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NUMERICAL ANALYSIS ABOUT THE FLOW PATTERN RESULTED BY EXHAUST AIR AND SUPPLY AIR

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ABSTRACT

Traditionally, jet flow is believed to be strong enough to supply air farther than exhaust air; exhaust air is believed to be only dominant near the outlet. However, there is little investigation about the difference between supply air and exhaust air in ventilated room. One two-dimensional ventilated room is taken as an example, in which both supply air mode and exhaust air mode are simulated by using CFD software. The flow pattern in the room without infiltrations and with infiltrations are compared. The numerical results indicate that the flow pattern resulted by exhaust air is almost the same with that resulted by supply air when there is no infiltration. When the infiltration exists, the flow pattern for exhaust air is different from that for supply air. When infiltration exists almost everywhere, the influence of exhaust air exists only near the outlet, while the influence of supply air has no obvious difference with the case without infiltration. Moreover, the specific influence caused by infiltration dimension is discussed. The study can explain the difference between exhaust air and supply air, and may be helpful for the design of different flow pattern.

INTRODUCTION

In traditional theory, a free air jet is a flow of air issuing from an opening or a nozzle into an air space where there are no solid boundaries to influence the flow pattern and where the temperature within the jet is the same as the surrounding temperature. In the free space, supply air is exactly a free air jet whose characteristics are that the velocity decays slowly and the influence region is large, as simulated in Fig. 1. By comparison, in free space exhaust air is just like a point sink, whose velocity is approximately quadratic attenuation and the influence region is small like a sphere, as simulated in Fig. 2.

Automatically people usually hold the idea that the characteristics of supply air and exhaust air in ventilated room are similar to those in the free space. Therefore, the influence of exhaust air is usually neglected in practical application.

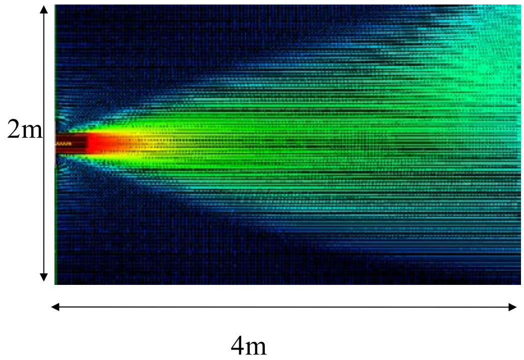


Fig. 1. Supply air in free space

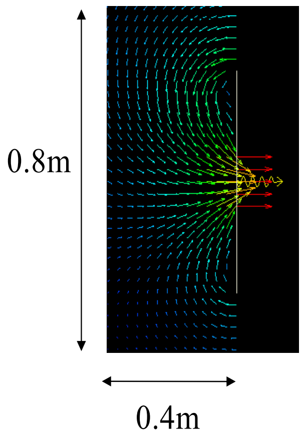
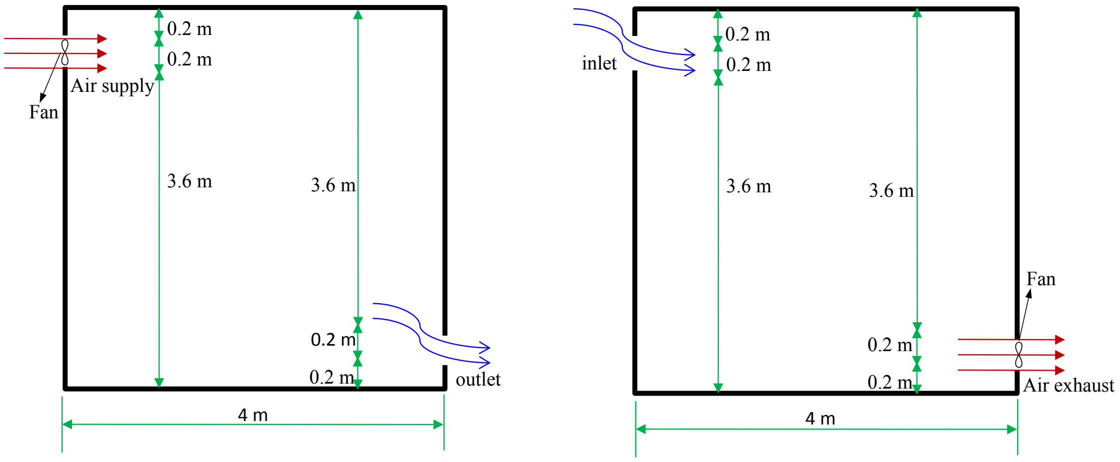


