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A Protected Occupied Zone Ventilation System to Prevent the Transmission of Coughed Particles

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INTRODUCTION

Human respiratory activities, such as breathing, coughing, and sneezing, can significantly contribute to inter-personal exposure. Due to a high initial velocity, a cough jet carrying infectious aerosols can easily travel a long distance within a built environment. According to a study by *Zhu et al.(2006)*, an unblocked cough travels up to meters in a calm environment. Exposure to coughed particles can be diminished through proper use of a respirator or a filter mask, or alternatively, by thwarting particle transport from a source to a receiver via ventilation (*Tang et al., 2009*). Previous studies have shown that the dispersion of coughed particles in a room is strongly affected by ventilation airflow patterns (*Qian et al., 2006; Wan et al., 2007; Chen and Zhao, 2010*). For interpersonal exposure to particles from sneezing, the exposed concentration at the breathing zone of a receiver occupant is slightly higher under displacement ventilation (DV) than mixing ventilation (MV) (*Seepana and Lai, 2012*). Nevertheless, traditional ventilation patterns (MV and DV) are limited in their ability to redirect a strong momentum cough jet because of low local air velocity. An "air curtain," with a high discharge velocity, is usually implemented to minimize cross infection (*Aubert and Solliec, 2011; Nino et al., 2011; Guo and Li, 2012*) or heat gains/loss (*Foster et al., 2006; Gil-Lopez et al., 2004*). Similar to an industrial air curtain, a protected occupied zone ventilation (POV) system was subsequently proposed by using a low turbulence plane jet to separate an indoor space into a source zone and a target zone (*Cao et al., 2014*). The findings have shown that a POV may reduce the risk of exposure to indoor gaseous pollutants emitted in the source zone. However, there is little data in the published literature on how an air curtain can effectively reduce interpersonal exposure to coughed particles between two occupants.

The objective of this paper is to investigate the performance of a POV system on preventing the direct exposure to coughed particles within a room. The direct exposure herein refers to the exposure to particles in a cough jet, not including those re-circulated afterwards by ventilation. The POV system consists of a "push-pull" air curtain at the ceiling and an exhaust grill at the floor level. This study compares the level of direct exposure to fine coughed particles (0.77μm) for a susceptible occupant under two POVs and a traditional MV. Moreover, direct exposure is characterized with the intake fraction metric for the three ventilation patterns.

METHODOLOGIES

The experimental study was conducted in a chamber with a volume of 9.4 m^3 (Figure 1). A commercial linear slot diffuser can produce a downward vertical or a ceiling attached horizontal plane jet through adjustment of the inner blades. The vertical jet created by a POV can split the room into two zones: a source and protected zone. On the contrary, two opposed ceiling-attached jets greatly entrain surrounding air and generate an MV ventilation pattern within the chamber. The width of each slot was approximately 1.9 cm. The slot diffuser was installed full-length of the ceiling from wall to wall in the chamber.

