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Acceptance of thermal conditions and energy use of three ventilation strategies with six exhaust configurations for the classroom

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ABSTRACT

The paper describes an experimental study from forty-eight subjects about the acceptable thermal conditions under three ventilation strategies with six exhaust configurations, including mixing ventilation (MV), displacement ventilation (DV), and four exhaust types of stratum ventilation (ceiling-level-exhausted “SV”, rear-low-level-exhausted “SV-1”, front-low-level-exhausted “SV-2” & rear-middle-level-exhausted “SV-3”) serving a confined 8.8 m × 5.1 m × 2.4 m (h) classroom. Tests were carried out in a specially constructed test chamber designed to represent a typical small-medium sized classroom in Hong Kong. Thermal comfort analyses were carried out under specific supply flow rates, room temperatures, and air speeds in three ventilation strategies with six exhaust configurations. From the collected data, SV at 26 °C & 10 ACH and SV-3 at 28 °C & 15 ACH are achieved 100% of acceptable vote, the highest percentage of 97.3%, scoring neutral (0), are under the SV-3 at 28 °C & 10 ACH. The thermal satisfaction acceptance percentage in stratum ventilation strategies can be improved by increasing the air flow supply from 10 to 15 ACH at the elevated indoor condition of 26.8 °C, 27.3 °C and 26.4 °C by SV, SV-1 and SV-3 respectively, but not under MV, DV and SV-2. It implies that the thermal comfort will be affected no only by the temperature and air supply flow, but also by difference ventilation strategies in this study of three ventilation strategies with six exhaust configurations. This result indicates that SV-3 can satisfy human perception of comfort with least value of energy consumption, due to higher neutral temperature in comparison with the other ventilation strategies.

1. Introduction

The analysis of thermal comfort based on human subject tests is one of main techniques used in the design of sustainable air-conditioning systems for buildings. Such an analysis can lead to designs which minimize HVAC energy, and hence CO_2 emissions, promoting environmental sustainability. One way to reduce energy consumption is to elevate the indoor air temperature in air-conditioned rooms; however in order to use this approach it is important to know the occupants can tolerate higher temperature without sacrificing thermal comfort.

The aim of this investigation is to measure and compare the thermal comfort experienced and energy performance of building HVAC systems using a range of three ventilation strategies with six exhaust configurations including a novel technique known as ‘stratum ventilation’. Tests were carried out in warm conditions in a specially constructed test chamber designed to represent a typical small-medium sized classroom in Hong Kong. The thermal neutral temperature of the three ventilation strategies with six exhaust configurations is also determined and compared.

The acceptance of thermal comfort condition is depended on six main parameters, which is air temperature, air velocity, metabolic rate, radiative temperature, clothing value, relative humidity [1–3]. This study focuses on the first two parameters and the others have closely monitored during the human comfort tests. Past studies find that Hong Kong people are thermally sensitive to air temperature and speed, but less so to humidity [4–6]. It found that thermal sensation was not sensitive to the humidity ratio in between 65 and 80%RH. Based on data collected from 203 subjects, aged 19–50, who participated in a Hong Kong studied. This finding is also in line

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with results obtained in Indonesia, Singapore, Thailand, and Japan [7]. In order to minimize the effect of RH on the sensation vote during each human subject test, the test conditions are limited to the range of 50%–70% RH.

The neutral temperature of air-conditioned offices in Hong Kong under the mixing ventilation (MV) mode is 23.6 °C in summer; a figure derived by analyzing the thermal comfort perceptions of 422 occupants of 61 air-conditioned office buildings [8]. The neutral temperature of college students in Hong Kong has been found to be 24.9 °C under MV mode air conditioning, based on 134 college-aged subjects wearing 0.6 clo standard clothing, under 0.1 m/s of mean air speed, and having a sedentary activity level [9]. However a study of 300 university students (with 0.55 clo standard clothing, metabolic rate 1 met and a sedentary working environment) showed that they will accept a higher neutral temperature of 25.4 °C with bodily air speed between 0.1 m/s and 0.2 m/s, measured at 0.6 m above floor level, [5]. Laboratory and field studies have shown that a higher air speed can compensate for warm summer temperatures in terms of thermal comfort [10]. This finding supports ANSI/ASHRAE Standard 55 [1], which allows a higher range of acceptable operating temperatures to be considered comfortable, thermal conditions with higher air speeds. From a building sustainability perspective, it is obviously desirable to achieve acceptable thermal sensation with the minimum use of energy. Increasing the air speed and varying the air supply positions in the occupied zone are possible methods of achieving optimal air distribution design. The neck area of human subjects has been investigated as an effective way to achieve a local cooling sensation of thermal comfort and as a major determinant of subjective thermal comfort [11–15]. The breathing zone/head-chest level, the area where cooling is most needed, is between 0.9 and 1.3 m above floor level for rooms involving primarily sedentary occupants.

