



Airflow circulation cell study of an air-conditioning energy-saving mechanism

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ABSTRACT

It is difficult for a traditional air-conditioning system to satisfy the thermal comfort demands of all occupants of a room as well as energy-saving goals. This is because, traditionally, air-conditioning airflow has been distributed without consideration of occupants' needs beyond setting temperature and fan speed to meet thermal comfort standards, such as the predicted mean vote index. Therefore, this paper presents a regional air-conditioning mechanism (RACM) which not only can provide thermal comfort according to each occupant's request, but may also significantly help save energy. The study investigated two areas: (1) the effect of cool air supply flow rate (Q_{in}), air inlet temperature (T_{in}), angle of inlet port (ϕ_1), and angle of outlet port (ϕ_2), and (2) determination of their suitable adjustment to create a better circulation cell. In the paper, nine simulated case studies were divided into three groups with various values of Q_{in} , T_{in} , ϕ_1 , and ϕ_2 . Group 2, in which T_{in} and ϕ_2 were fixed for all case studies but values of Q_{in} and ϕ_1 were not, was found to be the most sensitive in terms of vertical temperature profiles in the middle of the occupied zone in the room. It was also found that case 4 of group 2, in which $Q_{in} = 43.09 \text{ m}^3/\text{h}$, $T_{in} = 23^\circ\text{C}$, $\phi_1 = 85^\circ$, and $\phi_2 = 90^\circ$, consumed the least energy for the same level of thermal comfort demands compared with the two other groups. Two independent thermal environment regions were created in a simulated room, that is, the occupied zone and the rest of the room. Thus, the RACM can be successfully created. This investigation contributes to the research and design of RACM systems in various environments, including buses, trains, factories, public buildings, and so on.

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1. Introduction

As society's living standards have improved, interest has grown in providing occupants of a room with their own individual thermal comfort zones that are comfortable, healthy, safe, and energy-saving. Murakami et al. [1] show that when using a traditional air-conditioning system to distribute cool air into a room, a larger than expected percentage of office workers were not satisfied with their own personal environments. This is because some occupants prefer to be warmer, whereas other occupants prefer to be cooler, even though thermal environment indices were set according to the recommendations of ISO-7730 [2]. In recent years, several personal air-conditioning systems have been proposed in the literature to estimate and analyse airflow distribution in buildings. Although research has revealed some remarkable features of personal air-conditioning systems to date, more studies and concepts are needed to further improve thermal comfort for individuals, while also reducing energy consumption.

Cho and Kim [3] introduced a personal environment module (PEM), a system that has the potential to improve the occupants' thermal comfort because it can direct air towards the occupied zone. In addition, compared to conventional air-conditioning, the PEM is more flexible and easier to control.

Zeng et al. [4] showed that the design of personalized ventilation systems (PVSs) allows each occupant to control his or her thermal comfort provision, such as airflow direction and temperature. In their studies, the perceived air quality of the PVS is superior to that of a conventional ventilation system with the same amount of supplied air.

Faulkner et al. [5] studied the ability of two task/ambient conditioning (TAC) systems using air supplied from desk-mounted outlets to efficiently ventilate the breathing zone of heated manikins seated at desks. The TAC provided 100% outside air at a flow rate of $7\text{--}10 \text{ L s}^{-1}$ per occupant. A high value of air change effectiveness ($\sim 1.3\text{--}1.9$) was presented and high values of pollutant-removal efficiency ($\sim 1.2\text{--}1.6$) were achieved.

Niu et al. [6] investigated a chair-based PVS that can potentially be applied in theatres, cinemas, lecture halls, aircraft, and even offices. Perceived air quality improved greatly by serving cool air directly to the breathing zone. Feelings of irritation and local drafts

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Nomenclature

d	diameter of RACM pipe, m
g	gravitational acceleration, m/s ²
h_1	inlet port height, m
h_2	outlet port height, m
k	turbulent kinetic energy, m ² /s ²
L	length of RACM pipe, m
L_1	distance between inlet port and floor surface, m
L_2	distance between outlet port and floor surface, m
P_{out}	outlet vacuum pressure, Pa
PMV	predicted mean vote
PPD	predicted percentage dissatisfied, %
Q_{in}	cooling air supply flow rate, m ³ /h
q_{wall}	thermal conductivity, W/m.K
V_{in}	inlet air velocity, m/s
V	air velocity, m/s

T	air temperature, °C
T_{in}	air inlet temperature, °C
T_{mr}	mean radiant temperature, °C
T_{op}	operative temperature, °C
T_f	floor temperature, °C
$T_{a, 1.1}$	air temperature at 1.1 m, °C
$T_{a, 0.1}$	air temperature at 0.1 m, °C
t	time, s
x, y	Cartesian coordinates
φ_1	angle of inlet port, °
φ_2	angle of outlet port, °
ε	turbulent dissipation, m ² /s ³
η	temperature gradient, K/m

Subscripts

oz	occupied zone
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could be eliminated by proper designs. Personalized air with a temperature below that of room air was able to bring “a cool head” and increased thermal comfort in comparison with traditional ventilation.