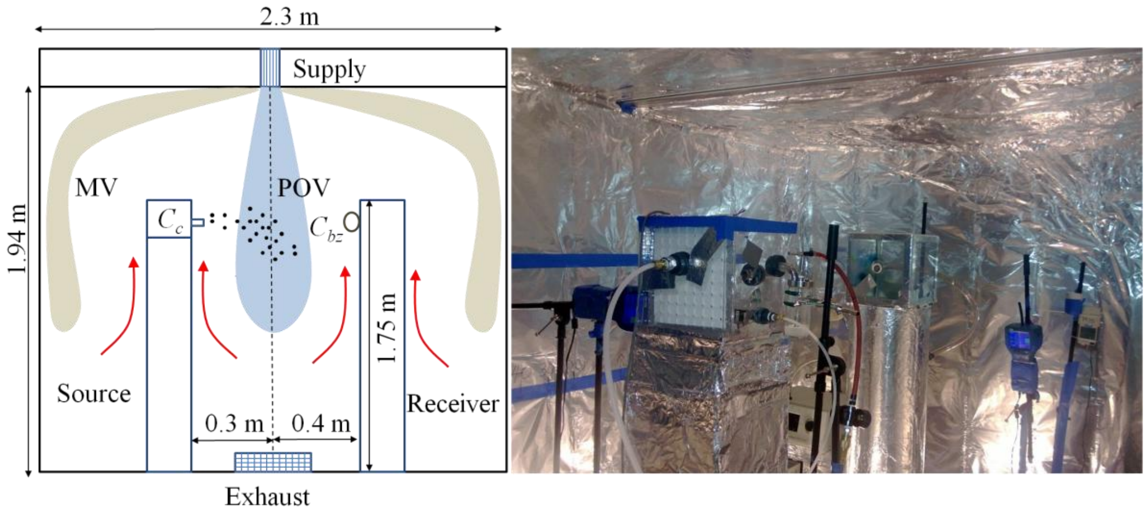

Figure 1. Schematic of the chamber and experimental setup

Two thermal manikins, each generating 75 W heat, were used to simulate both a source and a target occupant. The source manikin was positioned 0.3 m from the center of the POV jet, while the target occupant was 0.4 m. The source manikin generated a cough at a velocity of 6 m/s with a duration of 1 s by the use of a coughing box (*Liu and Novoselac, 2013*). The current study only considered the direct exposure to spherical 0.77 μm mono-dispersed particles in the breathing zone of the receiver occupant. This study explored direct exposure to coughed particles for three setups. The first two were POV systems with one-slot and two-slot downward curtains, respectively. The third one is a MV system using two opposed horizontal jets. All three setups employed an identical airflow rate, 244 m^3/hr. The average discharge velocity of the one-slot POV was 1.8 m/s. The two-slot POV and MV have an equivalent average discharge velocity, 0.9m/s.

In the coughing box, an Optical Particle Counter (OPC) measured the concentration of coughed particles. An Aerodynamic Particle Sizer (APS), with a high sampling frequency (1 s), monitored the particle variation within the breathing zone of the receiver occupant. The two devices were calibrated before conducting the experiments. The concentration in the breathing zone (BZ), C_{bz}, was normalized by the value of the coughed particles, C_c. The experiments were repeated three times for each ventilation setup. Because MV is widely applied in both residential and commercial buildings, the efficiency of a POV in protecting pollutant transmission is evaluated in terms of MV's performance. The protection efficiency (η) in this paper, as defined in Equation 1, is based on the peak particle concentration:

$$\eta = 1 - \frac{\left({C_{bz}}/{C_c} \right)_{POV}}{\left({C_{bz}}/{C_c} \right)_{MV}} \% \tag{1}$$

The intake fraction, IF, is the ratio of the mass inhaled to the mass released. The fraction can be calculated using Equation 2:

$$IF_{inhale} = \frac{\int_{\tau_{ep}=0}^{exposure\ time} \left(C_b \times Q_b \times \tau_{ep} \right)}{\int_{\tau_c=0}^{cough\ time} \left(C_c \times Q_c \times \tau_c \right)} \tag{2}$$

where Q_b is the breathing rate of a standing adult, 0.57 m^3/hr (Adams 1993), Q_c is the flow rate of a cough, 9.77 m^3/hr. τ_{ep} and τ_c are the direct exposure periods in the breathing zone and coughing duration, respectively.

To evaluate the performance of two POVs on the prevention of particle transmission, the study first conducted smoke visualization of a thermal cough. The indoor average temperature was approximately 25 ^oC, while coughed smoke had a temperature of 32^oC according to *Zhu et al.* (2006) with an Archimedes number (Ar) of 1.34×10^4. However, the experiments of coughed particles were performed under isothermal condition that coughed air had an identical temperature (25.3^oC) as the air in the cough box before coughing.

RESULTS AND DISCUSSION

This section presents the smoke visualization of a cough jet under different ventilation patterns. Furthermore, the protection efficiency of POVs and intake fraction of coughed particles is shown.

Smoke Visualization

Smoke tests were used to illustrate how a cough jet travels towards the target occupant under a calm environment, MV, and two-slot one-slot POV. In Figure 2, a cough jet penetrates slightly upwards towards the receiver occupant's breathing zone for a calm environment without ventilation. It implies that the buoyant human thermal plume has a little impact on a cough jet when the distance between the two occupants is shorter than 0.7 m. However, the cough jet is entrained upwards by the ceiling attached flows. With an identical airflow rate with MV, the two POVs bend a cough jet downwards before the jet travels to the target occupant. The results show that the one-slot POV with a double discharge velocity has a better performance to redirect the cough jet (compared to the two-slot POV at the same flow rate), leading to a shorter penetration distance. This suggests that the POV using a smaller slot opening while maintaining the same ventilation rate is more effective at deflecting cough jets away from susceptible occupants.

