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Investigation on the flow and thermal behavior of impinging jet ventilation systems in an office with different heat loads

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ABSTRACT

This paper presents the flow and temperature field within an office using impinging jet ventilation (IJV) under different heat loads ranging from 17 to 65 W per square meter floor area. The measurement was carried out in a full-scale test room to verify the reliability of three turbulence models, i.e., the RNG $k-\varepsilon$, SST $k-\omega$ and $\overline{v^2}-f$ models. It is found that all the tested models show good agreements with measurements, while the $\overline{v^2}-f$ model shows the best performance, especially on the overall temperature prediction.

The $\overline{v^2}-f$ model is used further to investigate a number of important factors influencing the performance of the IJV. The considered parameters are: cooling effect of chilled ceiling, external heat load as well as its position, number of occupants and supplied air conditions. The interaction effect of chilled ceiling and heat sources results in a complex flow phenomenon but with a notable feature of air circulation. The appearance and strength of the air circulation mainly depends on the external heat load on window and number of occupants. It is found that with higher external heat load on window (384 W and 526 W), the air circulation has a strong tendency towards the side wall in the opposite direction to occupant, while with lower power on window (200 W) the air circulation has a strong tendency in the center of the room and extends to a larger area. When two occupants are present, two swirling zones are formed in the upper region. The effects of air circulation consequently alter the temperature field and the level of local thermal comfort.

1. Introduction

The quality of indoor environment is increasingly recognized as a significant factor influencing the overall level of building occupants' health, comfort and productivity. An air-conditioning and ventilation system is usually used to provide good thermal comfort and indoor air quality. Displacement ventilation (DV) is widely used as a means of ventilation to provide good indoor air quality and save energy [1]. Despite the potential of high ventilation efficiency provided by DV, it has some shortcomings due to the low momentum supply, i.e., poor ventilation efficiency in some zones of the room and the fact that it can only be operated in a cooling mode [2]. Recently, a new ventilation system, termed impinging jet ventilation (IJV), was proposed by Karimipanah and Awbi [3] and Rohdin and Moshfegh [4], aiming to create better indoor environment and provide greater working flexibility.

In impinging jet ventilation, a high momentum air jet is discharged downwards, strikes the floor and spreads over it, thus distributing fresh air along the floor in the form of a thin layer. Similar to DV, cool conditioned air is heated by the heat sources and rises upwards to the ceiling in the form of a thermal plume, thus creating a temperature and contaminant stratification in the room. But superior to DV, the supplied fresh air has sufficient momentum to overcome the buoyancy force to reach further regions, and thus better ventilation efficiency in the occupied zone can be realized. In addition, IJV can also be used for heating purposes. However, there are two potential risks associated with the low-level supply systems of IJV and DV, as the cool air is directly supplied to the occupied zone, i.e., the draft discomfort due to cold air movement close to the floor, and the excessive temperature difference between head and ankle level [5]. Therefore, careful design considerations are required to avoid thermal discomfort.

To create a suitable indoor environment, room air movement and temperature distribution need to be controlled properly,

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Nomenclature

CC	chilled ceiling
C_p	specific heat (J/kg K)
DV	displacement ventilation
EHLF	external heat load due to solar radiation imposed on floor (W)
EHLW	external heat load due to solar radiation imposed on window (W)
g_i	component of the gravitational vector in the ith direction (m/s^2)
IJV	impinging jet ventilation
IHL	internal heat load generated from occupant and electrical equipment (W)
k	turbulent kinetic energy (m^2/s^2)
P	pressure (Pa)
PD	predicted percentage of dissatisfied due to draught
q_v	supply airflow rate (m^3/s)
R	portion of chilled ceiling cooling load to total cooling load
SHGC	solar heat gain coefficient
S_{ij}	strain rate (1/s)
T	air temperature (°C)
T'	fluctuating temperature (°C)
T_u	turbulence intensity
U	mean velocity (m/s)
x, y, z	coordinate (m)