Fig. 2 Exhaust air in free space

For example, ASHRAE Handbook-HVAC Applications (ASHRAE, 2011) mentioned that “the air velocity from the exhaust hood decreases rapidly with distance from the hood in a room”. Industrial Ventilation-Design Guidebook (Goodfellow, 2001) pointed out “it can be easier, inside a specific volume, to use supply than to use exhaust air to control contaminants because of the much longer range of influence air from a supply openings have the same size and the same airflow rate.” However, is this idea always correct? What is the reason why the influence of exhaust air decreases quickly? What is difference of flow pattern between supply air and exhaust air in the room ventilation? Several studies about the different influence between supply air and exhaust air in practical applications have been carried out, such as that in a passenger vehicle (Wan et al., 1991),



(a) Supply air mode (b) Exhaust air mode

Fig. 3. Physical model of the ventilated room

during the manual handling of flour additive powder (Heinonen et al. , 1996), in the laboratory (Cheng et al. , 2010). However, few studies point out the difference between supply air and exhaust air in ventilated room and the reason why the influence of exhaust air decreases quickly.

In this study, a two-dimensional ventilated room is taken as an example. Considering the huge cost of money and time for experimental study, and difficulties to build a room without any infiltrations, computational fluid dynamics (CFD) technique is used to simulate the flow pattern in the room. Moreover, the feasibility and accuracy of CFD technique has been verified in similar studies, such as Zhao (Zhao et al. 2003). The difference of flow pattern between supply air and exhaust air is compared, and the reason why the influence of exhaust air decreases quickly is explained.

METHODOLOGY

Physical model

To analyze the difference of flow pattern between supply air and exhaust air in ventilated room, a two-dimensional room has been built as shown in the Fig. 3, with the size of 4 m (Long) ×4 m (Height). There are two ventilation modes in the room. In supply air mode (mode A), only supply air fans exist and the air is exhausted by the pressure difference between indoor and outdoor air. In exhaust air mode (mode B), only exhaust air fans exist and the air is balanced from the intake without any mechanical power. The infiltration capability of the room is described with different number and positions of small holes. To simplify the problem, the temperature of supply air is the same with that in the room, and there is no heat source in the room and the walls are adiabatic. The supply air diffuser, exhaust air vent, and infiltrations are simplified to linear openings. In supply air mode, the supply air opening is 0.2 m in size and located in the upper left, the outlet is an opening in the lower left and 0.2 m in size. The distance between the inlet and the top is 0.2 m, and the outlet is 0.2 m away from the bottom. The Fig. 3(a) shows the details. In exhaust mode, the physical construction is almost same with supply air mode. The only difference is that there is an exhaust air fan at the outlet rather than the inlet, shown in Fig. 3(b).

Hereinafter, four cases will be discussed by simulation, shown in Table 1. Case 1 is the room without infiltrations. Case 2 refers to the room with some infiltrations, which are distributed in the side walls evenly, with the width of 0.1m. Case 3 shows the room with sufficient infiltrations, which are distributed in the walls uniformly, with the width of 0.1 m. Case 4 presents the situation when the infiltrations position and number are fixed, the dimension varies from 0.00125m to 0.2m.