Thermal comfort can be affected by draft, the whole body overall thermal sensation (OTS) and local thermal comfort (LTS) of body segments together with the correlation of different temperature and supply air flow rate. In stratum-ventilated room study, people can have the feeling of LTS “cool head and warm feet” with low draft risk at a room temperature up to 27 °C and people can feel neutral OTS, satisfactory OTC and low draft risk at room temperature of 27 °C under 10 air change per hour (ACH). The supply air temperature should not be below 20 °C to minimize draft complaints [16]. Mixing ventilation (MV) is a conventional and widely-used air distribution method with well-established design guideline for practitioner [17]. In MV, supply jet delivers the air outside the occupied zone at high air velocity rate. The delivered air volume will be completely mixed with the room air before it reaches the occupied zone and the rate has dropped to the desired level, depending on the room characteristic. Vertical supply from ceiling is common arrangement to avoid any unpredictable flow obstacles, such as partition walls for air distribution and decrease ventilation efficiency in occupied zone. Because the air supply terminals are ceiling-mounted, significant fan energy is consumed if higher air movement in the occupied zone is required, due to the distance between the terminals and the occupants. It is also difficult for this system to supply air horizontally in the occupied zone. Another common air distribution method is displacement ventilation (DV), in which the air for the breathing zone is supplied at floor level, transported by the boundary layer around an occupant's body, and extracted at ceiling level. Because the air flow in DV is thermally driven, any horizontal air movement can disrupt the thermal plume around an occupant and defeat the working mechanism. Jackman therefore recommended a mean air speed of less than 0.25 m/s in summer to ensure the comfort of sedentary occupants under DV [18]. Stratum ventilation is a third ventilation mode that can compensate for higher room temperature by supplying air horizontally by means of wall-mounted air diffusers to the head-chest level, i.e. the breathing zone. In personal ventilation, potential draft exists because of the short distances between the air supply inlets and the occupants [19]. On one hand, it is often difficult and/or expensive to equip nozzles and to connect ducts in various indoor spaces, especially to keep up with the spaces of re-partitioning and flexible seating configuration. These problems limit the application of task/personalized ventilation. In warm conditions, stratum ventilation can maintain thermal comfort due to its characteristic of reverse vertical air temperature difference between the head and ankle levels, and better air quality in the breathing zone [20–22]. The vertical air temperature difference will not exceed 3 °C for a seated occupant, which is matched with the relative requirement as stipulated in ASHRAE standard 55 [1]. From the other researchers studied, people can have the feeling of local thermal comfort (LTS) “cool head and warm feet” with low draft risk at a room temperature up to 27 °C and people can feel neutral in the whole body overall thermal sensation (OTS), satisfactory OTC and low draft risk at room temperature of 27 °C under 10 air change per hour (ACH). The supply air temperature should not be below 20 °C to minimize draft complaints [16]. Moreover, it probably overestimated the draft rating because people were less sensitive to horizontal airflows from side [23] or front directions [24]. In addition, draft sensitivity was closely related to OTS [25,26].

In term of thrown pattern, room air temperature under MV is more eventually distribution than DV and SV. Under DV, room air temperature is linearly elevated with the height of space. In SV, the room air temperature gradient is different from the straight line of MV and inclined line of DV. The supply air is directly distributed to the occupancy's head level, so a reverse temperature gradient is formed in occupied zone with lowest temperature at the head level [27,28]. Thermal comfort performance may be affected not only by including LTS, OTS, draft rating (DR), predicated percentage dissatisfied (PPD), but also various ventilation strategies. Due to the recent findings on the difference between stratum ventilation in comparison with the mixing and displacement studies [29–33], PPD level in Hong Kong may not fairly compared based on the Fanger's model and the relative international standard [1–3].

This paper describes an experiment designed to explore the relationship between various ventilation strategies and thermal neutral temperature, as well as acceptance level under identical boundary conditions. The experiments use human subject tests as the basis of thermal comfort analysis. Tests are conducted in a specially constructed test chamber to compare the perception of thermal comfort under three ventilation strategies with six exhaust configurations; namely MV, DV and four types of stratum ventilation labelled SV, SV-1, SV-2 and SV-3 respectively.

2. Experimental investigation

2.1. Subjects of survey

Forty-eight college-aged human subjects (24 females and 24 males) participated in this research. Most are students at the City University of Hong Kong and are in good health. All subjects are between 20 and 23 years old, and have resided in Hong Kong for more than ten years. The subjects report that they are accustomed to working in an air-conditioned environment. Testing was conducted during the summer break, and all subjects received remuneration for their participation. The anthropometric data of the subjects is shown in Table 1. The details of facilities and procedure of this human subject tests are similar to the pervious evaluation of thermal comfort conditions in similar classroom [34].

Before participating in the tests, each subject was instructed to wear typical local summer clothing. They then carried out