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Improved Thermal Comfort and Sensation with Occupant Control of Ceiling Personalized Ventilation System: A Lab Study

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Abstract**—**This study aims at determining the extent to which occupant control of microenvironment influences, improves thermal sensation and comfort, and saves energy in spaces equipped with ceiling personalized ventilation (CPV) system assisted by chair fans (CF) and desk fans (DF) in 2 experiments in a climatic chamber equipped with two-station CPV systems, one that allows control of fan flow rate and the other is set to the fan speed of the selected participant in control. Each experiment included two participants each entering the cooled space from transitional environment at a conventional mixed ventilation (MV) at 24 °C. For CPV diffuser, fresh air was delivered at a rate of 20 Cubic feet per minute (CFM) and a temperature of 16 °C while the recirculated air was delivered at the same temperature but at a flow rate 150 CFM. The macroclimate air of the space was at 26 °C. The full speed flow rates for both the CFs and DFs were at 5 CFM and 20 CFM, respectively. Occupant 1 was allowed to operate the CFs or the DFs at (1/3 of the full speed, 2/3 of the full speed, and the full speed) while occupant 2 had no control on the fan speed and their fan speed was selected by occupant 1. Furthermore, a parametric study was conducted to study the effect of increasing the fresh air flow rate on the occupants' thermal comfort and whole body sensations. The results showed that most occupants in the CPV+CFs, who did not control the CF flow rate, felt comfortable 6 minutes. The participants, who controlled the CF speeds, felt comfortable in around 24 minutes because they were preoccupied with the CFs. For the DF speed control experiments, most participants who did not control the DFs felt comfortable within the first 8 minutes. Similarly to the CPV+CFs, the participants who controlled the DF flow rates felt comfortable at around 26 minutes. When the CPV system was either supported by CFs or DFs, 93% of participants in both cases reached thermal comfort. Participants in the parametric study felt more comfortable when the fresh air flow rate was low, and felt cold when as the flow rate increased.

Keywords**—**Thermal comfort, thermal sensation, predicted mean vote, thermal environment.

I. Introduction

IN hot climates people spend most of their time in air conditioned spaces. The conventional air conditioner preserves the air conditioned space at a constant temperature and air quality through a MV system, via combining fresh air with recirculated air [1], [2]. Conventional air conditioning systems usually provide air for an entire space via ceiling diffusers at a specific air temperature that is typically controlled by a single thermostat whether the space is densely or sparsely occupied. Such a system has been adopted by many commercial and residential buildings because of its simplicity and ease of integration with the predicted mean vote (PMV) model of [3]. Because different people feel comfortable at a range of different temperatures, this system cannot fulfill the thermal comfort needs of all occupants in an open space since it is controlled by a single thermostat [4], [5], where everyone keeps altering the desired temperature on the thermostat. In addition, this system consumes a lot of energy when delivering conditioned air to a sparsely occupied space, and cannot provide good indoor air quality to densely populated space, as it struggles to maintain the room at a uniform temperature [6], [7]. For these reasons, [8] proposed the application of testing ceiling mounted personalized ventilators for offices in tropical climates. Furthermore, [9] proposed a coaxial ceiling-mounted personalized ventilation system characterized by high energy savings while insuring high breathing air quality and thermal comfort in the microclimate of occupants [10], [11]. The system consisted of ceiling coaxial personalized ventilator (PV) jets delivering clean fresh air effectively by lengthening the potential core region at the center of a peripheral angled diffuser creating a canopy localizing the flow around the occupant. However, coaxial nozzles presented the disadvantage of requiring additional ducting system and difficulty of control of two jets of equal velocities. To overcome the constraints of the coaxial system, [12] proposed to aid the single CPV jet of [8] with DF, and [13] similarly proposed adding CF which were able to control the convective thermal plumes originating from the human body allowing the personalized air to reach the breathing level more effectively. Nonetheless, the thermal comfort studies on the CPV systems were only done via 3D Computational fluid dynamics (CFD) model integrated with segmental bio-heat models for prediction of human segmental skin temperatures when exposed to the CPV system. In this study, a set of thermal comfort surveys were conducted by participants to compare the thermal comfort of an open space with the conventional MV system, and the proposed CPV system. One set of participants surveyed the CPV system assisted by the DF, and another set tested the CPV system aided by CF.

