Effect of the floor on the ventilation performance of the vortex vent

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ABSTRACT

The vortex ventilation system (VV) which uses a rotating finned swirler installed coaxially with the exhaust duct is a very effective local ventilator. VV can enhance the capture depth by a factor of 3-5 compared to the conventional exhaust hood, in the absence of any solid walls nearby. In real situations there may exist ceiling, side wall and floor, all of which can affect the flow field and suction performance by way of the no-slip condition on the walls. 3D CFD simulation was performed in order to see the effect of the floor on the capture performance of the VV. The presence of floor reduced suction flow velocity, and increased the critical rotational speed which is the rotational speed required for stable vortex formation. Flow velocity profile along the axis could be well approximated by a universal functional form when the distance from the exhaust inlet is non-dimensionalized by the distance to the floor. Capture depth, define by the distance from the exhaust inlet to a point of velocity decreased to 10% of that at the inlet, is reduced by about 10% when the floor distance is 6 times the exhaust hood diameter.

KEYWORD

Vortex ventilation system, swirler, floor effect, capture depth, critical rotational speed

NOMENCLATURE

u_z	:	axial velocity [m/s]
U_0	:	exhaust hood inlet velocity [m/s]
D	:	exhaust hood diameter [m]
z/D	:	non-dimensional distance from exhaust hood inlet
L/D	:	non-dimensional distance of the floor position

1. INTRODUCTION

The vortex ventilation system (Vortex Vent; VV) makes use of a strong vortex flow in the exhaust flow field in order to increase the capture depth. Lee & Lee (2005) achieved an enhancement by a factor of 3-5 depending on the definition of the capture depth, using a rotating swirler, compared to the conventional ventilation technique.

In the conventional exhaust system, the suction velocity generated by the negative pressure at the exhaust decreases very rapidly with distance from the exhaust inlet, approximately to the second power of distance like $(z/D)^{-2}$ (DallaValle 1993). In the VV with a rotating swirler, however, the axial velocity decreases much slowly, approximately to the first power of distance like $(z/D)^{-1}$ (Lee & Lee 2006). According to Shtren and Hussain (1996), the velocity owing to mass sink decreases as z^{-2}, while the velocity owing to momentum source decreases as z^{-1}. Therefore axial velocity characteristics of the VV are analogous to the jet flow.
In spite of the high capture performance of the VV, the effect of the floor has not been considered yet. The presence of a floor can affect the vortical flow, and the no-slip condition can also affect the general flow field. Since floors exist within a small distance from the exhaust in most real situations, understanding the effect of wall on the VV performance is for practical applications. This study performed the 3D CFD simulation on the effect of the floor on the capture performance of the VV.

2. CFD SIMULATION

The flow field around the VV was solved using the pressure-based solver of FLUENT which is a commercial CFD code using finite volume method. Figure 1 shows the schematic 3D model of the Vortex Vent used in calculation, and Table 1 gives the typical dimensions. The number of grids was about 100,000, and hexahedral mesh was densely populated near the swirler and the floor. The number of grids was determined so that the calculation results did not change appreciably with any further increase in grid number. Figure 2 shows the overall grid system of the VV, and the boundary conditions used in calculation are given in Figure 3 and Table 2.
The continuity equation (Eqn. 1) and the Reynolds-averaged Navier-Stokes equation (Eqn. 2) are the governing equations for the turbulent flow.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial t}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j}\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right] + \frac{\partial}{\partial x_j}(-\rho\overline{u_i' u_j'}) \tag{2}$$

In Eqn. 2, $-\rho\overline{u_i' u_j'}$ represents the Reynolds stress, and the Reynolds Stress Model (RSM) that directly solves for the Reynolds stresses was used in this study, because this model is known to be more accurate than the k- ε model. And the PRESTO scheme which is known to give stable results for rotational flow was used for the discretization of pressure field. The rotating flow was calculated for the steady state using the Single Reference Frame (SRF) method, and a quarter of the whole domain was calculated using periodic boundary conditions in order to reduce the computation memory and time. The basic domain size is 15D in radius and 20D in height.
The flow fields were obtained for a number of rotational speeds of the swirler (0 ~ 3500rpm) and distances to the floor (L/D = 3 ~ 33). Capture depth was determined by the distance along the axis from the exhaust where the suction velocity is 5% or 10% of that at the exhaust.

