

Heating performance of heating floor integrated with impinging jet ventilation system

Bin Zhou¹, Bin Yang^{1,2*}, Zhe Li¹ and Angui Li¹

¹ School of Building Services Science and Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China

² School of Energy and Safety Engineering, Tianjin Chengjian University, Tianjin, China

Abstract. Radiant floor heating systems provide comfortable indoor thermal environment. Primary air supply systems can be used to remove contaminants in the space heated by radiant floor. In this study, heating performance of integrated system of impinging jet ventilation (IJV) and heating floor was numerically investigated. The lowest floor heating capacity was 0 W/m² and gradually increased to 50 W/m², and the primary air temperature supplied by IJV were 14, 16 and 18°C, respectively. In terms of contaminant removal efficiency, contaminant removal efficiency (CRE) was applied. The vertical dimensionless temperature distribution was used to analyse the heating performance of HF on supply air. The numerical results showed that the supply air layer of IJV could be heated by 60% to 80% under the heat effect of HF. The same is true for low supply air temperature 14 °C. The integrated system IJV/HF generated the weakened thermal stratification which is beneficial for energy saving. The CRE of IJV/HF system was influenced by the downward airflow of external wall. Sufficient supply air could overcome the downflow and effectively increase the CRE value (> 2).

1 INTRODUCTION

It is recognized that occupants' health, comfort and work efficiency are highly related to the quality of indoor environment. Radiant floor systems are widely used for space heating in cold winter because it could uniformly heat the space without any cold corners. However, the indoor air could be stagnant and the accumulated contaminants are trapped in the space. Primary air systems are essential in an application with the heating floor (HF) to provide a comfortable thermal environment and air quality.

For radiant heated room, displacement ventilation (DV) is always served as the fresh air system because of the higher contaminant removal efficiency (CRE) than mixing ventilation (MV). Causone et.al analysed the temperature gradient in HF/DV and reported that the thermal stratification reduced as the floor heating capacity increased [1]. The thermal stratification gradually changed to the mixing mode. The recommended supply air temperature of HF/DV should be at least 2 °C lower than the room temperature and the floor temperature not exceed 25 °C [2]. The application of HF/DV is limited by the heating buoyancy effect of DV flow near the heating floor.

Impinging jet ventilation (IJV) provides a stratified air distribution both for heating and cooling mode [3]. The airflow is discharged from the IJV airvent which is fixed above the floor level and then downwards and impact the floor forming a floor-spreading air layer. For cooling mode, the fresh air is heated by local heating sources, such as electric devices and human bodies, and

flow upwards, thus creating a vertical thermal stratification. Meanwhile, IJV has a well performance on contaminant removal. The ventilation performance of IJV is similar to the DV, but the high air supply momentum of IJV is the most character that differ from DV [4]. Ye et.al analysed the affecting factors on the warm air spreading distance of IJV [5]. They reported that the larger required spreading distance is, the more supply air volume flow is. Yamasawa experimentally investigated the difference of indoor environment between IJV and DV [6]. The results showed that IJV worked as MV with high supply momentum and worked as DV with low supply momentum. In this study, the effect of IJV on indoor thermal environment and ventilation performance was numerically analysed in a HF office layout.

2 METHODS

2.1 Physical model and meshing setup

The typical office was constructed with the dimension of 5.4 m * 4.9 m * 2.6 m (Fig. 1a). The round duct of IJV was fixed near the interior wall and the supply outlet has a diameter of 0.25 m, 0.6 m above the floor. Four occupants were simulated with the heat generation of 80 W/per/person. Round noses with a diameter 0.01 m were constructed at occupants' faces to simulate respiratory process. In this office, external wall were considered to generate the heating loss because of the temperature difference between indoor and outside. Two windows

* Corresponding author: yangbin@xauat.edu.cn

(1.26 m * 0.62 m) were located at one of the external wall. Two square outlets (0.2 m * 0.2 m) were located at the ceiling level.

Poly-hexcore grid was applied to reduce the total number of the mesh (Fig. 1b). A fictitious box (1.2 m * 0.6 m * 0.6 m) was applied to provide body of influence on meshing. Thus, local grid refinement was conducted near the IJV inlet and the impinging area. The first mesh height at boundary was 1.5 mm [7] and 8 layers of boundary grid were meshed. After mesh independence analysis, 1.24 billion grids were sufficient for the accuracy of numerical results.

