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Comparing mixing and displacement ventilation in tutorial rooms: Students' thermal comfort, sick building syndromes, and short-term performance

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ABSTRACT

While mixing ventilation (MV) and displacement ventilation (DV) are widely used to regulate the indoor environment, very few studies compared occupants' responses under these two systems in the field. In this study, a field experiment was conducted in two identical tutorial rooms to compare human subjects' thermal comfort, sick building syndromes (SBS), and short-term performance under MV and passive displacement ventilation (PDV). Experimental results showed that MV could lead to significantly larger overall draft sensation than PDV due to high air velocity from the overhead diffusers. PDV on the other hand, led to significantly higher draft and colder sensation in the lower body level, while draft distribution was perceived relatively homogenous in the vertical direction in the MV room. Seat arrangement could lead to inhomogeneous sensations in the horizontal direction in both the MV and PDV rooms. Higher CO_2 concentration was the main factor causing SBS related to head, while both higher CO_2 concentration and lower relative humidity (RH) contributed to SBS related to eyes. As a consequence, SBS resulted from high CO_2 concentration and low RH could lead to decrease in short-term performance. In addition to the experiment, the results of the real-life occupants' feedback also resembled the experimental findings.

1. Introduction

Mixing ventilation (MV) is a traditional air distribution method to regulate the indoor environment, which supplies fresh air from ceiling level with high velocity to achieve an even distribution of temperature and pollutant in the whole space. Total mixing may not be the most effective in many aspects, e.g. heat removal or pollutant removal [1], and previous review studies showed that low ventilation rates in many commercial and institutional buildings had significant correlation with decrease in health and productivity [2,3]. High air velocity in MV can also lead to draft discomfort in workplaces [4]. Compared with MV, displacement ventilation (DV) method has been proposed to supply fresh air near floor level on the side wall and return exhausted air near ceiling level by buoyant force, as fresh air is warmed up by heat sources in the room. DV was originally proposed to save energy and improve indoor air quality (IAQ) in the breathing zone. Hamilton et al. summarized the main reasons for DV's energy saving potential, and reported that DV reduced the sum of cooling and ventilation energy by 13–45% as compared with MV [5]. For the IAQ and thermal comfort aspects, however, several studies revealed the potential problems in DV. DV can improve IAQ in the breathing zone if heat sources produce the contaminants, but may decrease IAQ if the contaminants are from the floor covering or other unheated sources [6]. DV can also lead to draft discomfort around feet and excessive air stratification [7]. Building occupants reported higher than expected complaints of cold discomfort around feet in a theatre installed with DV [8], while another survey study showed that draft did not seem to be a very serious problem in office rooms installed with DV [6].

Most studies that compared IAQ and thermal comfort between MV and DV adopted computer modeling or environmental chamber. He et al. used both experimental chamber and numerical modeling to study contaminant (SF_6) dispersion from the floor surface, and found that in DV stratification existed with a lower concentration at lower level and higher concentration at upper

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level, while in MV the contaminant was non-uniform [9]. Yang et al. also used experimental chamber and numerical simulation to study volatile organic compound (VOC) removal from floor level, and found that DV behaved similarly to MV in the breathing zone when the pollutant was not associated with a heat source or initial momentum [10]. Lin et al. found from a numerical simulation that for carbon monoxide (CO) and VOCs, DV might provide better IAQ in the occupied zone, and also expelled CO_2 generated by the occupants more easily as compared with MV [11]. On the other hand, Jurelionis et al. used both experimental chamber and computer modeling to study the dispersion of particles (a nebulized solution of sodium chloride) emitted from the air supply and exhausts sides, and found that DV was less efficient in the removal of particles [12]. Holmberg et al. found from numerical simulation that concentrations of 10 μm (aerodynamic diameter) particles at breathing zone were higher in DV [13]. Two other chamber studies both using manikins found that exhaled pollutants might be locked inside the occupied zone due to thermal stratification in DV, while pollutants were well-mixed in MV [14,15].

