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Indoor environment evaluation of a Dedicated Outdoor Air System with ceiling fans in the tropics – A thermal manikin study

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ABSTRACT

Energy savings of the Air-Conditioning (AC) system is crucial in achieving energy conservation in buildings in the tropical region. A Dedicated Outdoor Air System with ceiling fans (DOAS-CF) aims to achieve energy savings arising from elevated room air temperature and minimizing the air-conditioning requirements. The objective of this study is to investigate the cooling effect produced by the DOAS-CF system at various locations in an AC room using a thermal manikin. The sedentary thermal manikin was set at three different locations such as under the ceiling fan, outside the fan blades and the center of the room at temperatures of 24 °C, 27 °C and 30 °C and at 60%RH with air velocities ranging from 0.02 m/s to 2.26 m/s at the height of 1.1 m. Two ceiling fans formed circulation airflows around each fan. High air speeds and low turbulence intensity were measured right under the ceiling fan and near the floor while low air speeds and high turbulence intensity were found at other locations. The cooling effect at the whole body of −3.3 °C was higher under the fan than that of −1.3 °C at other locations. The cooling effect was affected by temperature, location and fan speed mode significantly. The maximum cooling effect by manikin based equivalent temperature was higher than that by SET model due to an evaluation of the local cooling effect on each body part. The knowledge of the cooling effect is important and useful for a mechanical engineer to design the thermal environment produced by the DOAS-CF system.

1. Introduction

In tropical and subtropical regions, the energy consumption of Air-Conditioning and Mechanical Ventilation (ACMV) system can reach more than 50% of the total energy consumption of a whole building [1]. Therefore, an innovation in ACMV system can pave the way towards achieving energy savings in buildings in the tropics. Some of the recent technologies for Air-Conditioning (AC) and air distribution such as Single-Coil Twin Fan (SCTF) system [2], personalized ventilation system [3,4] and Dedicated Outdoor Air System (DOAS), that deliver 100% outdoor air ventilation and handle the latent and sensible loads, coupled with radiant chilled ceiling [5] in a hot and humid climate were reviewed [6]. Although these systems are energy efficient, they are not popular in general office applications due to the perceived complexity of the system and control or the high initial cost. Energy saving potential of AC systems coupled with ceiling fans has attracted attention due to its simplicity and inexpensive features for installation in the tropics [7,8].

Ceiling fans received attention as energy saving devices in the US in 1970s and 1980s to reduce the energy impact of designs involving vapour compression systems [9–11]. Air-conditioning system energy savings around 17% was observed by employing the strategy of increasing room temperature in air-conditioned environments by elevated air movement [10]. Recently, ceiling fans have again drawn the attention for achieving both energy savings and thermal comfort. Simulation studies have shown that the cooling energy savings by increasing room temperature with elevated air movement can reach as high as 48% in European climate [12].

A Dedicated Outdoor Air System with ceiling fans (DOAS-CF) in the occupied zones is planned to be installed in the new net Zero Energy Building in the School of Design and Environment at the National University of Singapore (nZEB@SDE4-NUS). Although SS554-2016 ([13]) provides the acceptable limits of indoor air quality parameters, such as air temperature in the range of 23 °C–25 °C and relative humidity (RH) of less than 65% under 0.3 m/s air speed in air-conditioned buildings in Singapore, the features of this system are higher room set point temperatures of 27 °C–28 °C with air velocity of 0.7 m/s created by ceiling fans. ASHRAE Standard 55–2017 ([14]) allows extending the comfort zone by elevated air speeds. Studies, involving subjective experiments, have shown that thermal comfort, perceived air quality and

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humidity sensation were improved due to air movement right under the ceiling fans [9–11,15].

The effect of the local airflow on human sensation needs to be considered when the fan cooling is used. Zhang et al. [16] examined the relationship between local and overall thermal sensation under non-uniform and transient conditions. The overall thermal sensation followed the most uncomfortable sensation of the local body part. The local thermal sensation of the head region was sensitive in warm environments [16], especially the back of the neck [17]. The upper body parts of sedentary human right under the ceiling fan are cooled by air movement while the lower body parts are not cooled if the airflow is disturbed by the furniture. Thermal asymmetry may be caused by local airflow cooling at high air speeds although humans are not bothered by thermal asymmetry caused due to cooling on one-side by air speeds up to 1.0 m/s [18,19].

The local cooling effect of the personalized ventilation and the air terminal devices in a non-uniform environment has been evaluated utilizing a manikin-based equivalent temperature by a thermal manikin [20–23]. The thermal manikin is often used to simulate human body heat loss and is useful to understand the local heat exchange and the skin temperature distribution. A Cooling-Fan Efficiency (CFE) index, which is calculated to divide a cooling effect by fan power, was proposed based on the measurement results by the thermal manikin [24]. The CFE index of four kinds of fans such as ceiling, floor standing, tower and table fans was evaluated. Yang et al. [25] evaluated the CFE index of a brushless direct current stand fan using thermal manikin in a field environmental chamber. There were significant differences between the cooling effect and dry-bulb temperature, fan speed mode and fan-manikin distance, but not fan-manikin direction. Although the effect of the air movement provided by the ceiling fan was studied for subjects right under the ceiling fan [9–11,15], the local cooling effect of the ceiling fan was not much analyzed. Moreover, the cooling effect would be changed by the clothing value and the location of fan and manikin [24,25]. In addition, the cooling effect at the locations other than right under the ceiling fan is also not clear.

