https://doi.org/10.1051/e3sconf/202235601052

Performance evaluation of impinging jet ventilation combined with ductless personalized ventilation

Pengju Liu[1], *Bin* Yang[1,2*]

[1]Xi'an University of Architecture and Technology, China
[2]Tianjin Chengjian University, China

Abstract. Impinging jet ventilation (IJV), which supplies a high momentum air jet impinging and spreading over the floor, could be used in both cooling and heating modes. However, as a low-level supply system, the excessive temperature difference between head and ankle levels may exist due to the cool air being directly supplied to the occupied zone. As one type of different personalized ventilation (PV) terminal device, ductless personalized ventilation (DPV) is a self-standing system and doesn't require an extended air duct. In this study, numerical simulation was used to assess the performance of DPV combined with IJV in office buildings under different operating parameters. The results show that a large temperature difference between the occupant's head and ankle will be significantly decreased by the application of DPV while not influencing the stratification characteristics of impinging jet ventilation.

1 Introduction

The air distribution system inside a room is of great importance because it has a significant impact on the indoor environment, which is one of the main concerns in the design of an air conditioning system for buildings [1]. Displacement ventilation (DV) is widely used as a ventilation method to provide good indoor air quality and save energy [2]. However, there may be an imbalance between low supply air momentum and thermal buoyancy, resulting in poor ventilation efficiency in some zones of the room. In addition, DV can only be used for cooling and is not suitable for heating. To overcome these drawbacks, a new air distribution named impinging jet ventilation (IJV) was proposed [3]. 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. In this way, the air can be supplied to a further region of the occupied zone and better ventilation efficiency can be realized.

Focusing on the advantages of the IJV, some research papers have been published in recent years. For instance, Ye et al. [3] investigated a series of studies on IJV in the heating mode, and the results confirmed that compared with MV, IJV is easier to directly allocate warm air to the occupied area and also easier to distribute heating, with significantly lower energy consumption than MV [3].

However, like DV with the low-level supply system, the cool air with high momentum of IJV is directly supplied to the occupied zone, which could raise the potential risks of local thermal discomfort, i.e., draught due to cold air movement close to the floor, as well as excessive temperature stratification in occupied space. Therefore, the IJV system must be carefully designed by relevant recommendations in practical application.

Personalized ventilation (PV) could provide fresh and cool air directly to the breathing zone of each occupant, and the occupant can adjust the local air temperature and air supply velocity of PV to achieve individual thermal comfort preference. PV is often used in conjunction with ambient air conditioning [8]. To avoid the duct installation work caused by PV and the impact on the aesthetics and flexible layout of the room, ductless personalized ventilation (DPV) has been developed [9]. Ductless personalized ventilation (DPV) mainly employs an intake fan and brings fresh air from the room's lower level to the breathing zone around occupants [10]. The clean and cool air near the floor supplied by DV could be brought to occupants' breathing zone by an intake fan installed in DPV, and DPV still could improve the inhaled air quality when air stratification is disturbed by walking occupants [11].

Previous studies on DPV are mainly carried out under DV as background air conditioning, the influence of DPV on the indoor environment with IJV has not been studied. The present study investigates the impact of ductless personalized ventilation on the indoor thermal environment in the office with impinging jet ventilation. The indoor temperature and velocity distributions with/without DPV are simulated and compared by the validation CFD model.

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* Corresponding author: yangbin@xauat.edu.cn

2 Methods

2.1 Physical

The object of this study is an office building with impinging jet ventilation. The physical model is determined according to the climate chamber used to simulate the multi-person office environment, and the size of the chamber is 5.4 m × 5 m × 2.5 m. In this study, it is not necessary to assume the whole space as the region for analysis due to the symmetry of the geometrical configuration and heat source distribution of the climate chamber. Therefore, the space on one side of the symmetry plane is selected as the computational domain to simplify the model and save computational resources, as shown in Figure 1. Air supplied duct is adjacent to the sidewall of the chamber, and the installation height of the duct is 0.4 m above the floor. The outlet of the air supply device is circular with an opening diameter of 0.25 m. Two exhaust outlets are located on the ceiling and there are four ceiling-mounted lamps. Four workstations are installed in the occupied zone, and each workstation is equipped with a DPV device. The diameter of the DPV inlet is 0.1 m, and the intake height of DPV is 0.1 m.