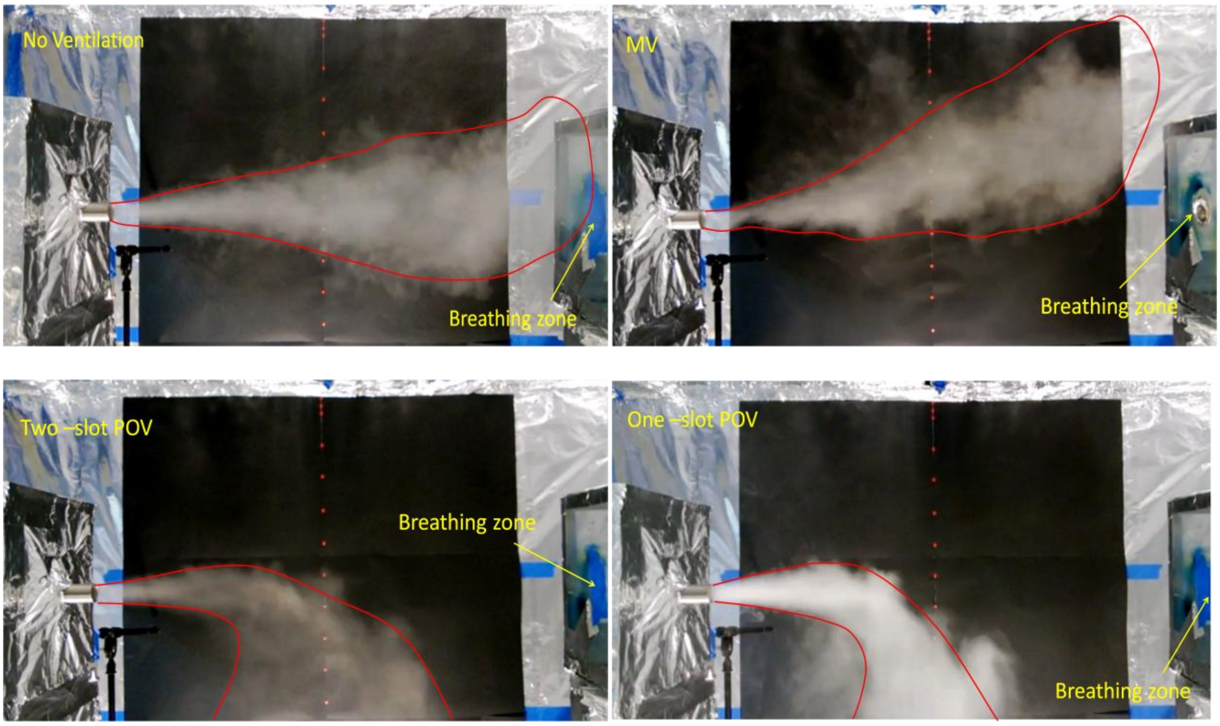

Figure 2. Smoke visualization of a cough jet under different ventilation patterns

Reduced Direct Exposure to Coughed Particles (0.77 μm) by POV Systems

The normalized concentration of coughed particles at the breathing zone of the receiver occupant was monitored for the three experimental setups. Figure 3 presents the variation of the concentration with time.