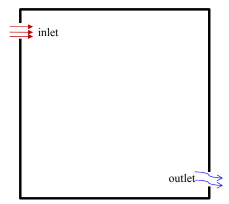
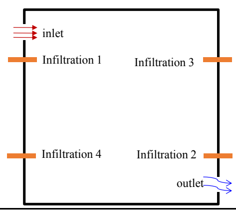
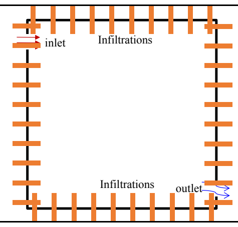
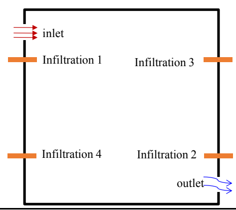
Simulation method

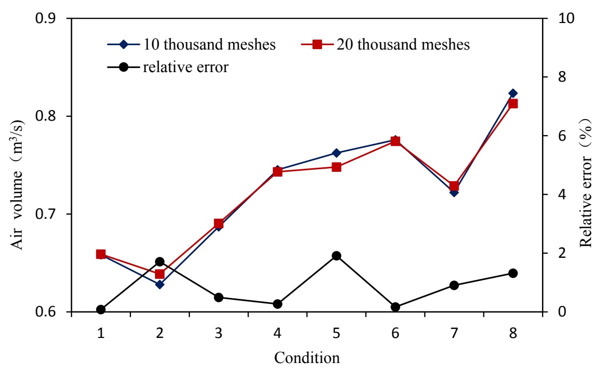
In this study, AIRPAK is adopted to simulate the airflow pattern in the room, which is a software widely used in indoor airflow simulation and verified by a wide range of case (Li, 2010).

In supply air mode, only supply air fans exist and the air is exhausted by the pressure difference between indoor and outdoor air. Therefore, the supply air inlet is defined as velocity-inlet, with velocity of 3 m/s, and the outlet is defined as outflow. In exhaust air mode, only exhaust air fans exist and the air is balanced from the inlet. Therefore, the exhaust air outlet is defined as velocity-outlet, with velocity of 3 m/s, the inlet is defined as inflow. The infiltrations are also defined as outflow, balanced by the pressure difference. All the walls are insulated, and temperature difference between airflow and surroundings is zero. The ambient gauge pressure is set as zero Pa.

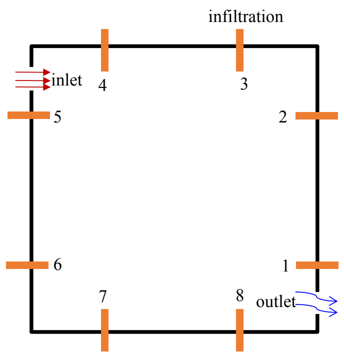
As for indoor turbulent flow, an indoor zero-equation turbulence model is used which adopts an algebraic expression of eddy viscosity directly in the near-wall region (Chen and Xu, 1998). The Reynolds Averaged Navier-Stokes (RANS) equations, together with averaged mass conservation equations,are discretized by using a finite volume method (FVM). The momentum equations are solved on non-uniform staggered grids using a Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm (Anderson, 1995). The discrete equations for each variable are solved using a point implicit (Gauss-Seidel) linear equation solver in conjunction with an algebraic multigrid (AMG) method. Linear under-relaxation iteration is applied to ensure convergence. The room in this study is discretized by hexahedral control volumes.

Table 1 The discussed cases in the study

	Case 1	**Case 2**	**Case 3**	**Case 4**
Position				
Velocity	3m/s			
Numbers	0	4	40	4
Width	0.1 m			0.00125m-0.2m
Remarks	without infiltration	Some infiltrations	Enough infiltrations	Different dimension



(a) The mesh independence test results



(b) Infiltration position in each condition

Fig. 4 Mesh independence test in the simulation

Mesh independence test is carried out by comparing air volume through the infiltration located in eight positions in different grid density. As shown in Fig. 4(a), the air volume difference through the infiltration between 10 thousand meshes and 20 thousand meshes is less than 2%, which indicates that 10 thousand meshes are enough to satisfy the calculation accuracy. So, the simulation with 10 thousand meshes is adopted. Fig. 4(b) shows the infiltration positions for the eight operation conditions in Fig. 4 (a).

RESULTS AND ANALYSIS

Case 1: without infiltration

For the room without infiltration (Case 1), both the supply air mode and the exhaust air mode have been simulated by using the model above. The results are shown in Fig. 5 and Fig. 6.

