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Characterizing the Dynamic Interactions and Exposure Implications of a Particle-Laden Cough Jet with Different Room Airflow Regimes Produced by Low and High Momentum Jets

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ABSTRACT

The objective of this study is to examine the dynamic interaction of a cough jet with different indoor airflow distributions created by linear slot diffusers considering the inter-personal transport of coughed particles. The experimental measurements were performed in a chamber, where the interaction of a cough jet and downward jets with various momentums was visualized by smoke. In this study, parameters related to the dynamic interaction of a transient cough jet and a steady downward jet have been studied: (1) distance between the cough jet source and an exposed dummy (ED); (2) the initial momentum of the downward plane jet. The experimental results indicate that the ceiling-attached horizontal jets that are widely applied in the over-head mixing ventilation systems have difficulties in deflecting the cough jet, and thereby have difficulties in reducing inter-personal transport of the coughed particles. This study found that a downward plane jet could prevent the transport of cough particles from the cough dummy to the ED. When the ED is standing 0.5 meter away from the cough dummy, the personal exposure (PE) level to coughed particles by using a downward plane jet could be two orders of magnitude lower than by using ceiling-attached horizontal jets. In addition, this study quantifies the interaction of a cough jet and a downward plane jet in their ability to reduce exposure to coughed particles. The results may be used in the process of diffuser selection and suggests that ventilation systems employing downward plane jets with high discharge velocities might be useful in public spaces to reduce inter-personal exposure to coughed particles.

Keywords: Downward plane jet; Jet Momentum; Coughed particles; Human exposure.

INTRODUCTION

Airborne transmission of infectious bacteria and virus carrying particles may be generated by infected persons and transported further via expiratory activities (Cole and Cook, 1998). Evidence of the associations between cross-infection, airborne transmission and airflow distribution in a ventilated space has been identified in different studies (Morawska 2006; Li *et al*., 2004; Nielsen *et al*., 2012; Huang *et al*., 2013). Relationships between supply airflow and microbial aerosol concentrations were also discovered in another study (Chuaybamroong *et al*., 2008). The Centers for Disease Control and Prevention (CDC) reported that tuberculosis is carried on airborne particles (droplet nuclei) that can be generated during a period of an infected persons' cough, sneeze, shout, or sing (CDC 2005). The particles have a size of approximately 1–5 µm and normal room air currents can keep them airborne for prolonged periods and disperse them throughout a room or building (CDC 2005). Particles smaller than 2.5 µm, which are also called respirable particles, can penetrate deep into the lung and cause serious adverse impacts on health (Nilsson, 2003). The respirable particles can stay airborne due to low gravitational settling and diffusional deposition. For example, droplets with a size of 1 µm may spend 8.3 hours falling 1 m. Likewise, an individual SARS corona-virus ranges from 0.075 to 0.16 µm in diameter may suspend in the air for a few days (Morawska, 2006).

Chao *et al*. (2008) found that the lateral dispersion behaviour was dominated by the ventilation airflow and the effect of the thermal plume was relatively minor for the 1.5–45 µm droplets with lower supply airflow rate. It is well known that a cough may be one of the prime infectious sources of airborne diseases as it has a high velocity and

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large quantity of droplets (Gupta *et al*., 2009, 2011). A number of studies have investigated the basic characteristics of a human's cough regarding velocity distribution and size distribution of droplets. The coughed particles may deposit to the floor and other indoor surfaces, such as clothing and bedding materials, where they can then become re-aerosolized through human-induced resuspension (Boor *et al*., 2013). Table 1 summarizes some of recent studies on the transport of cough particles in various room conditions. However, these studies did not examine how indoor airflow conditions will affect a cough jet, which may produce a huge amount of droplets and airborne particles.

An earlier study found that indirect exposure may indicate that the thermal boundary layer, with a velocity of 0.2 to 0.37 m s^{-1} (Voelker *et al*., 2014), may bring cough particles from lower body parts to the breathing zone after the impingement. In fact, the effect of thermal plumes from heat sources can be observed when the supply airflow was low and when the droplet size was small, < 12 µm (Chao *et al*., 2008). Practically, the spatial distribution of aerosol pollutants in close proximity to an occupant may be affected by the thermal boundary layer around a human body, occupant movement and breathing, and the overall airflow pattern in a space (Rim and Novoselac, 2009). The human's respiratory activities most likely affect the local airflow distribution and transport of contaminants from occupants' exhalation (Björn and Nielsen, 2002; Melikov *et al*., 2002, 2007). It has been reported that airflow patterns can be very important regarding indoor pollutant transmission (Pantelic *et al*., 2009; Bolashikov *et al*., 2012; Pantelic and Tham, 2013). The ceiling-attached horizontal jets (CAHJ) typically create mixing ventilation in a space (REHVA Guidebook NO. 19, 2013). In recent years, a new ventilation concept, protected zone ventilation (POV), which uses downward plane jets (DPJs) to separate internal space, has shown the potential to reduce the transport of pollutants from respiratory activities by using inert tracer gas (Cao *et al*., 2014a, b). However, there is still little knowledge of using DPJ's efficacy to prevent the transmission of airborne particles from respiratory activities, such as coughing. Because of the complexity in the interaction between a transient cough jet and a steady downward plane jet, the transport characteristics of coughed particles in a space requires further investigation to understand the prevention of coughed particle transmission using ventilation strategies, in specific, jet momentum and the distance between the cough source and plane jet.