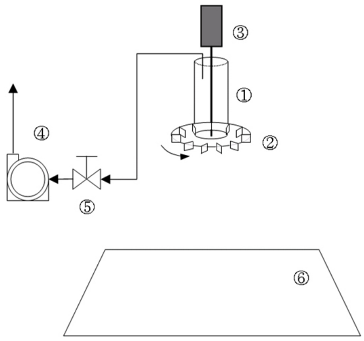

Figure 1 : Schematic of vortex vent ; ① Vortex Vent., ② Swirler, ③ Motor, ④ Blower, ⑤ Blower controller, ⑥ Floor

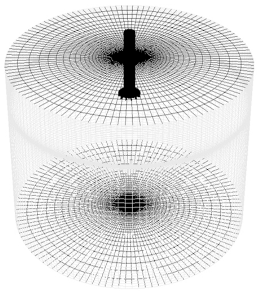

Figure 2 : Grid system of vortex vent

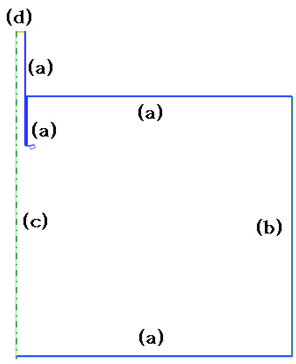

Figure 3 : Boundary conditions: (a) Wall, (b) Pressure outlet, (c) Axis, (d) Velocity inlet.

Table 1 : Dimension of vortex vent

Hood inlet diameter(D)	100 mm
Swirler diameter(D_S)	200 mm

Table 2 : Flow boundary condition

Velocity inlet(U_0)	-14.85 m/s
Swirler rotational speed	0 - 3500 rpm

3. RESULT

3.1 Axial velocity distribution

The ventilation performance of local ventilators is predominantly determined by the axial velocity distribution with distance from the exhaust hood. Figure 4 shows the variation of the axial velocity distribution with the floor position when the swirler rotates at 2500 rpm. The velocity curves closely follows the functional form of Eqn. 3, and the velocity profile for the simple suction, which corresponds to 0 rpm, is well approximated by Eqn. 4 (DallaValle 1993).

$$\frac{-u_z}{U_0} = \frac{1}{1 + a \cdot (z/D)^b} \quad (3)$$

$$\frac{-u_z}{U_0} = \frac{1}{1 + 40/\pi \cdot (z/D)^2} \quad (4)$$

Flow velocity is zero on the floor, and the distribution of axial velocity higher than 5 or 10% of U_0 which is the velocity range used for ventilation position is fitted to Eqn. 3. Then the best-fit coefficients are obtained as $a = \frac{0.68}{L/D - 2.89} + 2.86$ and $b = \frac{0.4}{L/D - 2.19} + 1.11$ at the rotational speed of 2500 rpm, which shows that the axial velocity(capture velocity) is in inverse proportion to the floor distance (L/D). Table 3 shows best-fit values of a and b for a number of rotational speeds of the swriler.

3.2 Suction depth

In the absence of the floor, the suction depth of the VV is determined by the rotational speed alone (Lee and Lee 2005). In the presence of the floor, however, the suction depth depends on two factors, the rotational speed and the floor position. Capture depth is usually defined by the distance from the exhaust to a point where suction velocity is 10% or 5% of that at the exhaust. Figure 5 shows the variation of the 10% suction depth for various floor positions and rotational speeds. It is observed in the figure that suction depth deviates from a monotonic trend at a rotational speed of about 2100 rpm. This rotational speed is called the critical rotational speed, and there appears a sharp transition of flow field at this rotational speed (Lee and Lee 2006). CFD simulation shows that the critical speed is increased and capture depth decreased as the floor comes closer to the exhaust. And capture depth does not change appreciably once the floor is farther than 10D from the exhaust.
Figure 6 summarizes the variation of the capture depth with floor distance for two different reference velocities of 10% and 5% and three rotational speed of the swirler (2500, 3000, 3500 rpm). And Figure 7 shows the reduction of the suction depth due to the presence of the floor. Capture depth is seen to reduce by about 10% when the floor distance (L/D) is 6 but is almost unchanged when L/D > 10.