Fig. 5 shows the velocity vector of the room without infiltration. As seen in Fig. 5, the velocity field in exhaust air mode is almost the same with that in supply air mode. There is a large vortex for both of them. The influence of exhaust air can be covered in the whole room. The phenomenon indicates that the exhaust air can also be strong enough to influence a relatively farther region just like air supply, rather than only to be dominant near the outlet in free space. The small difference is that the average air velocity in supply air mode (0.745 m/s) is a little larger than that in exhaust air mode (0.722 m/s).

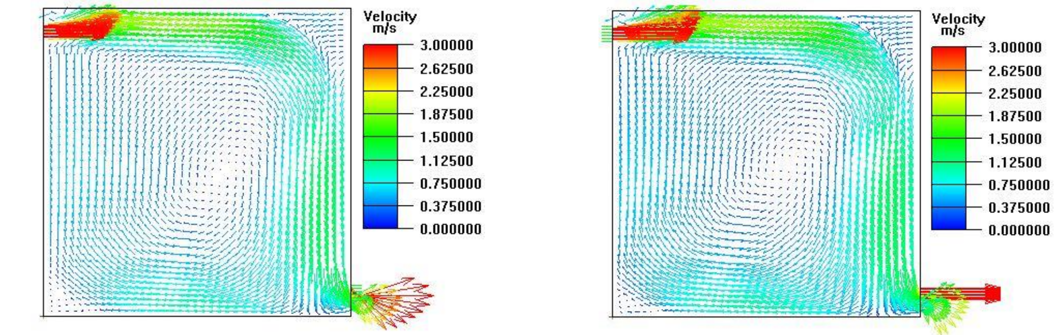
Fig. 6 shows the pressure distribution in the room. As seen is Fig. 6, the pressure field in supply air mode is similar to that in exhaust air mode, both of them are characterized by lower pressure in the middle and higher pressure in the corners. However, the absolute average pressure in supply air mode is 8.08 Pa a little bigger than 5.26 Pa in exhaust air mode (the actual value is -5.26 Pa).

As a whole, the flow pattern resulted by exhaust air is almost the same with that resulted by supply air when there is no infiltration in the room, which is different from the traditional theory about supply air and exhaust air(as shown in Fig. 1 and Fig. 2).

Case 2: with some infiltrations

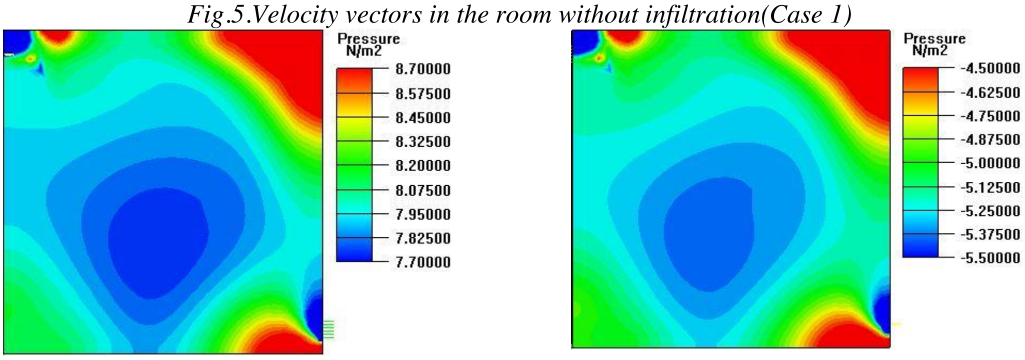
In practice, there must be some infiltrations in the room, due to the windows, doors, etc. Therefore, the room with some infiltrations (Case 2) is investigated by simulation. The simulated velocity field and pressure distribution are shown in Fig. 7 and Fig. 8 .

By comparing the velocity field in Fig. 7 with the velocity field without infiltration (as shown in Fig. 5), we can see that the velocity field of supply air mode changes only a little. The large vortex is similar for supply air mode with some infiltrations and without infiltration. However, in exhaust air mode, the velocity field changes a lot. The large vortex is broken into many small ones. And the average velocity is sharply decreased to 0.484 m/s, with a relatively lower ventilation ability.