Earlier studies shows that typical ceiling attached jets used in mixing ventilation schemes, coupled with the upward buoyant airflow generated by the human convective boundary layer, may enhance the dispersion of particles released by a human cough jet, thereby increasing the exposure (concentration and time) of receptor occupants (Melikov *et al*., 2002; Morawska, 2006; Pantelic *et al*., 2009; Nielsen *et al*., 2012; Nilsson, 2013). A downward jet with high discharge momentum may be able to deflect the cough jet downwards and reduce airborne concentrations of coughed particles in the breathing zones of recipient occupants. The objective of this study is to evaluate and examine the dynamic interaction of a cough jet and three different airflow distribution methods, which include DPJs with different discharge velocities, CAHJs, and no supply-flow driven solely by buoyancy of thermal dummies. The interactions in different conditions were evaluated by the ability of a certain airflow distribution method to reduce exposure to coughed particles in a chamber.

EXPERIMENTAL SETUP

Test Chamber and Airflow Regimes

The experiments were performed in a test chamber, which is located at The University of Texas at Austin Center for Energy and Environmental Resources (see Fig. 1). HEPA filters were installed before the supply fan to keep total particle number concentration (based on the instrument scan range 0.3 to 20 µm) of the room at a certain cleanliness level, about 7×10^5 particles m^{-3}, which is 100 times lower than the particle concentration in the simulated cough jets as shown in next section. This study used a commercial linear slot diffuser (PRICE-SDS75 type diffuser with slot spacing of 19 mm) to generate DPJs and CAHJs. The average discharge velocity at the slot used in this study varies from 0.6 m s^{-1} to 1.8 m s^{-1}. The two linear slot diffusers were installed in the chamber with full length of the width, which is 1.94 m (see Fig. 1). A cough jet generated by a cough generator traveled towards an exposed cylindrical thermal dummy in the protected zone (see Fig. 1). The particle number concentration of a cough is measured inside the cough generator, as described below. Meanwhile, the particle number concentration was measured at the mouth position of the exposed dummy, with a sampling flow rate of 5 L min^{-1}. Both thermal dummies have 75 W heat load inside, which can generate convective boundary layer around human body. More detailed description can be found in the earlier study by Rim and Novoselac (2009). As the cough velocity is much higher than the velocity of the thermal boundary layer generated the human body, the usage of the two thermal dummies mainly simulates the approximate geometry of a cough person and a target person, and more importantly, realistic room airflow conditions as governed by the ventilation jet discharge, cough jet, and buoyant thermal plumes of the two dummies.

Generation of Particle-Laden Cough Jet

A cough generator was built to produce cough jets. The cough generator has dimensions of 0.25 m × 0.25 m × 0.25 m and is supplied with pressurized air. A more detailed overview on the structure of the cough generator can be found in our latest study (Liu and Novoselac, 2014). The cough generator produces a square-wave manner cough that is different from cough's released from the human body and in previous studies (Zhu *et al*., 2006; Gupta *et al*., 2009). During measurement period, a stable particle concentration in the cough jet was achieved. In the cough generator, an optical particle counter was used to monitor the discharge particle concentration. The airtemperature was kept as 32.0 ± 0.5°C inside the cough generator by using a 12-voltage 20-watt tungsten halogen bulb. The total cough volume may have a variation of 0.8–5.0 L $cough^{-1}$ (Zhu *et al*., 2006;

Table 1. Summary of recent studies on the transport of cough particles.

	Cough duration (s)	Cough velocity (m s^{-1})	Particle size (μm)	Cough temperature (°C)	Remark
Zhu *et al.* (2006)	-	11.2	30–500	32	The results indicate that the transport characteristics of saliva droplets due to coughing change with size.
Sun and Ji (2007)	0.15–0.6	8–30	60–300	-	DV has high efficiency in removing small passive droplets, but not for nuclei of large droplets.
Chao *et al.* (2009)	-	11.7	13.5	37	The average expiration air velocity was 11.7 m s^{-1} for coughing with 947 to 2085 droplets per cough.
Lai and Wong (2010)	0.1	10	0.05	-	The particles emitted from the source travelled a long horizontal distance with both MV and DV.
Lai and Wong (2011)	0.1	10	0.05 and 10	-	It is a high risk of infection if the receiver is located near the exhaust vent, even the expiratory process being taken place back toward the exhaust.
Gupta *et al.* (2011)	0.4	9.0	8.5	33	The total airborne cough droplet fraction reduced from 48 to 12% after entering the cabin air for 1 and 4 min.
Yin *et al.* (2011)	< 1	2.9	3	-	The contaminant concentrations in the upper part of the room were higher for the coughing case with DV.
Zhang and Li (2012)	0.4	14	30	27	The droplets are found to evaporate rapidly and become droplet nuclei in the first second.
Kwon *et al.* (2012)	-	6–22	-	-	The average initial coughing velocity was 15.3 m s^{-1} for the males and 10.6 m s^{-1} for the females.