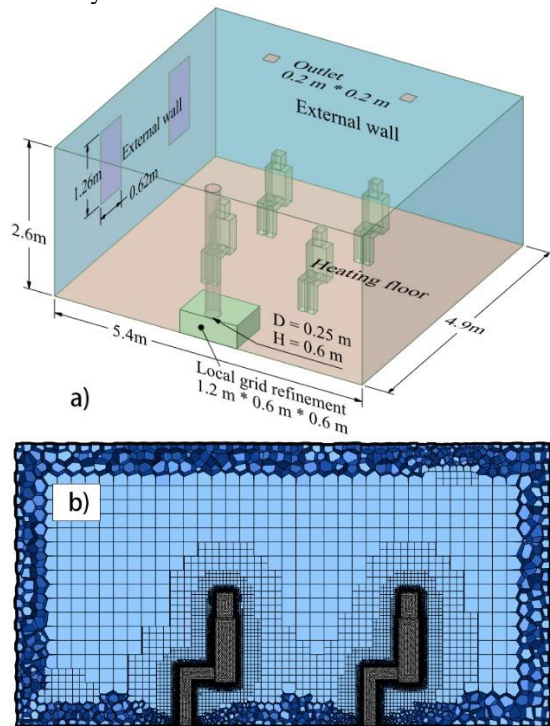


Fig. 1. Computer domain: (a) office layout in numerical investigation and (b) mesh distributions (cross section)

2.2 Numerical details

The whole floor was considered to be covered by the heating pipe (i.e. HF). Occupants and HF provided indoor thermal input and the external wall and window provided thermal loss. Constant heat flux was applied on these boundary surfaces. Indoor contaminants were marked by carbon dioxide (CO₂) which mainly produced by occupants' respiratory process [8]. Detailed numerical settings were listed in Table 1.

Table 1. Numerical setups.

CFD code		Ansys 2019 R3
Turbulence Model		RNG k-ε Model
Radiation Model		Discrete Ordinates Model
Species Model		Species transport Model
Algorithm		Coupled
Boundary Conditions	Inlet	Velocity-inlet; Mass fraction of CO ₂ : 0
	Outlet	Pressure-outlet
	HF/Occupants	Positive Heat Flux
	External Wall/Window	Negative Heat Flux
	Interior Wall	Adiabatic wall

	Nose	Velocity-inlet: 1.12 m/s; Temperature: 35 °C; Mass fraction of CO ₂ : 0.04
--	------	---

2.3 Studied cases

To analyse the heating and ventilation performance of IJV/HF system, the supply air temperature of IJV, heating capacities of HF and the supply airflow rate were combined, as seen in Table 2. The target air temperature was set at 22 °C. The volume of supply air was determined by personal required fresh air, 10 L/s, 15 L/s and 20 L/s, respectively. In this study, supply air volume was expressed by air changes per hour (ACH).

Table 2. CFD simulation conditions.

Case Number	T_s °C	V_s m/s	ACH h ⁻¹	Heating capacity (W/m ²)
1	14	0.82	2	30
2	14	1.22	3	30
3	14	1.64	4	30
4	16	0.82	2	30
5	18	0.82	2	30
6	18	0.82	2	0
7	18	0.82	2	10
8	18	0.82	2	50

2.4 Evaluating index

The numerical results provided detailed information of the flow filed. It was convenient to analyse the performance of IJV/HF system. The vertical dimensionless temperature T_0 was applied to evaluate the heating effect of HF on IJV supply air. The expression is described as:

$$T_0 = (T_y - T_s) / (T_e - T_s) \quad (1)$$

where T_s and T_e are the temperature at outlet and inlet, T_y is the air temperature refer to the relevant height. CRE was used to qualify ventilation performance of IJV on removing indoor pollutant, the equation is:

$$CRE = (C_e - C_s) / (C_y - C_s) \quad (2)$$

C_e , C_s and C_y are the CO₂ concentration at outlet, inlet and occupied zone. In all numerical results, C_s was zero at inlet.

3 Results and discussion

3.1 Indoor temperature distribution

Fig. 2 shows the temperature contour on the axial plane and the horizontal plane which is 0.1 m above the floor. The abbreviation of cases was applied. For instance, 14_30W_2ACH means the supply temperature is 14 °C, heating capacity of HF is 30W/m² and the ACH is twice. While the three cases had the same heating capacity, the supply temperature was 14 °C, 16 °C, and 18 °C. After impinging the floor, the IJV supply air was rapidly heated by the HF. For case 1, the temperature rise of supply could be higher than 5 °C that may effectively reduce the draught effect at lower body parts. With the

increase of the supply temperature, the air layer at 0.1 m height was more easily to be heated to the target room air temperature. Reflected on the axial profile, the vertical temperature stratification slightly decreased.