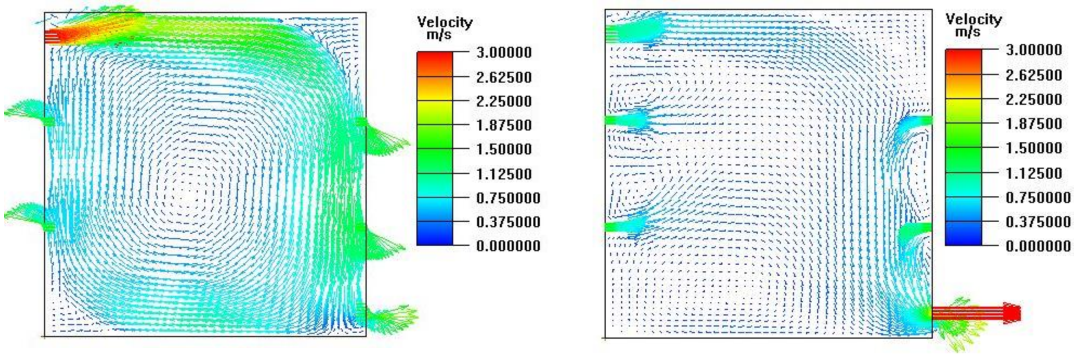
(a)Supply air mode (b)Exhaust air mode

Fig.5.Velocity vectors in the room without infiltration(Case 1)



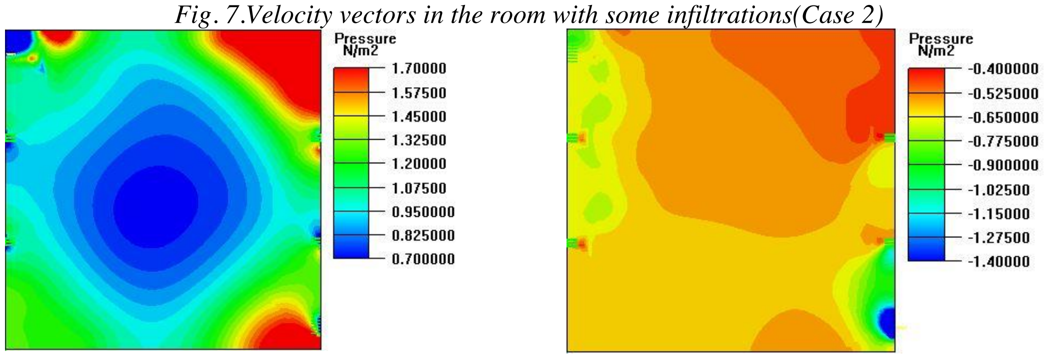
(a)Supply air mode (b)Exhaust air mode

Fig. 6. Pressure field in the room without infiltration(Case 1)



(a)Supply air mode (b)Exhaust air mode

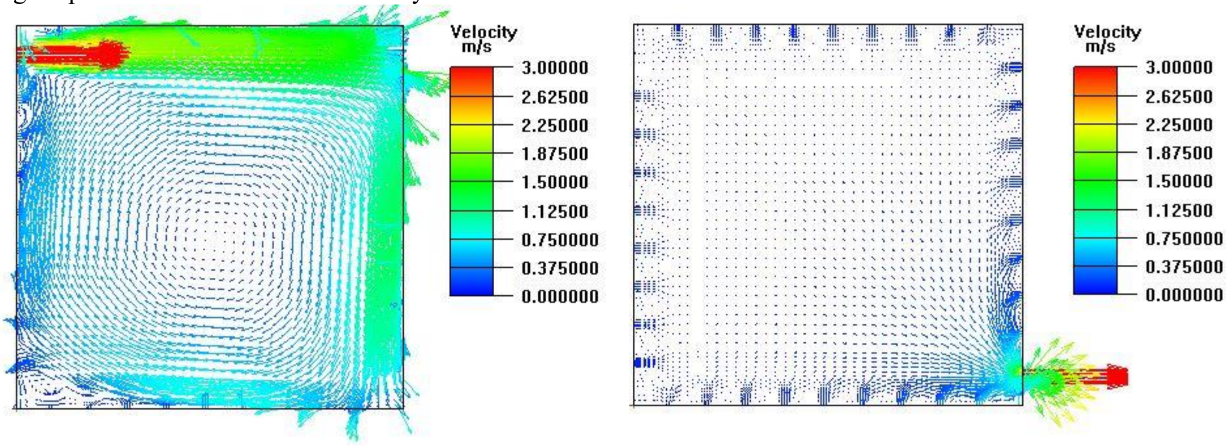
Fig. 7.Velocity vectors in the room with some infiltrations(Case 2)