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II. Problem Description

A testing chamber was ventilated with a CPV system, with DFs fitted right below the desks at a 70 cm height, pulling air horizontally, while four CFs per seat were installed (Fig. 1), blowing air downwards, at a height of 47 cm from the ground. A total typical office space load of 60 W/m^2 of floor area is distributed between conventional lighting load (10 W/m^2) [14], occupant load of 70 W simulating sedentary activity [15], computer load of 93 W [14] and uniformly distributed walls load of 11.74 W/m^2. The personalized ventilation jet delivers 20 CFM of fresh air in accordance with the ASHRAE standard [16] at 16 °C at the center of a peripheral ceiling diffuser supplying recirculating 71 L/s of air at a temperature of 16 °C. When DF or CF are operated at the optimal flow rate of 10 L/s [14], they pull CPV air jet downward [15].

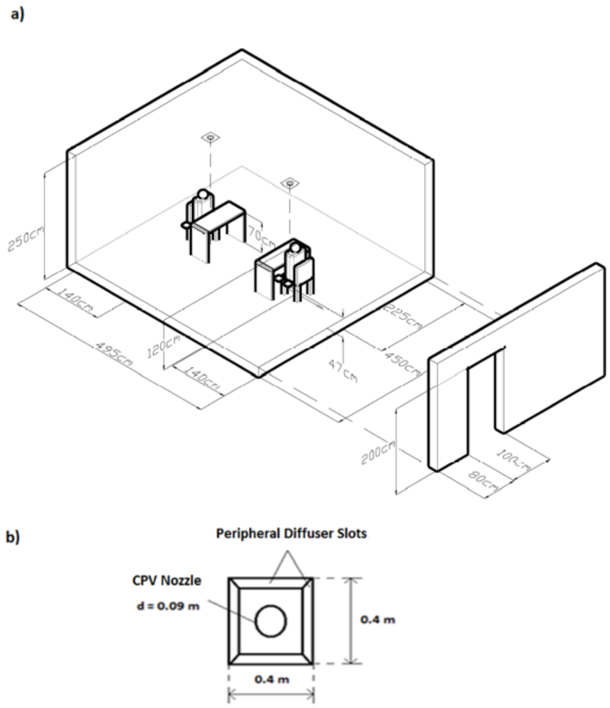

Fig. 1 Schematic of (a) the 3-D experimental set-up; (b) Top view of the CPV system

In order to assess the effectiveness of the CFs and DFs in providing a quicker thermal comfort to occupants, two different surveys were carried out, (i) CPV assisted by CFs and (ii) CPV assisted by DFs. A random sample of participants was asked to complete each survey. Also, studies were made to compare these two surveys with the convention HVAC MV system. Participants were asked to fill in their thermal comfort and whole body sensation level provided to them in the questionnaire. The thermal comfort level was from 0 to 5, where 0 is neutral, 1 is comfortable, 2 is slightly uncomfortable, 3 is uncomfortable, 4 is very uncomfortable, and 5 is extremely uncomfortable. The whole body thermal sensation level was from -3 to 3, where -3 is cold, -2 is cool, -1 is slightly cool, 0 is neutral, 1 is slightly warm, 2 is warm, and 3 is hot.

It is of interest to determine operating conditions of CPV assisted by DF or CF that will make occupants feel thermally comfortable and provide them with a neutral thermal body sensation.