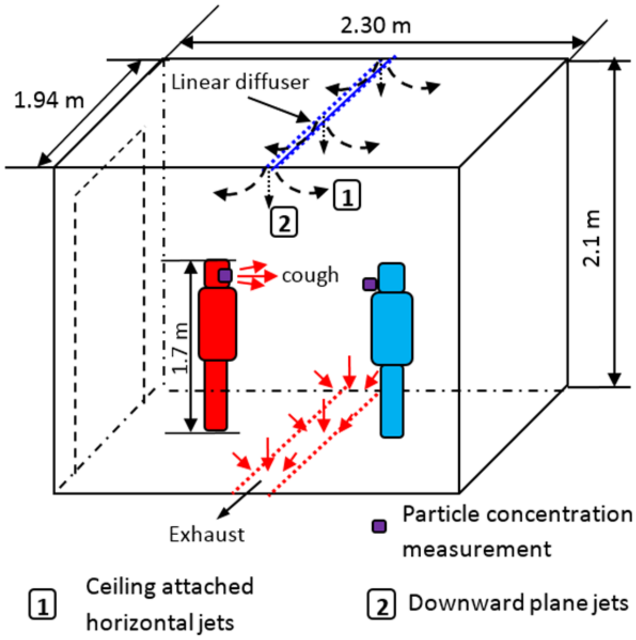

Fig. 1. Experimental setup.

Gupta *et al*., 2009). In this study, the total cough air volume was set as 1.4 L cough^{-1} with a maximum cough velocity of 6.0 m s^{-1} over a period of 1 second. In the current study, monodisperse particles with a diameter of 0.77 µm are used to simulate droplets expelled by the influenza-infected subjects due to long term existence in the air. Due to longer suspension time in the air, small particles (e.g., 0.77 µm) might pose more serious threats on disease transmission than large ones. Moreover, control strategies could perform more efficiently when reducing the transmission of large particles with higher gravitational effects. The purpose of using particles with a diameter of 0.77 µm, which may behave in a similar manner as gaseous pollutants, is to exam the effect of different airflow patterns on personal exposure to cough particles. The source particles were latex microspheres with a density of 1.05 g cm^{-3}, which has a composition of Polystyrene divinylbenzene (PSDVB). The source particle solution was diluted in 91% Isopropyl Alcohol and seeded by a nebulizer used in the cough generator. Particle number concentration in the cough generator was kept about approximately 7 × 10^{7} particles m^{-3}.

Measurement Conditions

The pressure difference between inside and outside the test chamber was kept at +0.3 (Pa), in order to avoid infiltration of ambient particles. Each measurement of the particle concentration at the mouth position of the exposed dummy was 60 seconds in duration. The cough jet was triggered after a 30 second measurement of background concentration. Each measurement case was repeated three times. To achieve a thermally stable experimental condition, the ventilation system and the two thermal dummies were turned on for at least 3–4 hours before the measurement. The supply air temperature was approximately equal to the air temperature outside the chamber, which was 23 ± 1.0°C during the experimental period. Each measurement case was repeated three times and the average value was used to calculate the personal exposure. Table 2 provides detailed measurement conditions of each case.

As for Case 0 - no supply airflow, the room was first ventilated to achieve a stable thermal condition before the measurement. Due to the small volume of the chamber, it was assumed that the airflow pattern will be dominated by the thermal plumes generated by the two thermal dummies within a few minutes after shut down the supply airflow. Even though a stable condition may not be reached, the cough jet and sampling lasted a very short period, during which the chamber was quasi-stable and this condition could simulate an environmental space with intermittent HVAC operations. In all measured conditions, the chamber temperature varies from 24.5°C to 26.7°C, according to the supply airflow rate.

Aerosol Sampling Instrumentation

Two types of particle measurement instrumentation were used: an Aerodynamic Particle Sizer Spectrometer (APS) Model 3321 (TSI Inc., Shoreview, MN, USA) and an optical particle counter (OPC) Model 8220 (TSI Inc., Shoreview, MN, USA). Prior to experiments, the APS and OPC were calibrated side-by-side. (Liu and Novoselac, 2014). Correction factors were applied to raw concentration data to account for the systematic differences between the two instruments based on their different particle sizing and counting techniques. Table 3 shows the accuracy/limit of all instruments used in this study. The APS was used to measure the particle concentration near the mouth of the exposed dummy and the OPC was used to monitor the particle concentration in the released cough jet. The sampling time of the particle concentration measuring by APS at the exposed dummy mouth is 60 s with a sampling rate of 1 Hz.