Sun et al. [7] studied the performance of a circular perforated panel air terminal device for PVS operating under two levels of turbulence intensity (Tu). The paper presents findings on how the Tu of the local air supply impacts the cooling effect in the facial and whole body areas and the corresponding thermal sensation of tropically acclimatized occupants.

Schiavon et al. [8–10] studied the energy consumption of a PVS and energy saving strategies which can be used to control a PVS and to develop and test an index for evaluating the cooling fan efficiency in a laboratory. The potential saving of cooling energy elevated air speed was quantified by means of simulations using EnergyPlus software. Fifty-four cases covering six cities (Helsinki, Berlin, Bordeaux, Rome, Jerusalem, and Athens), three indoor environment categories, and three air velocities (<0.2, 0.5, and 0.8 m/s) were simulated. Cooling energy savings in the range of 17–48% and a reduction of the maximum cooling power in the range of 10–28% have been obtained. The PVS may reduce the energy consumption substantially (up to 51%) compared to mixing ventilation when the control strategies are applied.

Melikov and Knudsen [11] investigated an individually controlled system (ICS) comprising a convection-heated chair, an under-desk radiant heating panel, a floor radiant heating panel, an under-desk air terminal device supplying cool air, and a desk-mounted personalized ventilation using forty-eight human subjects at room temperatures of 20 °C, 22 °C, and 26 °C. The results reveal that the thermal and air quality acceptability was significantly higher with the ICS at all room temperatures compared to the reference condition at a room temperature of 22 °C without ICS. Thus, ICS will increase the number of satisfied occupants when applied in practice.

Watanabe et al. [12] developed and tested the same ICS as described above with 48 human subjects and reported that at a room air temperature of 20 °C the maximum whole-body heating effect was 5.9 °C, and at a room air temperature of 26 °C the maximum whole-body cooling effect was only −0.8 °C.

In recently published designs, Huang et al. [13–17] adopted computational fluid dynamics (CFD) simulations and experimental measurements in a room with an airflow management technique to control airflow in the room to meet the demand for a regional steady-state temperature. A regional air-conditioning mechanism (RACM) system was constructed with an air uptake and outlet that created airflow circulation cells in the seating area of an occupant.

Those studies considered the change in distance between the inlet and outlet ports, port heights, and air-inlet velocity. Results showed that the RACM could successfully establish an individual thermal environment zone. Compared to traditional air-conditioning systems, the RACM is predicted to save energy. Validation of the CFD using experimental work has also been done by Huang et al. [18,19]. Experimental and CFD data include the temperature and velocity in the occupied zone. The results of simulation differ slightly from the results of the experiments, by around 11%. The fairly good agreement between experimental and simulation results indicates that it is possible to use the CFD simulation in the investigation of in-room characteristics of the RACM.

This paper presents nine cases divided into three groups in order to study the effect of four parameters on the creation of the airflow circulation cell: the cool air supply flow rate (Q_{in}), air inlet temperature (T_{in}), angle of inlet port (φ_1), and angle of outlet port (φ_2), which were also described in detail in our previous studies [13–19]. The simulation results showed that it is possible to create two independent temperature regions in a simulated room. The airflow circulation cell itself can be established in the occupied zone. When suitable values of the RACM's parameters are chosen ($Q_{in} = 43.09$ m³/h, $T_{in} = 23$ °C, $\varphi_1 = 85^\circ$, and $\varphi_2 = 90^\circ$), the most energy saving and the greatest thermal comfort can be achieved. Among the three groups studied, group 2, in which T_{in} and φ_2 but not Q_{in} and φ_1 were fixed for all case studies, is the most sensitive from the perspective of vertical temperature distributions in the middle of the occupied zone in the room. In comparison with the other two groups, group 2 could create a desirable thermal comfort zone and reduce energy consumption by as much as 12%.

2. Thermal comfort indices

2.1. Predicted mean vote

The thermal comfort of an occupied zone is an important issue. One method of assessing thermal comfort is to use the equations for predicted mean vote (PMV) proposed by Fanger [20,21]. PMV is defined by six thermal variables of indoor air and conditions of human occupants: air velocity, air temperature, mean radiant temperature (MRT), relative humidity of the air, clothing, and physical activity. Fig. 1 shows a combination of each thermal variable affecting PMV level. Fanger showed that values of PMV between −0.5 and +0.5 are in the range within which 90% of people are satisfied [20,21]. The PMV corresponds to a prediction of the

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