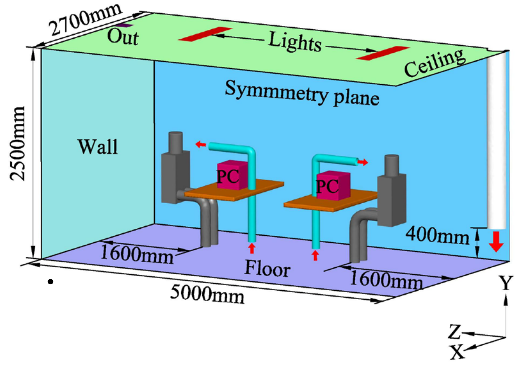


Fig. 1. Side view of the computational domain.

2.2 Numerical details and boundary conditions

The 3-D numerical simulation software ANSYS FLUENT is used for simulation. The governing equations are solved with a segregated scheme and the pressure-velocity coupling is controlled by a SIMPLE algorithm. The governing equations' momentum, turbulent kinetic energy, and turbulent dissipation rate are discretized using the second-order upwind scheme. To make sure the numerical convergence, the normalized residuals of continuity, momentum, turbulent kinetic energy, and dissipation rate should be less than 10^{-3}, and the energy residuals should be less than 10^{-6}.

To simulate the thermal environment in the multi-person office, settings of heat gains from heat sources (e.g., occupants, computers, and lamps) can be found in Table 1.

Furthermore, the boundary condition of inlet is set to a velocity inlet and the outlet is specified with an outflow boundary condition. The inlet values of turbulent kinetic energy (k_{in}) and dissipation rate (ε_{in}) profiles are determined as follows [12].

$$k_{in} = 1.5(V_{in}T_u)^2 \quad T_u = 0.16(Re_L)^{-1/8} \tag{1}$$

$$\varepsilon_{in} = C_\mu^{3/4} k_{in}^{3/2} / l \tag{2}$$

where V_{in}, T_u and Re_L are the averaged velocity, turbulence intensity, and Reynolds number at the inlet, respectively. DPV is used to suck the cold air near the floor and transport it to the occupants' breathing zone.

Table 1. Heat gains in the room.

Heat sources	Heat gains, W
Lamp	50×4
Occupant	100×4
Computer	60×4
Total	840

2.3 Mesh generation and independency

The ANSYS ICEM software is used to generate a 3D tetrahedral unstructured mesh in the simulation domain. And a non-uniform grid strategy is adopted, and mesh refinement is applied to the inlet, outlets, and solid walls. The accuracy of numerical simulation can be greatly improved by properly setting the first layer height in the boundary layer meshes.

Four numbers of meshes are generated for grid independence analysis, with the number of grids being 1.43 million, 2.24 million, 3.14 million, and 4.33 million respectively.

As shown in Fig. 2, 16 points 0.2 m away from the occupants at the height of 0.1 m and 1.1 m respectively are selected and the temperature and velocity distributions at these points are also compared for independence analysis. And the values of root-mean-square error for the test of velocity between different meshes are 1.55%, 0.87% and 0.94%, and the values for the test of temperature between meshes are 0.74%, 0.71% and 0.49%. Finally, the mesh number of 3.14 million is used for simulation.

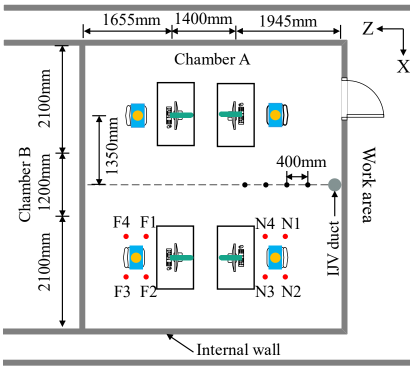
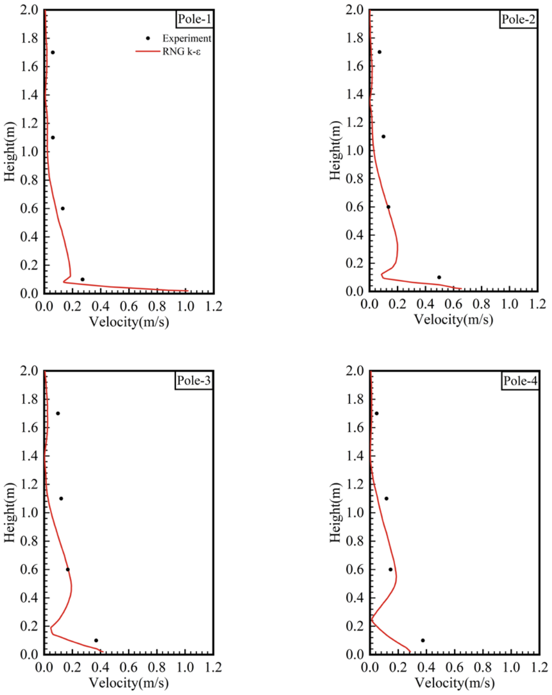


Fig. 2. Horizontal view of chamber setup.