III. Experimental Setup

An experimental set-up was built in order to conduct thermal comfort studies in a two stationed office space ventilated by a CPV system. Fig. 1 (a) represents a schematic of the experimental set-up. The climatic chamber of inner dimensions of (4.95 m x 4.5 m x 2.5 m) was conditioned by a CPV system with the possibility of assisting it by DF or CF (Fig. 1 (a)). The CPV system consists of a CPV nozzle of 0.09 m in diameter at the center of four peripheral diffuser slots (Fig. 1 (b)). Two fan coil units were used for air conditioning one delivering re-circulated air (150 CFM at 16 °C) via the diffusers at a canopy angle of 45° and the other supplying fresh air (20 CFM at 16 °C) through the CPV nozzle. Temperature measurements at CPV system inlets were performed to ensure the room remained in the conditions desired, via K-type thermocouples.

Each participant was asked to fill in a clothing questionnaire form, for their typical summer clothes. The participants were then seated in a transitional room for 30 minutes with a conventional MV HVAC system, with an ambient temperature of 24 °C and 50% humidity ratio. The participants were then transferred to the testing chamber. Occupant 1 is designated to the participants who got to control the CFs speeds, through a 12 V dimmer. Occupant 2 is designated to the participants who got no control on the fans, and the fans' speeds at his/her station were selected by occupant 1. Occupant 1 was allowed to operate the CFs at (1/3 of the full speed, 2/3 of the full speed, and the full speed). The full speed of each CF has a corresponding flow rate of 5 CFM. Although, both participants were seated right below the diffuser for 1 hour, they were allowed to move around on their seats as they please. During that hour, participants were asked to fill in a questionnaire every couple of minutes for their thermal comfort and whole body sensation level on the same scale. A large group of participants were used, and the results were then averaged to obtain the overall thermal comfort behavior. A similar procedure was followed for the CPV assisted by DFs.

IV. Results and Discussions

For the case of CPV assisted by CFs, most participants who got to control the CFs felt comfortable within the 24 minutes (Fig. 2). Nonetheless, all occupants who controlled the CFs felt comfortable or neutral within the first 30 minutes. However, the participants who did not control the CF speeds felt comfortable in the first 6 minutes which is faster than the ones who did (Fig. 2). This is most likely due to the fact that the participants who controlled the CFs were preoccupied with them and could not settle on the desired speed during the first

24 minutes. Most participants who controlled the CFs felt comfortable when the fan speeds were operated at 20 CFM per occupant. This validates the CFD model previously achieved [15].

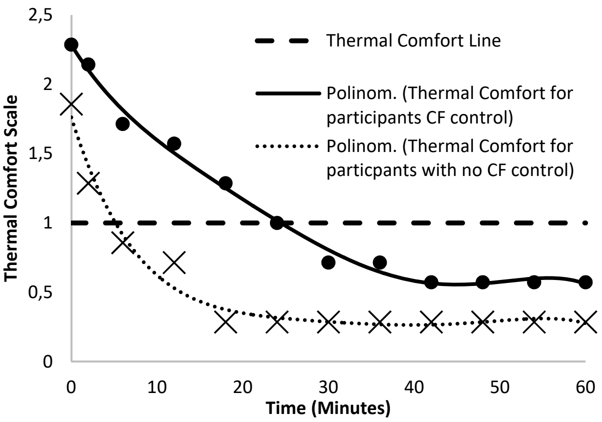

Fig. 2 Thermal comfort for occupants using CPV+CF

The corresponding percentage for the participants who felt comfortable in the transition room was 61%, while the percentage of participants who felt comfortable in the testing room, where the CPV system was aided by CFs, for the first 30 minutes it was 93%. They only participant, who did not feel comfortable during the first 30 minutes in the testing room, did not feel comfortable at all in the transition room.