For thermal comfort aspect, a study used numerical simulation and found that DV could maintain thermally comfortable environment that had low air velocity, small temperature difference between the head and ankle level, and low percentage of thermal dissatisfaction [16]. Another numerical study suggested that DV had better performance on heat removal, air exchange efficiency and energy saving, but was difficult to provide acceptable vertical temperature gradient between the ankle and neck levels for a standing person [17]. Khankari used numerical simulation to study the two-story lobby of a health care facility, and found that both systems could provide similar thermal comfort for the occupants [18]. An experiment compared human subjects' thermal sensation in an environmental chamber in Hong Kong and found that thermal neutral temperature in DV was slightly higher than that in MV [19,20], and MV had shorter pull-down process (the time used to achieve a comfortable thermal environment before a room is ready for occupation) than DV [21]. In the same chamber, MV maintained uniform distribution while DV maintained the vertical gradient distributions of air velocity and temperature [22], but with either a manikin or a real occupant moving in the chamber, temperature and CO_2 distribution were not influenced significantly for a short time but would be influenced for a long time, and the influence under mixing ventilation was smaller [23,24]. A chamber measurement in Demark revealed that the vertical distributions of air temperature and velocity were more uniform in MV than those in DV, and local turbulence intensities at neck level were larger in MV than those in DV [25]. Another chamber study which involved human subjects and compared different ventilation strategies including MV and DV suggested that operative temperature alone was not sufficient for the prediction of thermal sensation under non-uniform conditions [26].

Very limited studies however, have compared occupants' responses to MV and DV in the field, which might due to the difficulty in finding appropriate site or in controlling indoor environmental parameters in the field. Two studies can be found in literature, which compared pupils' perceived IAQ and sick building syndromes (SBS) in elementary classrooms (all with heating mode) in Sweden. SBS is widely and loosely defined by many, but overall, it is understood as a group of symptoms related but not limited to the irritation of the eyes, nose, throat, skin, breath, and other general symptoms such as headache and lethargy that temporally occur among occupants of a certain building [27]. Smedje et al. found that environmental parameters (temperature and concentration of CO_2) were similar in each ventilation mode at breathing height, and children's perceived IAQ were similar in the two ventilation modes, except that DV had more reported eye symptoms [28]. Norbäck et al. found that temperature at desk level and many pollutants' concentration (CO_2 and formaldehyde) were numerically elevated in MV, and DV may have certain positive health effects among pupils [29].

In this study, a field experiment in tropical region was conducted to check the performance of MV and DV, which compared thermal comfort, SBS, and short-term performance of human subjects using questionnaires and computerized tasks. In addition, feedback from real-life occupants using tablet devices with simplified subjective questions further complemented the experiment.

2. Methodology

2.1. Experiment

The experiment was conducted in two side-by-side tutorial rooms on Nanyang Technological University, Singapore. Layout of the rooms is illustrated in Fig. 1. The rooms are 8 m in length, 8 m in width, and 2.75 m in height (floor to false ceiling). The two rooms are identical except for their ventilation systems. One tutorial room has traditional mixing ventilation with cooling coil, and the other room has displacement ventilation with cooling coil. Both rooms do not have exhausts, so the indoor air is driven out through natural leaking. In particular, the displacement ventilation used in the tutorial room is passive displacement ventilation (PDV). The PDV system does not mechanically pump the cool fresh air into the room through outlets at ground level, but let the temperature gradient in the room to drive the fresh air.

Thirty-nine healthy university students (male–female ratio was 6:7) were recruited as human subjects to participate the experiment and they were required to wear common attire of local students (short-sleeve shirt, shorts, and saddle without socks as shown in the Fig. S1) in Singapore. This clothing level is 0.36clo according to the ASHRAE Standard 55 [7]. Before the experiment, they were asked to keep good physical conditions. Seating was arranged to avoid positions close to doors or computer control panels.

Human subjects first participated in two consecutive non-working days, i.e. within-subject, in the MV room in day 1 and in the PDV room in day 2. Subjective questionnaires were designed to investigate thermal comfort and SBS. Computerized task-based tests were designed to evaluate performance, and measurements were taken to control for learning effect, including 1) tasks were chosen such that they require very basics abilities; 2) a practice session was conducted to help human subjects to be proficient with the tasks before the formal experiment, and 3) two parallel sets of questions with similar difficulty but different contents were used in formal experiment.

The experimental procedure in each session is shown in Fig. 2. Thirty-nine human subjects formed three groups evenly to participate in three sessions in each day: one morning session from 9:30 am to 11:30 am, one afternoon session from 1:00 pm to 3:00 pm, and one afternoon session from 3:30 pm to 5:30 pm. To minimize other confounding factors, human subjects attended the same session in the same time slot in both days.

Since concentration of many indoor air pollutants correlates to CO_2 concentration when building occupants are present, concentration of CO_2 was used as the indicator of IAQ in this experiment. During the first two-day experiment, CO_2 built-up was as high as 2600 ppm in the MV room due to poor ventilation design of the MV system while CO_2 concentration in the PDV room was normal (below 1000 ppm). The high CO_2 scenario was not part of the original experimental design. It happened due to the inadequate air exchange rate by the fan-coil unit (FCU) in the actual tutorial room.