The aim of this study is to investigate the cooling effect of the ceiling fan using the manikin based equivalent temperature at various locations in a room. The cooling effect of the ceiling fan would be different depending on the location because the air distribution is non-uniform in the room. In addition, the range of the cooling effect by the rotational speed of the ceiling fan is important to decide the room temperature. It is envisaged that it would be useful for the designer to plan good indoor environment for occupants by a DOAS-CF system.

2. Methods

The study adopted two steps to evaluate the cooling effect of the ceiling fan. The first preliminary study was conducted to measure the distributions of temperature, RH and air velocity for understanding the non-uniform environment. Secondly, the cooling effect in local and whole-body region is evaluated by the manikin-based equivalent temperature using the thermal manikin. The thermal manikin is installed to analyze the fan-manikin distance at three different locations (right under the ceiling fan (L1), outside the fan blade near the ceiling fan (L2) and the center of the room far from the ceiling fan (L3)) in a room. Finally, the cooling effect is analyzed by the manikin equivalent temperature and SET model in non-uniform environment.

2.1. Facilities

A classroom (5.6 m*7.6 m*4.3 m) was used for this experiment at the National University of Singapore. The room has windows (5.025 m*2.2 m) with 1.2 m overhang at the southern side. The white roller blinds were closed at the window side to neutralize the effects of radiant heat gain and move the radiative temperature closer to air temperature. An outdoor package AC unit with VAV boxes supplies conditioned outdoor air to the experimental and adjacent rooms from two square air diffusers (0.6 m*0.6 m) at the height of 3.4 m. An additional outdoor air duct is installed to supply outdoor air to the air duct of existing AC system to raise the supply air temperature and humidity. Additional outdoor airflow rate was fixed at each temperature using the invertor during the test. The VAV damper opening at the test room was controlled manually every 5 min while checking the temperature and relative humidity at perimeter, center and interior of the room. To maintain the constant off-coil temperature from 16 °C to 18 °C, the VAV opening of the adjacent room was kept at 100% to get the expected level of airflow from the AC unit. The air movement is provided by two ceiling fans. The fan diameter is 1.3 m (52in). It has 3 air foils and can change its speeds in 7 phases (60RPM-182RPM). The power of the fan ranges from 2W (60RPM) to 32W (182RPM). The ceiling fans are installed at the height of 2.6 m from the floor.

The primary focus of this study is to investigate the cooling effect variations at different locations in an air-conditioned room that is simultaneously operated with ceiling fans. These locations are directly under a fan, outside the fan blade and the center of the room essentially representing a vertical plan at the mid-point between two ceiling fans. A typical ceiling fan design will be based on a grid and the mock-up room used in this study is based on the design specifications of the nZEB@SDE4-NUS. The study is also focused on a typical operation of the grid-based ceiling fans and, hence, two fans, representative of two adjacent occupied zones in an open-plan layout, were used as the basis of this study.

2.2. Instruments

Air temperature, globe temperature and RH were continuously measured at 5 min interval with thermocouple wires and logger at the height of 0.1, 0.6, 1.1, 1.7 and 2.2 m, that was the level for seated occupants [14], at the locations under the ceiling fans and the center of the room with an accuracy of ± 0.5 °C and ± 3%RH of reading (Fig. 1). In addition, air temperature (30s interval), RH (30s interval) and air velocity (180 times at a second interval) were measured by spot measurement method using thermocouple wires, logger and omnidirectional anemometer (an accuracy of ± 0.1 m/s). Turbulence intensity (Tu) refers to the level of airflow fluctuations, as shown in equation (1).

$$Tu = u'/U \tag{1}$$

where Tu is turbulence intensity [−], u′ is root-mean-square of the turbulent velocity [m/s], U is the mean velocity [m/s].

The manikin is 1.68 m female and has 26 body segments. The surface temperature and the dry heat loss were measured. Evaporative heat loss could not be measured in this manikin. The thermal manikin seated with typical summer clothing of 0.5clo (short-sleeve shirt, underwear, thin trousers, socks, shoes and chair), which is almost the same as a typical Singaporean office worker (0.44clo) [26]. The operation mode is comfort mode in that the manikin's surface temperature is controlled as the skin temperature of an average person in a given environment [27]. The manikin surface temperatures were measured every minute for at least more than an hour after they reached steady-state condition. The surface temperature of the whole body which was changed within 0.1 °C was used as steady-state condition. Manikin-based equivalent temperature (T_{eq}) was used to evaluate the cooling effect by the DOAS-CF system at each location in the room. The T_{eq} is the uniform temperature with no air movement in which a thermal manikin will exchange the same dry heat as in the actual non-uniform environment [28]. The thermal manikin was calibrated to get the equation for manikin-based equivalent temperature of body segments at 23 °C, 27 °C and 31 °C. Constant values of A and B in equation (2) were obtained by substituting room air temperature as equivalent temperature and dry heat loss from each body segment (Table 1). The T_{eq} of the whole body was calculated as the area-weighted average of the body segments.