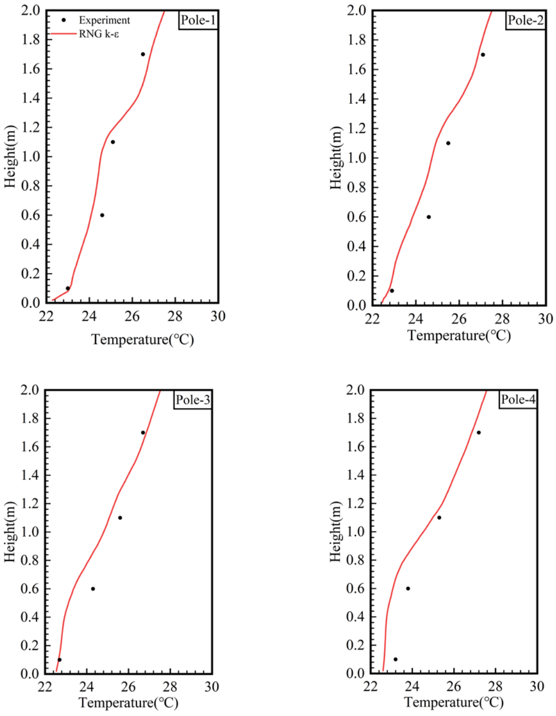
2.4 Model validation

The selection of turbulence models affects the accuracy of numerical simulation. Previous studies show that the RNG k-ε model has been widely used and recommended for its ability to accurately simulate the indoor airflow distribution of IJV [7].

Fig. 3 show the comparisons of the velocity and temperature profiles at the four measurement positions between the numerical simulation from the RNG k-ε model and the experimental data, respectively. In the simulation, the air supply speed is 2 m/s and the supply temperature is 21.5 °C. And results show that the numerical simulation results are in good agreement with the experimental data.



(a) Velocity distribution



(b) Temperature distribution

Fig. 3. Comparisons of numerical simulation results and measurements.

2.5 Studied cases

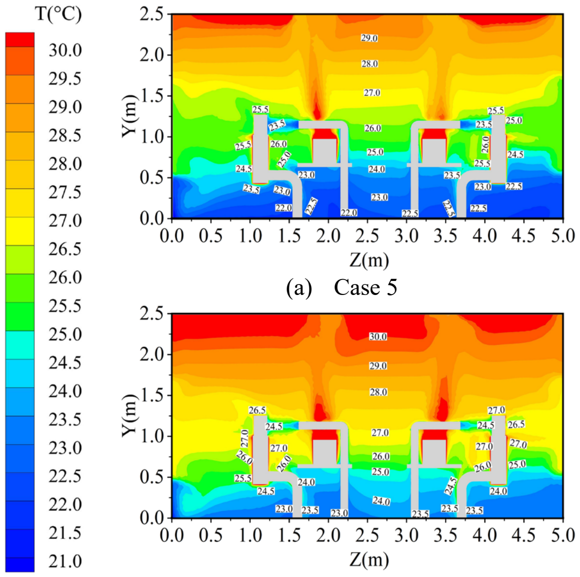
As an air distribution with high supply air momentum, the recommended value of supply air velocity of IJV ranges from 1-3 m/s [3]. In this present study, two typical values of IJV supply velocity, 1.5 m/s and 2 m/s, are used to keep the indoor temperature at 1.1 m height at 25 °C, and 27 °C, respectively.

Table 2. Variable parameters for studied cases.