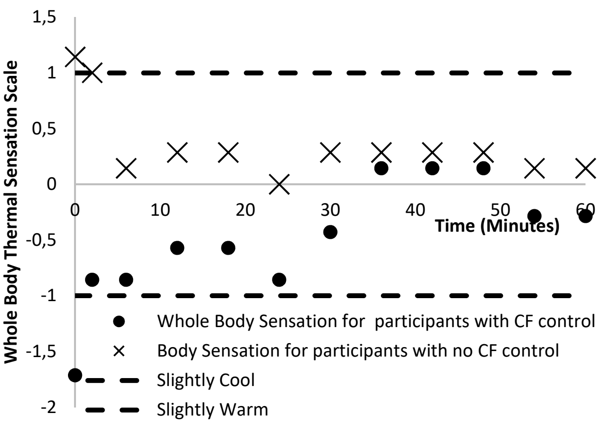

Fig. 3 Whole body thermal sensations for occupants using CPV+CF

All participants initially did not feel comfortable during the first couple of minutes due to them moving from the transition to the testing chamber, where their bodies most likely did sweat while they were walking. Such sweats made them slightly uncomfortable at the beginning when walking into a cooler environment. However, once the participants settled down, they began feeling comfortable or neutral. Similar interpretations can be made for the overall body thermal sensations. The participants initially felt either cold or hot. Given that people feel thermally comfortable between -1 and 1 on the body thermal sensations scale, after two minutes participants started going into that range. Nonetheless, participants who controlled the CF speed were very close to the -1 slightly cool lines, because they were preoccupied with the CF speeds (Fig. 3)

A similar survey was conducted for DF speed control; most participants who got to control the DFs felt comfortable around the 26th minute (Fig. 4). Nonetheless, most occupants who controlled the DFs felt comfortable or neutral for the remaining hour. Like the CPV+CF, the participants who did not control the DF speeds felt comfortable at a quicker rate than the ones who did, for the same reasons (Fig. 5).

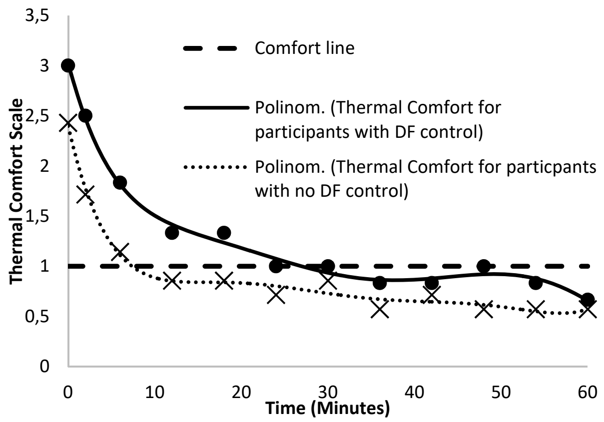

Fig. 3 Thermal comfort for occupants using CPV+DF

The percentage of participants, who felt comfortable in the testing room, where the CPV system was aided by CFs and DFs, for the first 30 minutes, was 93%. This proves that the CPV system with both of its configurations tested is far better than the convention MV system in providing thermal comfort to occupants.

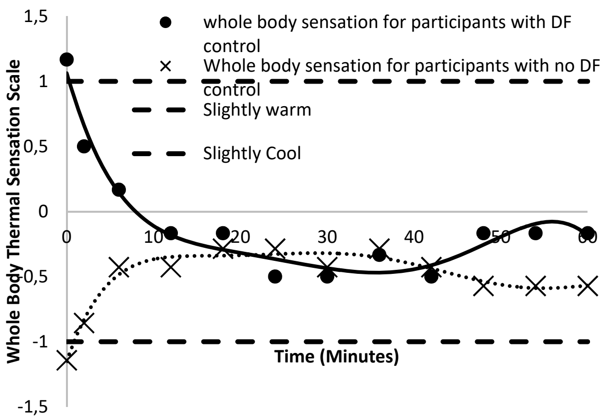

Fig. 4 Whole body thermal sensations for occupants using CPV+DF

V. Parametric Study

One of the main concerns is to always improve the indoor air quality (IAQ) of area around the occupant. One main method was increasing the fresh air flow rate, from 20 CFM, to 25 and 30 CFM. Therefore, a separate survey was conducted where the fresh air flow rate was increased for certain time intervals. The fresh air supply was originally turned off, prior to the entrance of the participants. The thermostat control was used to alter the fan speeds of the fresh air fan coil unit (FCU). The thermostat has three speed options, low, medium and high. The low speed has a corresponding fresh air flow of 20 CFM, while the corresponding flow rates for the medium and high speeds are 25 and 30 L/s, respectively. During the first 12 minutes the FCU will be off, after that, the fresh air was turned on at the low speed. The FCU fan speed was then increased to medium then to high at increments of 12 minutes each. The participants were asked to evaluate thermal comfort and body sensation level for each speed.