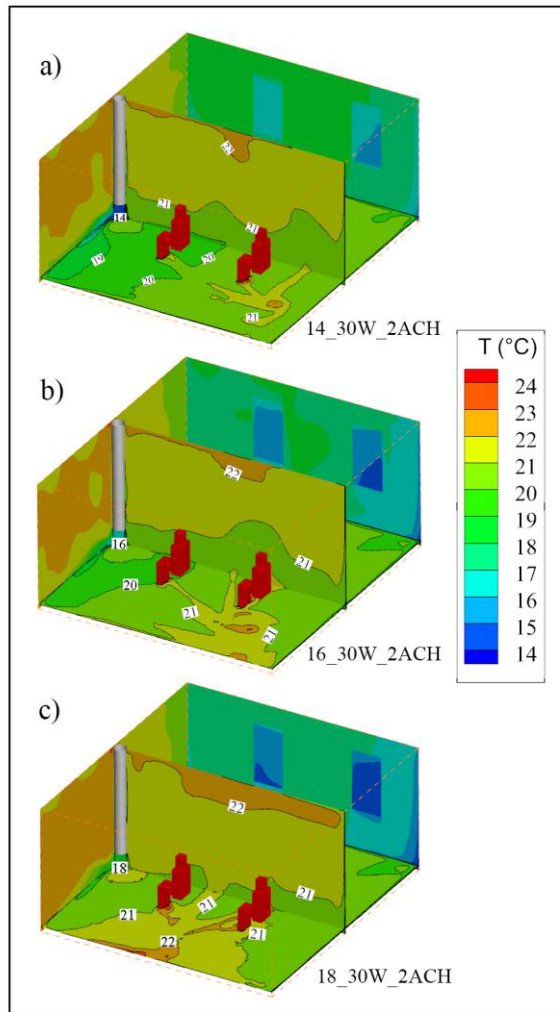


Fig. 2. Temperature profile (axial plane and horizontal plane ($y = 0.1$ m)): (a) case 1; (b) case 4; (c) case 5

Fig. 3 shows the vertical dimensionless temperature distribution of all the cases. The higher value of dimensionless temperature at 0.1 m height, the supply air of IJV will be effectively heated. The vertical temperature distribution with lower supply air temperature is more close to the 80% boundary and the vertical temperature distribution is more close to the 60%. When the dimensionless height is higher than 0.6 (1.56 m in this office), no obvious difference between the eight cases. The heating effect of HF mainly influence the seated occupied zone. All the temperature distribution were located between the boundary of 60% and 80%. Causone et.al indicated that the temperature distribution of DV/IJV system were located between the boundary of 40% and 70% [9]. It means that HF has higher heating performance on the supply air layer of IJV than that of DV. Lower supply temperature could be allowed in IJV/HF system than in DV/HF system without resulting in draught sensation.

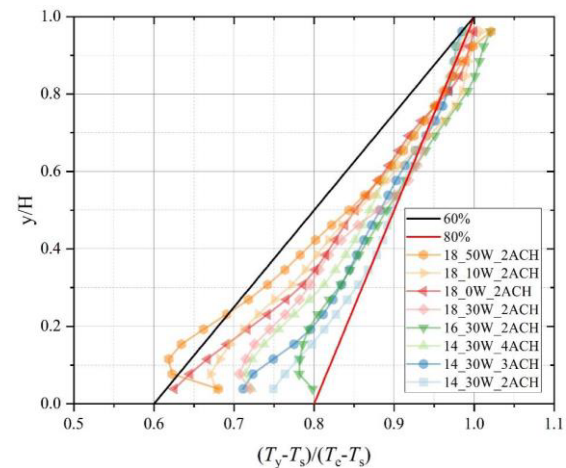


Fig. 3. Vertical dimensionless temperature gradient

3.2 Contaminant removal performance

Fig. 4 plots the CRE profile along the vertical direction. For perfect mixing condition, the CRE could be close to 1. In this study, all the cases have a high performance for removing indoor contaminants. When the air change rate was twice, the supply air temperature and the heating capacity of HF have limited effect on accelerating the remove of contaminants. The CRE at the height of respiratory zone (1.1 m) are from 1.0 to 1.5. Increasing the ACH to thrice, CRE slightly increased at 1.1 m height but still lower than 1.5. When increase the ACH to four times, the CRE could be obviously increased above 2.0 at 1.1 m height.