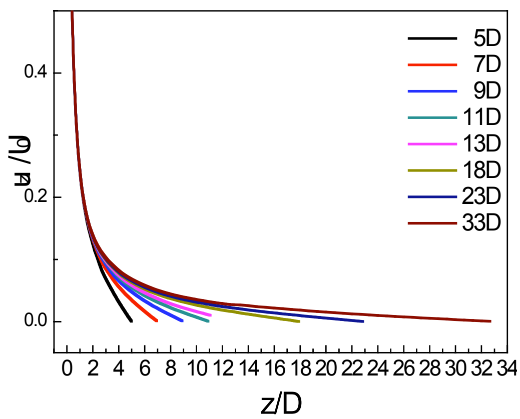

Figure 4 : Axial velocity distributions with L/D at 2500rpm.

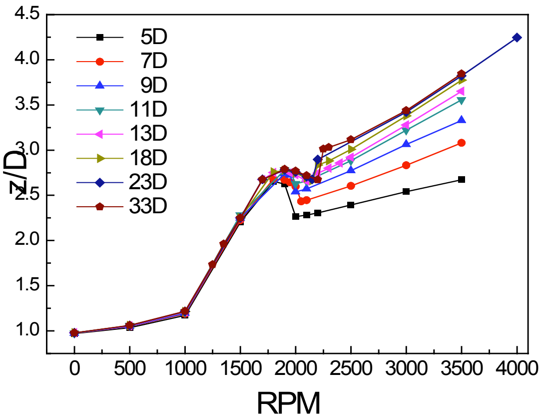

Figure 5 : 10% capture depth for various swirler rotational speeds and floor positions.

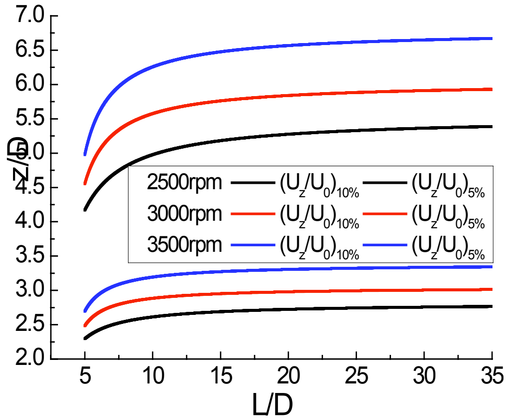

Figure 6 : Capture depth (z/D) versus the distance to the floor (L/D) for three rotational speeds and two different reference velocities for the definition of capture region.

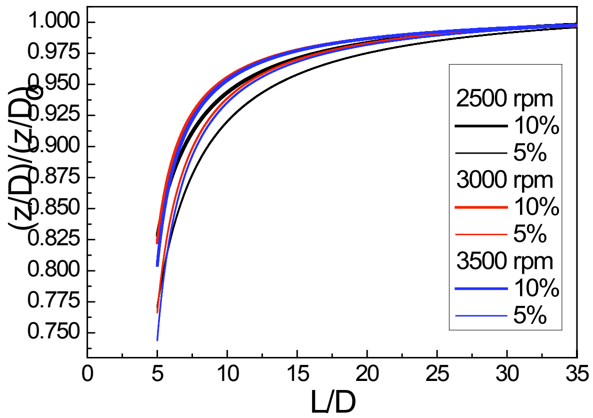

Figure 7 : Reduction in capture depth versus the distance to the floor (L/D) for three rotational speeds and two reference velocities for capture region.

Table 3 : Best-fit constants at various rotational speeds

	a			b		
rpm	C1	C2	C3	C1	C2	C3
2500	2.89	0.685	2.86	2.19	0.403	1.11
3000	3.90	0.299	2.66	3.01	0.277	1.09

3500	3.99	0.262	2.43	3.21	0.259	1.07

$$a = \frac{C_2}{L/D - C_1} + C_3\ ,\ \ b = \frac{C_2}{L/D - C_1} + C_3$$

4. CONCLUSION

CFD simulation was performed in order to see the effect of the floor on the capture performance of the VV and the following conclusions can be drawn from the study.

(1) The capture depth decreased as the floor is closer to the exhaust and capture depth is nearly constant as the floor position is farther than 10D from the exhaust hood.

(2) The axial capture velocity can be represented by a function of the rotational speed and the floor position.

(3) Capture depth is reduced by about 10% when the floor distance is 6D and the degree of reduction decreases close to zero monotonically with L/D up to 10D.

REFFERENCE

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