(a)Supply air mode (b)Exhaust air mode

Fig. 8. Pressure field in the room with some infiltration(Case 2)

In Fig. 8, compared with the results without infiltration shown in Fig. 6, the pressure field of supply air mode changes a little. It maintains the characteristic of lower pressure in the middle and higher pressure in the corners. The only difference is that the average pressure decreases to 1.15 Pa. However, in exhaust air mode, the pressure field is very different from that without infiltrations, and tends to be uniform.



(a)Supply air mode (b)Exhaust air mode

Fig.9.Velocity vectors in the room with some infiltrations(Case 3)

Case 3: with sufficient infiltrations

For further analysis, suppose that there are sufficient infiltrations in the room (Case 3).As seen in the Fig. 9, when there are sufficient infiltrations in the room, the influence of exhaust air exists only near the outlet just like that in the free space, while the influence of supply air has no obvious difference with Case 1. Apparently, the infiltration has larger influence on exhaust air mode than supply air mode. Therefore, it is the infiltration that makes the flow pattern different between the supply air mode and the exhaust air mode. And the sufficient infiltrations make the flow pattern in ventilated room tend to be that in free space.

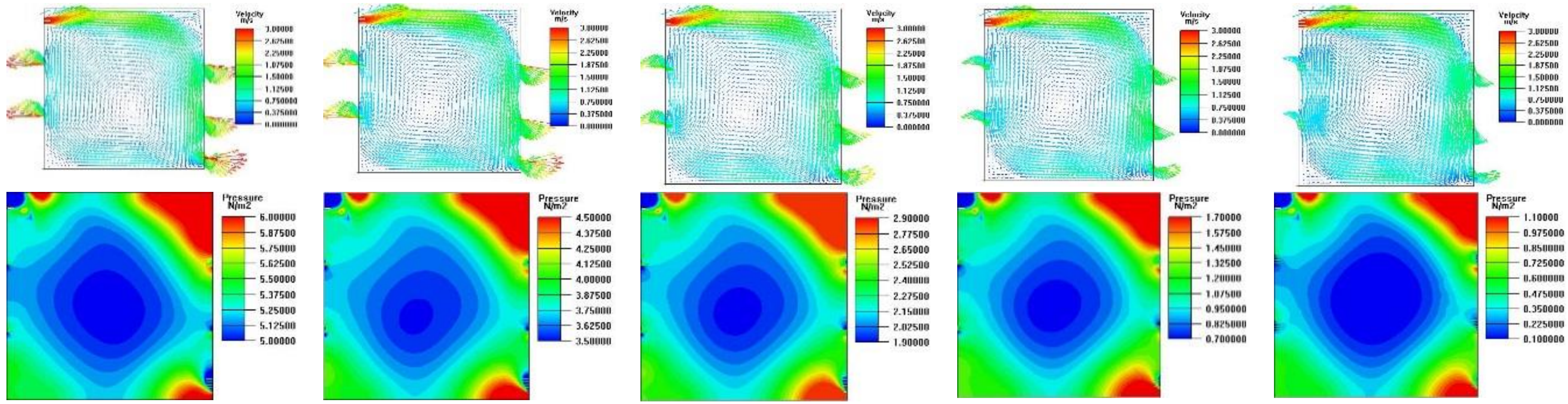
Traditionally, the supply air is a jet flow, which is strong enough to ventilate farther than exhaust air. Exhaust air is believed to be only dominant near the outlet of air and the influence of exhaust air decreases quickly when the distance to the outlet is increased. In fact, the traditional idea roots in the free space ventilation. However, in the room without infiltrations, the flow pattern resulted by exhaust air is almost the same with that resulted by supply air, which indicates that the exhaust air is also strong enough to ventilate the room just like the supply air. In practice, there must be some infiltrations in the room, which makes the flow pattern different between the supply air and exhaust air. The infiltrations have little effect on flow pattern in supply air mode, but have large effect on flow pattern in exhaust air mode. When infiltration exists almost everywhere, the influence of exhaust air exists only near the outlet, just like the free space case.