Table 2. Measurement conditions.

Case NO.	Average Supply air velocity (m s^{-1})	Ventilation mode	Average Reynolds number at slot	Supply air Temperature, °C	Room temperature, °C
Case 0	-	-	-	-	25.0 ± 0.5
Case 1	0.9	CAHJ	1140	23.1 ± 0.3	25.5 ± 0.5
Case 2	0.9	DPJ (two-jet)	1140	23.1 ± 0.3	25.5 ± 0.5
Case 3	1.8	DPJ (one-jet)	2280	23.1 ± 0.3	25.5 ± 0.5
Case 4	0.8	CAHJ	1013	23.0 ± 0.3	25.8 ± 0.5
Case 5	0.8	DPJ (two-jet)	1013	23.0 ± 0.3	25.8 ± 0.5
Case 6	1.6	DPJ (one-jet)	2026	23.0 ± 0.3	25.8 ± 0.5
Case 7	0.6	CAHJ	760	23.2 ± 0.3	26.2 ± 0.5
Case 8	0.6	DPJ (two-jet)	760	23.2 ± 0.3	26.2 ± 0.5
Case 9	1.1	DPJ (one-jet)	1520	23.2 ± 0.3	26.2 ± 0.5

Table 3. Uncertainty and limits of the measurement instruments.

	Instruments	Accuracy/limits
Air speed	DG-500	± 2.0% of reading
Temperature	HOBO Temperature sensor	± 0.1°C
Airflow	GTX116Digital Transmitter	± 3.0% of supply air)
Pressure	DG-500 Digital Pressure Gauge (Micromanometer)	± 1% of reading from –1,250 to +1,250 Pa
Particle concentration	Aerodynamic Particle Sizer Spectrometer (APS)	1000 particles cm^{-3} at 0.5 µm with less than 2% coincidence and 1000 particles cm^{-3} at 10.0 µm with less than 6% coincidence, sampling frequency 1 Hz
Particle concentration	Optical particle counter (OPC)	70 particles cm^3 (5% coincidence)

Visualization of the Interaction between Particle-Laden Cough Jet and Different Airflow Regimes

To gather additional insight into the spatial dispersion of the particle-laden cough jet under different room airflow conditions, smoke visualization method was utilized. The interaction between a cough jet, ventilation discharge jet, and the convective boundary layer around thermal dummies was studied by smoke visualization in four conditions: Case 0, Case 1, Case 2, and Case 3. The results for other cases can be found in supplemental documents. Smoke particles were generated by a smoke machine, Model EF-1000 (Eliminator Lighting, Los Angeles, CA, USA), with normal unscented water based fog juice, which had a density of 1.043 × 10^3 kg m^{-1} at temperature 23.0°C. The size distribution (0.3 to 20 µm) of the smoke was measured by the APS. Measurement results showed that over 60% of particles in number (0.3 to 20 µm) had a size less than 1.0 µm and over 99% had a size less than 2.5 µm. The cough velocity was 6 m s^{-1} with a cough period of 1 second. The exposed dummy, which was exposed to a cough, stood against the source dummy at a distance of 0.5 m and 0.8 m. Three different airflow rates were supplied by two ventilation methods: mixing ventilation (MV) and protected zone ventilation (PZV). The temperature of a cough with smoke was kept as 32.0 ± 0.5°C in the cough generator. Earlier studies show that droplet dispersion may extend to 0.6–0.9 m from mouth (Jennison, 1942; Edgerton and Barstow, 1995; Gupta *et al*., 2009). The smoke visualization of the interaction between a cough jet, ventilation discharge jet and thermal plumes were made for two distances between two dummies, 0.5 m and 0.8 m.

METRICS TO CHARACTERIZE INTERACTION BETWEEN A COUGH JET AND DIFFERENT AIRFLOW REGIMES

In this study, the impact of different airflow regimes on the dispersion of a particle-laden cough jet was characterized through several metrics, which are inherently based on exposure at the location of the receptor dummy. The ceiling-attached horizontal jets (CAHJ), generating mixing ventilation, was defined as the typical airflow case and downward jets, creating protected zone ventilation, were used to reduce dispersion of the coughed particles by deflecting them downwards. Concentration of cough particles was measured in the cough generator and near the mouth of the exposed dummy. A dimensionless exposure index is used to express the risk of personal exposure (PE) to a cough jet as:

$$PE = C_{exp}/C_{cough} \quad (1)$$

C_{exp}: particle number concentration measured in the mouth position of the exposed person, count of particles cm^{-3}, APS was used to measure C_{exp} value.
C_{cough}: particle number concentration measured in the source zone, count of particles cm^{-3}, OPC was used to measure C_{cough} value.

C_{cough} represents the particle concentration measured in the cough box before a cough was triggered, whichwas kept stable in each triggered cough for each case measurement. This index of PE may reflect the transient exposure of a target person to coughed particles generated by a source person with the combining effects of room airflow and the convective boundary layer of human bodies. It can also indicate how well the airflow regime reduces the dispersion of the coughed particles throughout the room.