Greek symbols

β	coefficient of thermal expansion (1/K)
δ	Kronecker delta
$\delta_k, \delta_\varepsilon, \delta_\omega, \delta_t$	turbulent Prandtl numbers
ε	dissipation of turbulent kinetic energy (m^2/s^3)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (kg/ms)
μ_t	turbulent viscosity
ω	specific dissipation rate (1/s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ρ_0	reference density (kg/m^3)
τ	solar transmittance

Subscripts

i, j	coordinate index
s	supply
in	inlet
op	operative

because they have fundamental roles in thermal comfort and indoor air quality. In practice, room air movement is complex, not only governed by the supplied momentum from the supply device, but also influenced by buoyant plumes from heat sources. In addition, when high heat load exists in a room, a cooling system such as chilled ceiling (CC) is usually considered to supplement the cooling load, since the cooling capacity of the ventilation system (i.e., IJV and DV) is limited by thermal comfort requirements. The combination of chilled ceiling and ventilation system offers an opportunity to maintain an acceptable operative temperature in the occupied zone without increasing the draft risk, provided that chilled ceiling is operated properly, see [6,7], otherwise it will impose some characteristics on room air [8], see [9–12,15]. Alamdari et al. [9] stated that at cooling load of 60 W/m^2 of floor area, CC panels reduce air temperature near the ceiling, which creates downward air movement and hence increases the depth of the mixed warm air layer adjacent to the ceiling. Furthermore, CC panels reduce the wall surface temperature below the room air temperature by radiation and downward convection occurs along room surface, thus impairing indoor air quality in the occupied zone. Tan et al. [10] and Schiavon et al. [11] examined the effect of CC, based on the parameter η defined as the cooling load provided by CC to the total cooling load on temperature gradient. As η increases, the cooling load provided by CC becomes larger, while the temperature difference in the occupied zone and upper zone is reduced. Larger CC load, however, would probably lower air quality due to the increased mixing of room air [12]. The parameter of the ratio of CC load to total cooling load is used as one of the parameters for proposing the operational design charts of the hybrid air conditioning system of CC/DV [13,14]. Besides, studies [11,15] also showed that low ceiling surface temperature can destroy the displacement flow pattern.

When a chilled ceiling is used, high heat load exists in a room, which can be contributed by internal heat load from occupants and electrical equipment, or external heat load due to solar radiation, or both. In this case, a number of thermal plumes are developed around heat sources; each of them entrains air and creates an upward convective flow, thus bringing heat and contaminants that are less dense than air from surrounding occupied zones to the upper part of the room [1]. A number of studies have been conducted to examine the effects of buoyant plumes on airflow pattern in a room with displacement ventilation (and cooling ceiling/beam), see [16–21]. Mattsson [16] performed smoke visualizations in a DV ventilated mockup office, equipped with occupant, PC simulator and ceiling lighting. It is observed that the flow field is significantly influenced by the convection currents from the heat sources, and the resulting flow phenomena is rather complex. The author also noticed that the combination of heat source power, shape, and in particular the height above the floor has a great impact on the temperature stratification. Park and Holland [17] numerically investigated the effect of vertical location of a convective heat source on displacement ventilation, and found that the characteristics of circulation flows formed in the upper region vary with the heat source location: when the source is located at a low level, the plume develops fully and generates a large circulation, thus a strong static pressure is built up in the upper region and consequently reduces the stratification level. Rees et al. [18] studied the buoyant flow in a room with displacement ventilation and chilled ceiling system by means of numerical transient simulation. It was found that the flow becomes quasi-periodic at higher internal load in the room. Complex lateral oscillations are observed in the plumes above the heat sources which impinge on the ceiling and induce significant reticulation flows in the room. Ahmed et al. [19] performed a numerical simulation and presented the results of three-dimensional turbulent buoyant recirculating flow within a room with heated obstruction. Kosonen et al. [20] experimentally investigated the impact of heat load location and strength on airflow pattern with a chilled beam system. The results indicated that the point where the maximum velocity occurs in the occupied zone depends on the heat source and its location in the room. The authors also emphasized that the air flow interaction in rooms ventilated with chilled beams is important for occupant's comfort. Koskela et al. [21] studied air distribution in office environment experimentally and numerically. It was revealed that the asymmetric room layout of heat sources and chilled beams generates a large scale circulation in office environment, which can cause