Case 4: infiltrations with different dimension

Since infiltration plays an important role in the room ventilation, further analysis about different dimension of the infiltrations have been discussed by simulation, shown as Case 4, where the infiltration number and position are fixed and the width of infiltrations varies from 0.0125 m to 0.2 m. The flow patterns in supply air mode and exhaust air mode are shown in the Fig. 10 and Fig. 11 respectively. In addition, the calculated results such as airflow volume are shown in Table 2 and Table 3.

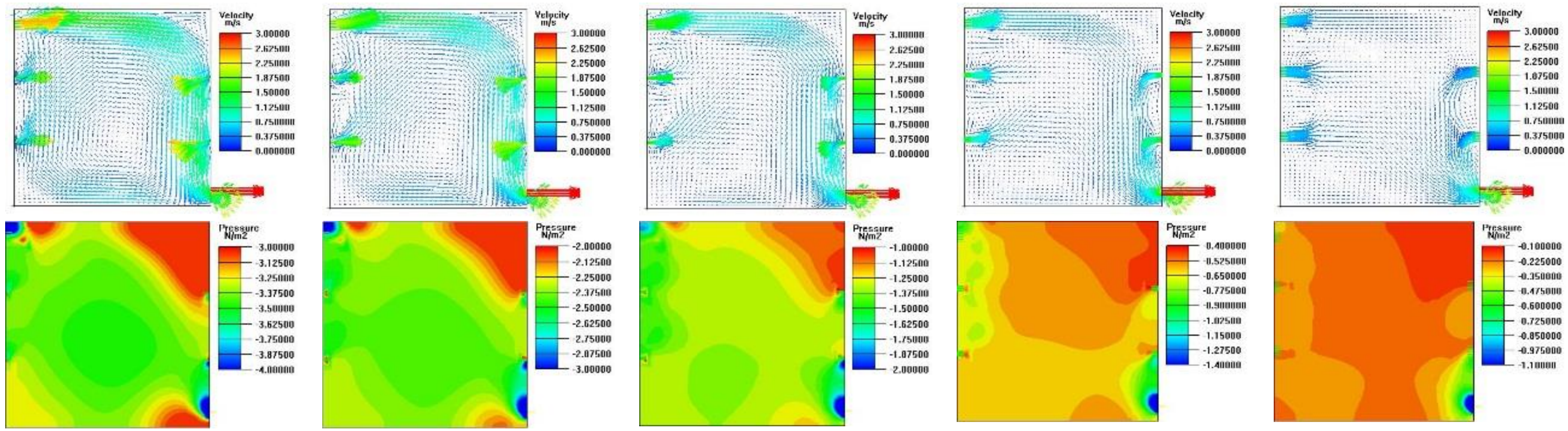
From Fig. 10 and Table 2, it is found that in supply air mode the large vortex in the flow pattern is almost the same and the pressure is higher around the corners and lower in the middle when the dimension of infiltration changes. As the dimension of the infiltration increases, the average velocity decreases slightly and the average pressure decrease sharply. Finally, the airflow volume through the infiltration becomes larger and the airflow volume through the outlet becomes less relatively.

From Fig. 11 and Table 3, it is found that in exhaust air mode the large vortex in the flow pattern disappeared gradually and the pressure distribution tends to be uniform with the increase of infiltration dimension. Additionally, as the dimension of the infiltration increases, the average velocity decreases faster than that in supply air mode. Similarly, the airflow volume through the infiltration becomes larger and the airflow volume through the inlet becomes less relatively.