	Vs(m/s)	Ts(°C)	Ta (at 1.1 m)	DPV
Case1	2.0	21.5	25	off
Case2	1.5	20.0	25	off
Case3	2.0	23.0	27	off
Case4	1.5	21.0	27	off
Case5	2.0	21.5	-	11L/s
Case6	1.5	20.0	-	11L/s
Case7	2.0	23.0	-	11L/s
Case8	1.5	21.0	-	11L/s
Case9	2.0	21.5	-	8L/s
Case10	1.5	20.0	-	8L/s
Case11	2.0	23.0	-	8L/s
Case12	1.5	21.0	-	8L/s
Case13	2.0	21.5	-	5L/s
Case14	1.5	20.0	-	5L/s
Case15	2.0	23.0	-	5L/s
Case16	1.5	21.0	-	5L/s

3 Results and discussion

3.1 Indoor temperature distribution



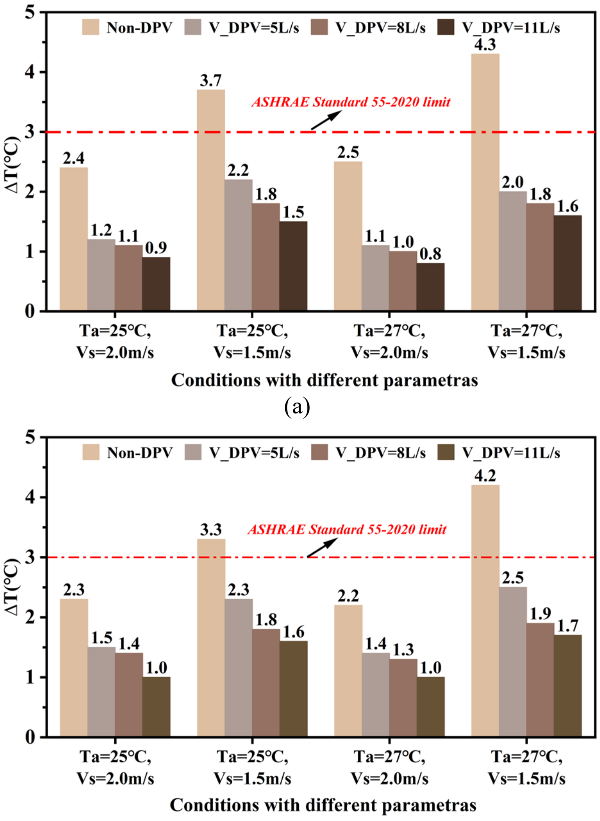
(a) Case 5

(b) Case 11

Fig. 4 Vertical temperature profile at X=1.35 m: (a) Case 5; (b) Case 11.

Fig. 4 shows two cases, i.e., case 5 and case 11 of the indoor vertical temperature profile at X=1.35 m when the flow rate of DPV is 11 L/s at the ambient temperature of 25 °C and 27 °C, respectively. The results show that the indoor vertical temperature distribution with impinging jet ventilation has obvious stratification, and the temperature in the lower part of the room is lower than that in the upper part. In all cases, the temperature distribution near the floor is uniform, due to the high supply momentum of impinging jet ventilation overcomes the thermal buoyancy and supplies cool air to the region far from the supply opening. The cool air near the floor is transported by DPV and supplied to the occupant's breathing zone, resulting in the thermal plumes generated by the occupant being removed and the temperature around the occupant's head being decreased.

3.2 Vertical temperature difference



(b)

Fig. 5 Vertical temperature difference between occupant's head and ankles (a) near the supply opening; (b) away from the opening;

A high vertical temperature difference around occupants can cause local discomfort: the temperature difference between occupants' head level (1.1 m) and ankles level (0.1 m) under different conditions is calculated and shown in Fig.5. As shown in Fig. 9, the vertical temperature difference between occupants' heads and ankles can be significantly decreased due to the cooler air being supplied directly to the occupants' breathing zone with the application of DPVs, resulting in all cases meeting the specification requirements. And the vertical temperature difference is decreased with the increase in DPV flow rate. In addition, the decrease of ΔT is not obvious when the DPV flow rate is 11 L/s compared to the lower rate at 8 L/s. The results by comparing Fig.9 (a) with Fig.9 (b) show that the ΔT is also almost independent of occupants' position, which means the application of DPV is not restricted by personnel location, and it could be used to meet the requirements of different occupants on air velocity. In addition, although the ambient temperature is at the same level, the vertical temperature difference is different with different supply velocities of impinging jet ventilation. When the supply velocity of IJV is 1.5 m/s, the vertical temperature difference is a little higher than that with the higher supply velocity of 2.0 m/s, but both don't beyond the specification limit.

4 Conclusions

In this study, numerical simulations are conducted to evaluate the performance of ductless personalized ventilation combined with impinging jet ventilation. The results show that the use of DPV has almost no influence on the stratification characteristics of impinging jet ventilation which is the ambient air conditioning. The high vertical temperature difference that may cause local thermal discomfort between the occupant's head and ankles can be significantly decreased by applying DPV.

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