To quantify the interaction of a particle-laden cough jet with different ceiling-attached horizontal jets and downward plane jets, the personal protection efficiency (PPE) is defined as:

$$\eta = (1 - PE_{regime\ i}/PE_{regime\ 0})\ 100\% \qquad (2)$$

where $PE_{regime\ i}$ is the personal exposure by using downward plane jets from one slot (i = 1) or two slots (i = 2) PZV, $PE_{regime\ 0}$ is the personal exposure value by using ceiling-attached horizontal jets.

If η is higher than 0, it means that the downward plane jet may prevent more the transport of cough particle than ceiling-attached horizontal jets.

RESULTS AND DISCUSSION

Visualization of the Interaction between a Cough Jet, Ventilation Discharge Jets and the Convective Boundary Layer around Thermal Dummies

The visualization test was performed for all studied cases but only four cases are shown in the main body of the paper. Fig. 2 shows the visualization results of a cough when the distance between two dummies is in various conditions. As the cough velocity was kept as 6 m s^{-1}, the time of a cough jet approaching the exposed dummy was less than 1 s when the distance between the two dummies was less than 1.0 m without downward jet. Without supply airflow, it's very clear to see that a cough jet can directly reach the mouth area of the exposed dummy (see Fig. 2(a)), even if the cough jet rises a bit due to the combined effect of the buoyancy force on the heated cough jet and the rising thermal plume from exposed dummy. This may indicate that the exposure level of the exposed person to a cough may be high without airflow supply. With the same amount of supply air (68 L s^{-1}), ceiling-attached horizontal jets and downward plane jet (1 or two-jets) result in different exposure conditions (see Figs. 2(b)–2(d)). Horizontal airflow has little effect on the reduction of personal exposure to a cough jet. Downward airflow (two-jet) can bend the cough jet downward to some extent. Some fraction of the released smoke particles may reach the mouth area via diffusion. With a one-jet downward airflow, the trace of cough jet is dramatically changed. The major part of the cough jet is bended to the low part of the exposed dummy. A small amount of smoke particles seem to reach the chin, which may be caused by the diffusion of the smoke particles and the combined effect of the buoyancy force and the convective boundary layer around the exposed dummy.

Table S1 shows the visualization results at a distance of 0.5 m between two dummies with different supply airflow rate by ceiling-attached horizontal jets and vertical downward plane jet. With horizontal airflow, the cough jet can directly approach the mouth of the exposed dummy independent of the supply airflow rate from the linear diffuser at ceiling level. By vertical downward plane jet (two-jet), the supply air velocity varies from 0.6–0.9 m s^{-1}, which generates low momentum and higher momentum jets. By vertical downward plane jet (one-jet), the average supply air velocity is increased to 1.1–1.8 m s^{-1}. The initial momentum of the downward jet will be increased due to

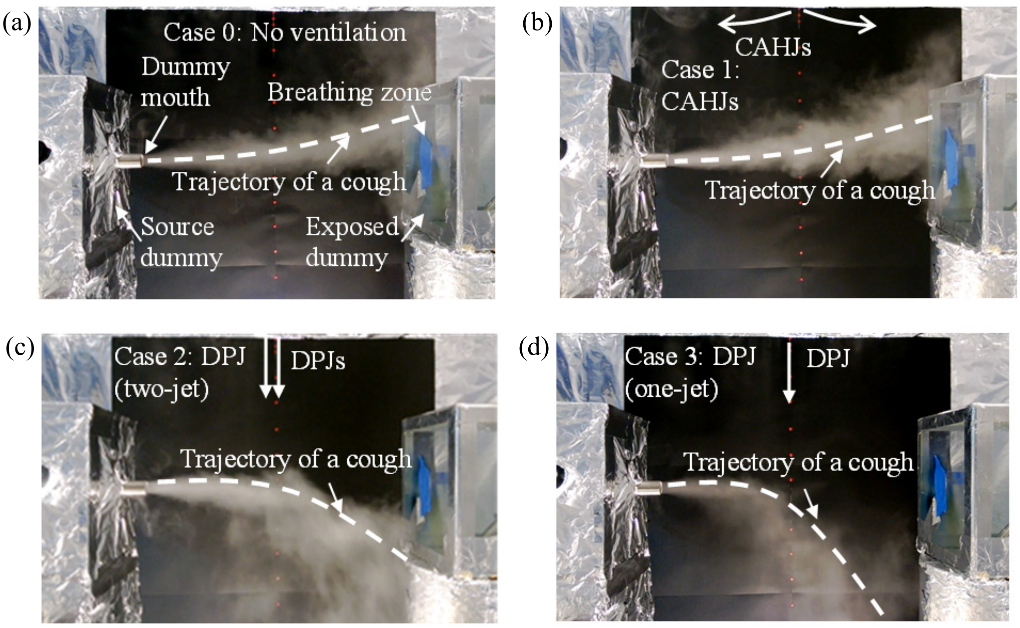

Fig. 2. Photos of smoke visualization with a distance of 0.5 m between two dummies under different conditions, a) without ventilation, b) CAHJs with an average supply air velocity 0.9 m s^{-1}, c) DPJ (two-jet) with an average supply air velocity 0.9 m s^{-1}, d) DPJ (one-jet) with an average supply air velocity 1.8 m s^{-1}.