W=0.0125 m W=0.025 m W=0.05 m W=0.1 m W=0.2 m

Fig. 10. The flow field with different infiltration dimension in supply air mode (Case 4)



W=0.0125 m W=0.025 m W=0.05 m W=0.1 m W=0.2 m

Fig. 11. The flow field with different infiltration dimension in exhaust air mode(Case 4)

Table 2. The airflow parameters with different infiltration dimension in supply air mode (Case 4)

Infiltration width	Airflow volume through						Average Pressure	Average velocity
	inlet	outlet	Infiltration 1	infiltration 2	infiltration 3	infiltration 4		
m	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	Pa	m/s
0.0125	2.400	1.970	0.112	0.100	0.107	0.109	5.232	0.807
0.0250	2.400	1.699	0.186	0.159	0.173	0.182	3.813	0.791
0.0500	2.400	1.362	0.279	0.225	0.254	0.274	2.323	0.773
0.1000	2.400	1.024	0.366	0.285	0.356	0.362	1.155	0.761
0.2000	2.400	0.755	0.367	0.306	0.553	0.418	0.473	0.712

Table 3. The airflow parameters with different infiltration dimension in exhaust air mode (Case 4)

Infiltration width	Airflow volume through						Average Pressure	Average velocity
	inlet	outlet	Infiltration 1	infiltration 2	infiltration 3	infiltration 4		
m	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	Pa	m/s
0.0125	2.400	1.942	0.116	0.116	0.110	0.116	-3.352	0.731
0.0250	2.400	1.634	0.194	0.196	0.182	0.191	-2.351	0.611
0.0500	2.400	1.256	0.286	0.289	0.297	0.270	-1.343	0.479
0.1000	2.400	0.865	0.388	0.391	0.398	0.357	-0.612	0.368
0.2000	2.400	0.498	0.480	0.489	0.497	0.436	-0.246	0.271

CONCLUSION

To analyze the difference of flow pattern between supply air and exhaust air, a two-dimensional ventilated room has been investigated by using CFD software. Both the room without and with infiltrations has been investigated by simulation. For further analysis, dimension of the infiltrations have been discussed in detail. The conclusions are listed as follows.

(1) In the ventilated room without infiltration, the flow pattern resulted by exhaust air is almost the same with that resulted by supply air, which is different from the traditional theory, i.e., the supply air is strong enough to supply air farther than exhaust air, and exhaust air is only dominant near the outlet of air..

(2) In the room with some infiltrations, the flow pattern for exhaust air is different from that for supply air. When infiltration exists almost everywhere, the influence of exhaust air exists only near the outlet, while the influence of supply air has no obvious difference with the case without infiltration.

(3) The infiltration dimension have a larger influence on exhaust air mode than supply air mode. When the infiltration dimension increases, the supply air mode maintains the same flow pattern. While the flow pattern in exhaust air mode changes a lot. The average velocity decrease sharply and the pressure distribution tends to be uniform.

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REFERENCES

ASHRAE, 2011, ASHRAE Handbook—Applications Ch.32: Industrial local exhaust, Atlanta, USA.

Cheng, S. F., Luo, W. J., Wu, Y. L., et al. 2010. The effect of air supply and air exhaust locations on particle restraint and removal in a laboratory utilizing a lagrangian particle-tracking method. Int. J. Phys, 5(10), 2150-2160.

Goodfellow, H. D. 2001. Industrial ventilation design guidebook. Academic press.

Heinonen, K., Kulmala, I., and Säämänen, A. 1996. Local ventilation for powder handling—combination of local supply and exhaust air. American Industrial Hygiene Association, 57(4), 356-364.

Anderson, J. D. 1995. Computational fluid dynamics. New York: McGraw-Hill.

Li, Y. 2010. Computational Fluid Dynamics Technology and Its Application in Wind Environment Analysis. Journal of Urban Technology, 17(3), 67-81.

Chen, Q. Y., Xu, W. 1998. A zero-equation turbulence model for indoor airflow simulation. Energy and Buildings 28 (2), 137–144.

Wan, J. W., and van der Kooi, J. 1991. Influence of the position of supply and exhaust openings on comfort in a passenger vehicle. International Journal of Vehicle Design, 12(5), 588-597.

Zhao B., Li X. T., Yan Q. S. 2003. A simplified system for indoor airflow simulation. Building and Environment. 38(4) 543-552.