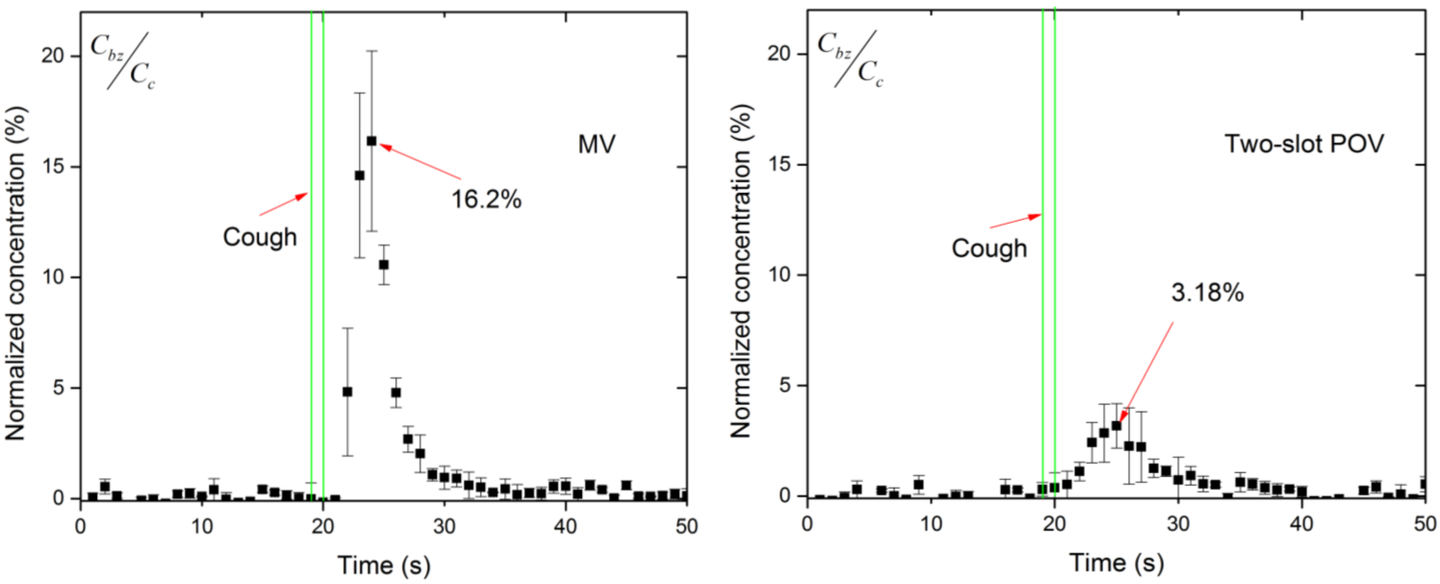

Figure 3. Normalized concentration of coughed particles (0.77 μm) in the breathing zone

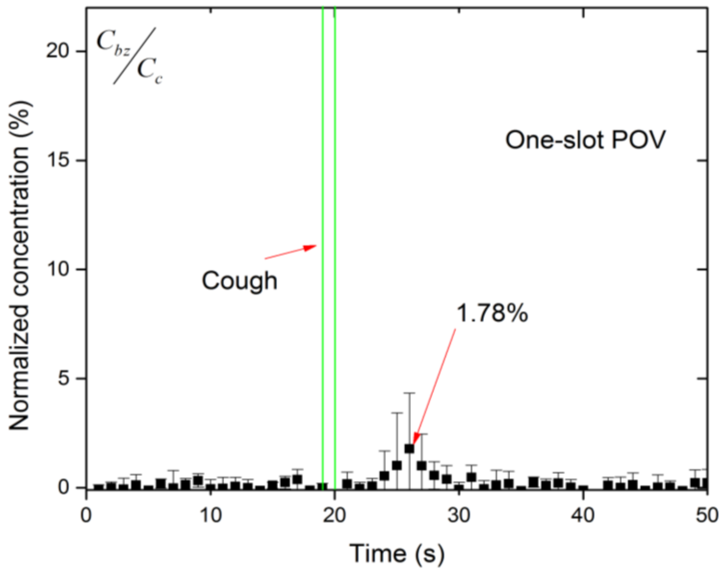

Figure 3. Normalized concentration of coughed particles (0.77 μm) in the breathing zone (*Continued*)

The results show that the average peak normalized concentration in the breathing zone for MV, two-slot POV, and one-slot POV are 16.2%, 3.18% and 1.78%, respectively. The one-slot POV reduces the peak concentration one order of magnitude lower than the use of a traditional MV. Both one-slot POV and two-slot POV can prevent the direct exposure to coughed particles with a protection efficiency at or above 80%, as described in Table 1. Because the one-slot POV significantly deflects the coughed jet, the direct exposure time of the receiver occupant to coughed particles is reduced, resulting in a lower direct intake fraction of 0.05%.

Table 1. Protection efficiency and intake fraction of coughed particles for three ventilations

Ventilation	Protection efficiency (%)	Intake fraction (%)	Direct exposure time (s)
MV	Not applied	0.55	8 (from 22 to 30)
Two-slot POV	80.4%	0.16	8 (from 22 to 30)
One-slot POV	88.9%	0.05	6 (from 24 to 30)

Discussion

The POV system in this study used a commercial linear slot diffuser to generate an "air curtain" to prevent the transmission of coughed particles. Since the diffuser was installed full length of the ceiling, a high supply airflow rate (air exchange rate of 26 h^{-1}) is required to maintain a strong discharge-velocity of the slots. It should be pointed out that the POV's performance can also be fulfilled by optimizing slot's geometry and operation strategy while using a low airflow rate. To reduce the energy penalty, furthermore, the POV system can be applied between office partitions or other scenarios where people stay in a dense population. Another important application is a retail store checkout, reception, and nurse and healthcare consulting counters. The reception employees tend to have many more possibilities to be exposed to respiratory particles. Furthermore, the POV is a "push-pull" system that requires a floor level grill to remove captured contaminants by an "air curtain". The implementation of POV systems demands additional ductwork and special design of airflow distribution.

CONCLUSION

To conclude, the POV is able to reduce the risk of direct exposure to particles coughed by another person by deflecting a high momentum cough jet. The intake fraction of coughed particles and the peak exposure level in the breathing zone of the receiver occupant is decreased up to one order of magnitude compared to a MV system. While maintaining the airflow rate, the one-slot POV presents an enhanced protection efficiency than the two-slot POV. These results suggest that a narrowly concentrated plane jet is more effective at reducing the direct exposure to expiratory particles than multiple low velocity jets. Due to possible limitations in application, our ongoing research will investigate the impact of other factors on POV's performance and consequently explore strategies to cut down supply airflow rate and energy cost.

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