the increase of supply air velocity. When the velocity of the downward jet is 1.1 m s^{-1}, the cough jet may penetrate the downward jet and reach the chin area of the exposed dummy. When the supply velocity increases up to 1.6 m s^{-1}, the coughed airflow can only partly penetrate the download plane jet and reach the chest area of the exposed dummy. When the supply air velocity is 1.8 m s^{-1}, the coughed airflow is bent towards the lower part of the exposed dummy, where the mouth area is free of direct exposure to the cough jet from the smoke visualization. When the distance between two dummies increased from half meter to 0.8 m, a cough jet can still approach the mouth area of the exposed dummy by ceiling-attached horizontal jets mode (see Table S2). By using vertical downward plane jet, the cough jet may not reach the mouth area of the exposed dummy with different supply air velocities. However, the cough jet penetrates the download plane jet to some extend and impinge the chest of the exposed dummy or the lower part of the exposed dummy, which depends on the supply airflow rates and average supply velocity.

Personal Exposure to Coughed Particles in Various Ventilation Scenarios

This section describes the personal exposure (PE) to coughed particles when a cough jet travels to the breathing zone of a recipient subject in four different ventilation scenarios: (1) No ventilation; (2) mixing ventilation with ceiling-attached horizontal jets; (3) PZV with two downward plane jets; and (4) PZV with one downward plane jet. The metric of PE represents the normalized concentration of coughed particles transported in the breathing zone of the recipient dummy (Fig. 1). It also suggests the extent to which a ventilation system reduces interpersonal exposure to coughed particles.

Dispersion of Particle-Laden Cough Jet in Absence of Ventilation

The transport of a jet is mainly governed by the exerted jet momentum, therefore, the parameter of the initial jet momentum is used to characterize the jet intensity. As the jet momentum is calculated from the discharge velocity and airflow rate, similar to Reynolds number, naturally, it is used to distinguish the effect of jet discharge velocity and airflow rate on the personal protection efficiency. A higher discharge velocity will result in a higher momentum jet and a lower discharge velocity will cause a lower momentum jet. Fig. 3(a) shows the average maximum personal exposure values, which was calculated by averaging the measured