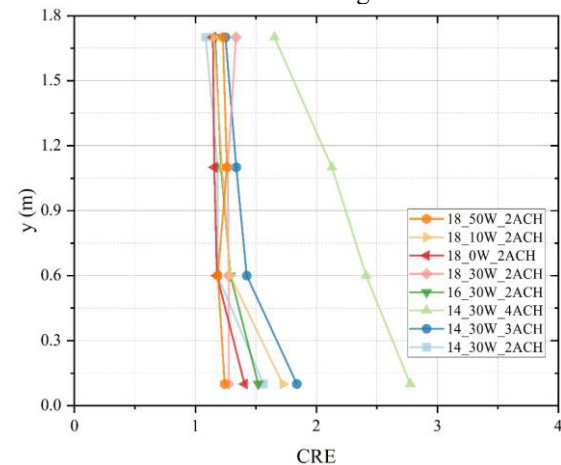


Fig. 4. Vertical contaminant removal efficiency

The increase of CRE may be explained according the streamline in Fig. 5. The external wall undertake the heating load and has a lower surface temperature than room temperature. Thus, the air near the external wall is cooled and flows downward. The downward airflow with entrainment destroys the vertical stratification of contaminant concentration. Little differences were observed on vertical CRE for the cases with 2 ACH. While the air change rate increases to three and four times, the supply air layer above the floor could gradually overcome the downward airflow. For 4 ACH, the supply air layer totally exceed the downward airflow, and the vertical contaminant concentration stratification

could be maintained, resulting a relative high CRE than other cases.

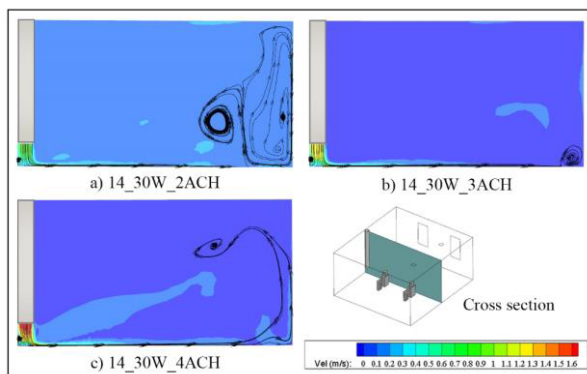


Fig. 5. Velocity contour and streamline: (a) case 1; (b) case 2; (c) case 3

4 Conclusions

In this paper, the heating and ventilation performance of IJV/HF system were investigated. IJV creates similar vertical thermal stratification under different supply temperature and floor heating capacity. The supply air layer is rapidly heated by HF and weaken vertical thermal stratification was generated. For heating mode, the weaken thermal stratification shows more energy saving potential than strong stratification. Attribute to high supply momentum, the supply air layer could overcome the buoyancy effect of HF and avoid transforming into mixing mode. With sufficient supply air, the downward airflow at external wall entrains polluted air at upper zone and reduces the contaminants removal performance at occupied zone. If supply air velocity is well designed, the downward airflow could be overcome and high CRE could be reached.

References

1. F. Causone, B. W. Olesen, S. P. Corgnati, F. Energy Build 42, 2338–2352 (2010)
2. H. Skistad, E. Mundt, P.V. Nielsen, K. Hagström, J. Railio, Displacement ventilation in non-industrial premises. REHVA, (2002)
3. X. Yang, X. Ye, B. Zuo, K. Zhong, Y. Kang, Build Simul **14**, 749–762 (2021)
4. H.J. Chen, B. Moshfegh, M. Cehlin, Build. Environ **59**, 127–144 (2013)
5. X. Ye, Y. Kang, B. Zuo, K. Zhong, Build Environ **120**, 1–12 (2017)
6. H. Yamasawa, T. Kobayashi, T. Yamanaka, N. Choi, M. Matsuzaki, Int. J Vent 1, 1–18 (2021)
7. B. Yang, B. Zhou, W. Su, Z. Li, A. Li, Tl. Olofsson, J Build Eng **36**, 102155 (2021)
8. W. Su, B. Yang, A. Melikov, C. Liang, Y. Lu, F. Wang, A. Li, Z. Lin, X. Li, G. Cao, R. Kosonen, Build Environ **207** 108555 (2022)
9. F. Causone, B.W. Olesen, S.P. Corgnati, HVAC&R Res **16** (2), 139–160 (2010)