The thermal comfort and whole body thermal sensations results were then averaged. As the fresh air flow rate was changing, most participants felt comfortable at the low fresh air flow of 20 CFM (Fig. 5). Participants felt slightly uncomfortable when the fresh air FCU was off. As the fresh air flow rate was increased to 25 CFM, participants started to feel uncomfortable. All participants did not feel comfortable when the fresh air supply was at 30 CFM. This makes the 20 CFM fresh air supply the most suitable.

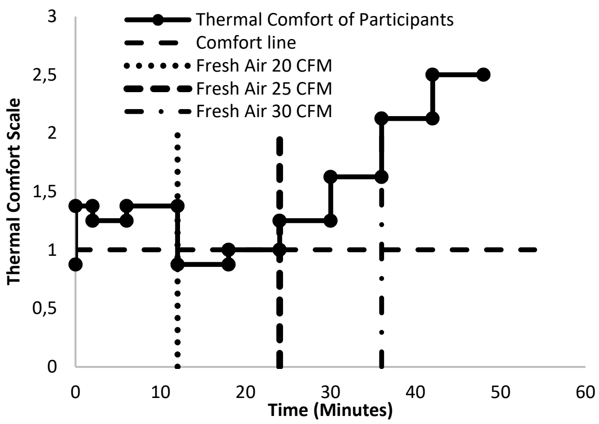

Fig. 5 Thermal comfort for occupants with increasing fresh air flow rates

In this survey, it was clear that most participants feel warm or neutral at the beginning, and they reach a point of comfort, or slightly cool when the fresh air FCU is turned on to 20 CFM. However, when the fresh air flow rate is increased, most participants started feeling cold, and slightly uncomfortable. At the high fresh air flow rate, all participants felt cold and uncomfortable since the nose level temperature dropped to 19.5 ℃ (Fig. 6).

VI. Conclusion

In summary, the ability of CPV system assisted by DF/CF in providing thermal comfort to occupants was investigated. The thermal comfort survey showed that most participants felt comfortable, when the CPV was supported by DFs, as well as by CFs. Most participants who controlled the DFs or CFs felt comfortable within the first 24 minutes. For both cases, 93% of the participants felt comfortable during the first 30 minutes.

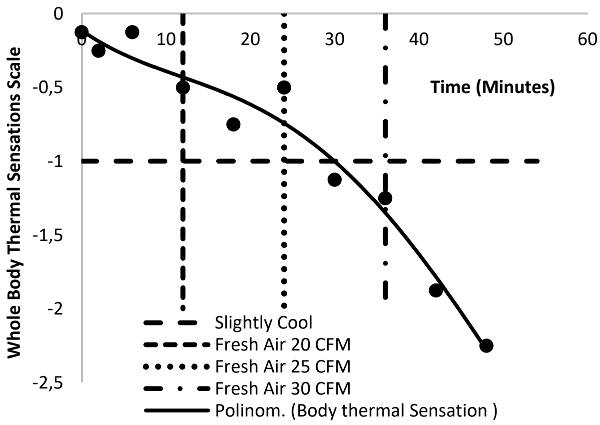

Fig. 6 Whole body thermal sensations for occupants with increasing fresh air flow rates

The thermal comfort experiment also showed that 93% participants felt comfortable when the fresh air flow rate was 20 CFM. Most participants did not feel comfortable at the high flow rates of 25 and 30 CFM, because the overhead temperature dropped to 19.5 ℃. Most participants felt comfortable at temperatures ranging from 21-22 ℃. In addition, most participants did not feel comfortable with no fresh air.

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