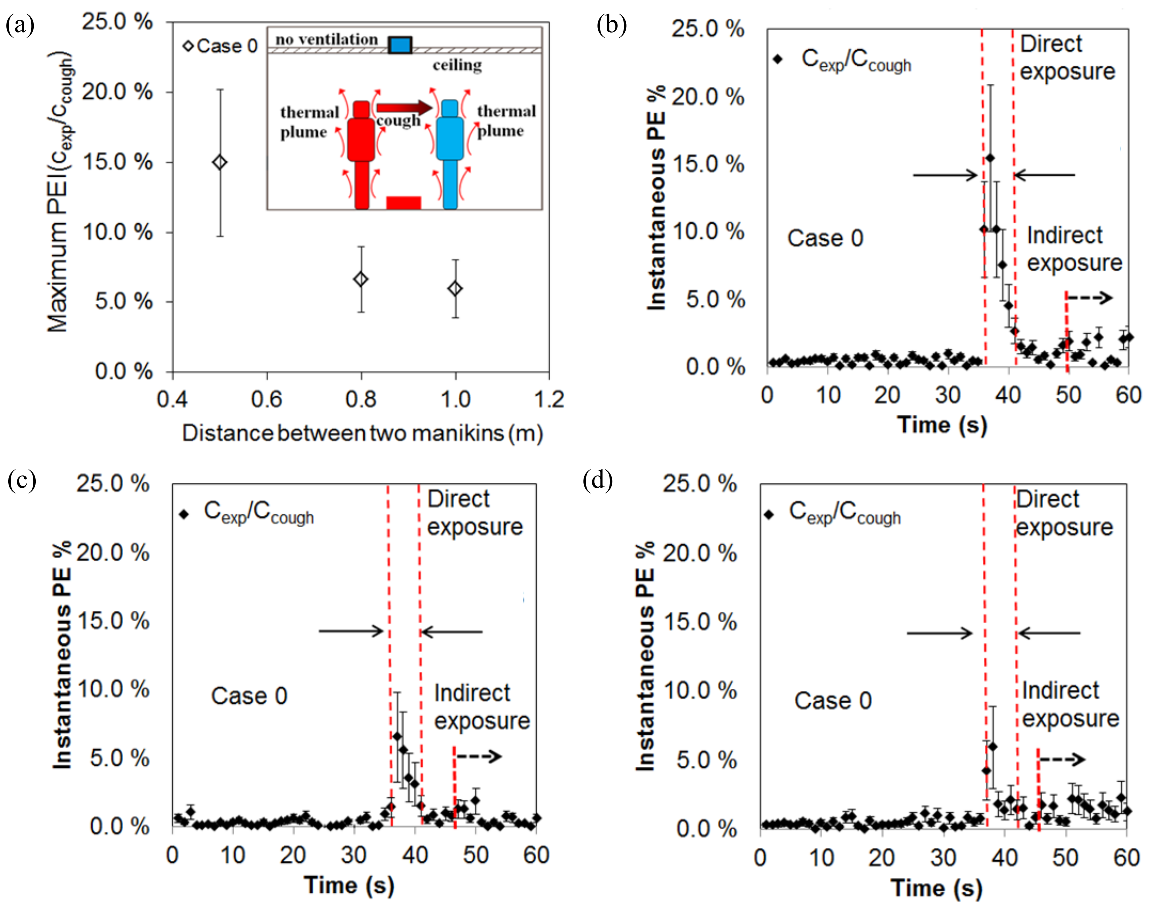

Fig. 3. Measurement results of Case 0, (a) average maximum personal exposure value of the exposed dummy to a cough from a source dummy without ventilation, (b) instantaneous personal exposure with a distance of 0.5 m between two dummies, (c) instantaneous personal exposure with a distance of 0.8 m between two dummies, (d) instantaneous personal exposure with a distance of 1.0 m between two dummies.

maximum personal exposure values in a condition of no ventilation. The personal exposure value is approximately two times higher at a distance of half meter than a distance of 0.8 m and 1 m, respectively. Fig. 3(a) also illustrates that a cough jet may be affected by the uprising convective boundary layer generated by the thermal dummy. When the cough jet became weaker with an increasing of travel distance, the upward thermal convective boundary layer may be able to elevate the cough jet upward and enhance dispersion (or mixing) of coughed particles throughout the room. Fig. 3(a) found that the exposure of the exposed dummy to a cough remained high with a PE value over 5.0% at a distance of 1.0 m between the two dummies, which may indicate that a cough jet may transfer particles at least 1 m away downstream of the source. Zhu *et al*. (2006) even found that a coughed air can travel within a range of more than 2.0 m at a maximum velocity of 22 m s^{-1} and temperature of 32°C by using flour as a tracer. Even with personalized ventilation, a cough of 10 m s^{-1} still can penetrate the local airflow distribution with an approaching velocity of 2.0 m s^{-1} after travelling 1.75 m (Pantelic *et al.* 2009). So, the distance of a cough traveling will be dependent upon the initial cough velocity and local airflow patterns.

Figs. 3(b), 3(c) and 3(d) show the average instantaneous value of personal exposure, which was calculated by averaging these three times measured instantaneous values. These figures show a decrease of PE value with the increase of distance between two dummies.

Personal Exposure to a Cough with Ceiling-Attached Horizontal Airflow

Fig. 4(a) shows the maximum PE value of the exposed dummy to a cough from a source dummy with ceiling-attached horizontal jets. By using horizontal airflow, when the initial jet momentum of supply air is reduced (as case 7), the PE value becomes higher than case 1 and case 4 with a distance of 0.5 m between two dummies. With a distance of 0.8 m and 1.0 m between two dummies, the personal exposure became very low due to the air movement of indoor mixing airflow. In addition to the effect of indoor airflow, coughing entrains surrounding air into the jet region and thereby reduces the particle concentration during transport. Figs. 4(b), 4(c) and 4(d) show instantaneous personal exposure with a distance of 0.5 m between the two dummies with ceiling-attached horizontal jets with different supply airflow rate.

As this study use smaller particles and a higher supply airflow, the domination of ventilation airflow may still occur. However, the effect of the thermal boundary layer around the thermal dummy on the PE value to a cough jet

