitoring were carried out in 18 randomly chosen offices located in 6 different buildings at a local university. All the offices were served by central ACMV systems with variable air volume (VAV) controls. The fresh air ratio was generally fixed at 5% and the upper threshold of indoor CO_2 concentration was set at 800 ppm. Primary and secondary filters of the ACMV system were replaced every 3 months, and the cooling coils were cleaned at a 3-month interval. Blinds or curtains were used as interior shading to prevent sunlight from penetrating into the indoor spaces. All the offices were equipped with conventional office facilities such as office furniture, desktops, printers and photocopiers.

In the online survey, one floor in an office building was separated into three sections for the three-week controlled experiment. Each section was served by an individual air-handling unit (AHU). The basic information about the office building and its ACMV system was similar with that in the onsite investigation. An online questionnaire along with single-blind method was employed to study the occupants' overall sensitivity to the temperature fluctuations. During the three weeks, the occupants were asked to make responses on their thermal sensation levels for each week, without knowing the temperature adjustment information.

2.2. Indoor parameters

The concerned indoor parameters include temperature (T, °C), relative humidity (RH, %), carbon dioxide (CO_2, ppm), ventilation rates (L/s-person), indoor air velocity (m/s), mean radiant temperature (MRT, °C). Temperature, RH and CO_2 were monitored and recorded at a 5-min interval by the IQM 60 Indoor Air Monitors (Aeroqual Inc., Auckland, New Zealand). Three IQMs were placed within the human activity zones about 1.1 m above the floor in each office. The sampling period was typically over 24 h. Ventilation rate was measured by tracer gas dilution method [16] with Sulfur hexafluoride (SF6) as the tracer gas. Decay profiles of SF6 concentration were recorded by an InfraRan® Specific Vapor Analyzer (Wilks Enterprise, Inc., East Norwalk, U.S.A.). Indoor air velocity was measured by TSI VelociCalc® Air Velocity Meter (Model 9555, TSI Inc. Shoreview, U.S.A). MRT was recorded by Quest Temp° 36 Heat Stress Monitor (Quest Tech., Singapore). All the monitors, specific vapor analyzer and air velocity meters were calibrated or stabilized before and after each sampling run. As all the surveys were conducted during the office hour, the occupants were assumed to be in sedimentary level with metabolic rate at 1.1 met based on the observation.

2.3. Paper-based questionnaire investigations

The paper-based questionnaire used on the on-site investigation involves two major portions to address the issues on the occupants' SBS symptoms and thermal levels. The portion regarding SBS symptoms is similar with the questions recommended by the Institute of Environmental Epidemiology of Singapore [17]. Onset of two or more symptoms at least twice weekly while in the building was taken as the criteria to define a case of SBS, which was compatible with the previous study [10]. The questions to investigate the occupants' subjective perceptions of indoor thermal condition were designed based on the ISO standard 10551: 2001 [18]. The insulation values of the respondents' garment were calculated based on the recommended values in ASHRAE 55-2010 [19]. Compared to other questionnaires, the survey also includes some customized questions to explore some other potential influential factors such as the occupants' exercise habits, their residence history and stress levels.

3. Results and discussions

3.1. Basic information of the respondents

In the onsite investigation, 210 occupants, including 76 females and 124 males, responded to the questionnaires. Most of the respondents were between 20 and 40 years old and about 90% of them were Chinese-origins with the balance to be Malays, Indians, or others.

Ninety-eight occupants (53 females and 45 males) were invited to participate in the online survey. Eighty-seven responses were received in the first week, and the number decreased to 71 and 55 in the second and third week, respectively. The majority of the occupants were between 30 and 50 years old.

3.2. Indoor thermal conditions

Table 1 shows the statistical results of the indoor parameters in the onsite investigations. The indoor air temperatures ranged from 23 to 26 °C with mean at 24.4 °C. The indoor RHs ranged from 50% to 70% with mean at 62%. The air velocities were around 0.1 m/s in all of the offices. The temperature is comparable with the other studies in Singapore [10,12,13] and Hong Kong [14,20], but is about 1.1 °C lower than that in Taiwan [21]. The RH value is also comparable with those reported locally and in Taiwan, but is about 10% higher than those in Hong Kong and about 10% lower than that in Hunan, China [22]. Based on these data, we can see that the indoor mean air temperature and RH varied within the thermal comfort ranges (23–26 °C) suggested by ASHRAE Standard 55-2010 [19].