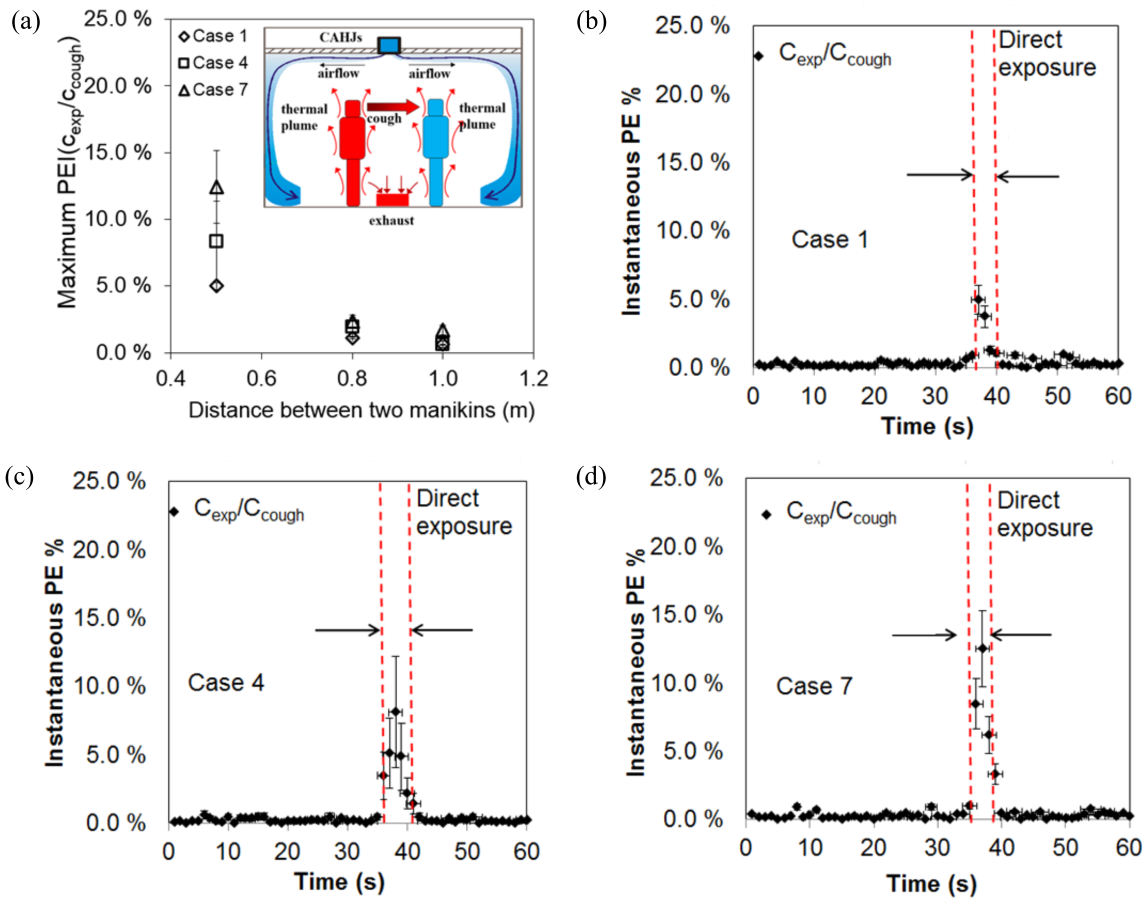

Fig. 4. (a) maximum PE value of the exposed dummy to a cough from a source dummy with CAHJ, (b) instantaneous personal exposure value in case 1, 0.5 m between two dummies, (b) instantaneous personal exposure value in case 4, 0.5 m between two dummies, (d) instantaneous personal exposure value in case 7, 0.5 m between two dummies.

becomes complex with the presence of mixing airflow in the room. As the distance increases between two dummies, the entrainment of ambient air by the attached airflow on the ceiling may direct the uprising cough jet and the thermal plume from the dummy. The entrainment prevents the transport of coughed particles directly to the mouth of the exposed dummy. It might be a combined effort of rising thermal boundary layer and the entrainment of ambient air to lower the risk of exposure to the cough jet from the source dummy.

Personal Exposure with Two Downward Plane Jets

The protection efficiency varies from case to case depending on the supply air velocity, the location of exhaust and the use of a partition (Cao *et al.*, 2014a, b). This section introduces the measurement results by using vertical downward plane jet consisting of two downward plane jets. However, the impact of physical obstructions was not evaluated in this study, which will influence how the coughed particle disperse throughout the room. Using two downward jets may generate higher initial momentum jet, which may have influence on the spreading of particles of a cough jet. As the measured instantaneous PE value of Case 2 is very low, suggesting a high efficacy of the downward plane jet system, this section only shows that the PE values in Case 5 and Case 8. Fig. 5 shows that the instantaneous PE value remain high at a distance of 0.5 m between two dummies when the velocity of the downward plane jet airflow rate are 0.6 m s^{-1} and 0.8 m s^{-1}. The PE value drops significantly when the downward jet velocity reaches 0.9 m s^{-1} at all distance. It indicates that a cough jet may not penetrate the downward jet and reach the breathing zone directly. In another words, a vertical downward plane jet (two-jet) method with a higher initial momentum may prevent the transport of virus or bacteria after coughing, which may affect the local micro-environment and the entire indoor environment effect due to the mixing airflow in a space (Yan *et al.*, 2009). Figs. 5(b) and 5(c) show the instantaneous personal exposure with a plane jet velocity 0.8 m s^{-1} and 0.6 m s^{-1}, respectively at a distance of 0.5 m between two dummies.

Personal Exposure with One Downward Plane Jet

As the measured instantaneous PE values of Case 3 and Case 6 are very low, this section only shows that the PE values in Case 9. Fig. 6(a) shows that the maximum PE drops to a very low level when the velocity of the downward plane jet increases from 1.1 m s^{-1} to 1.8 m s^{-1} with one-jet vertical downward plane jet. When the distance between two dummies is 0.5 m, The PE value with 1.1 m s^{-1}

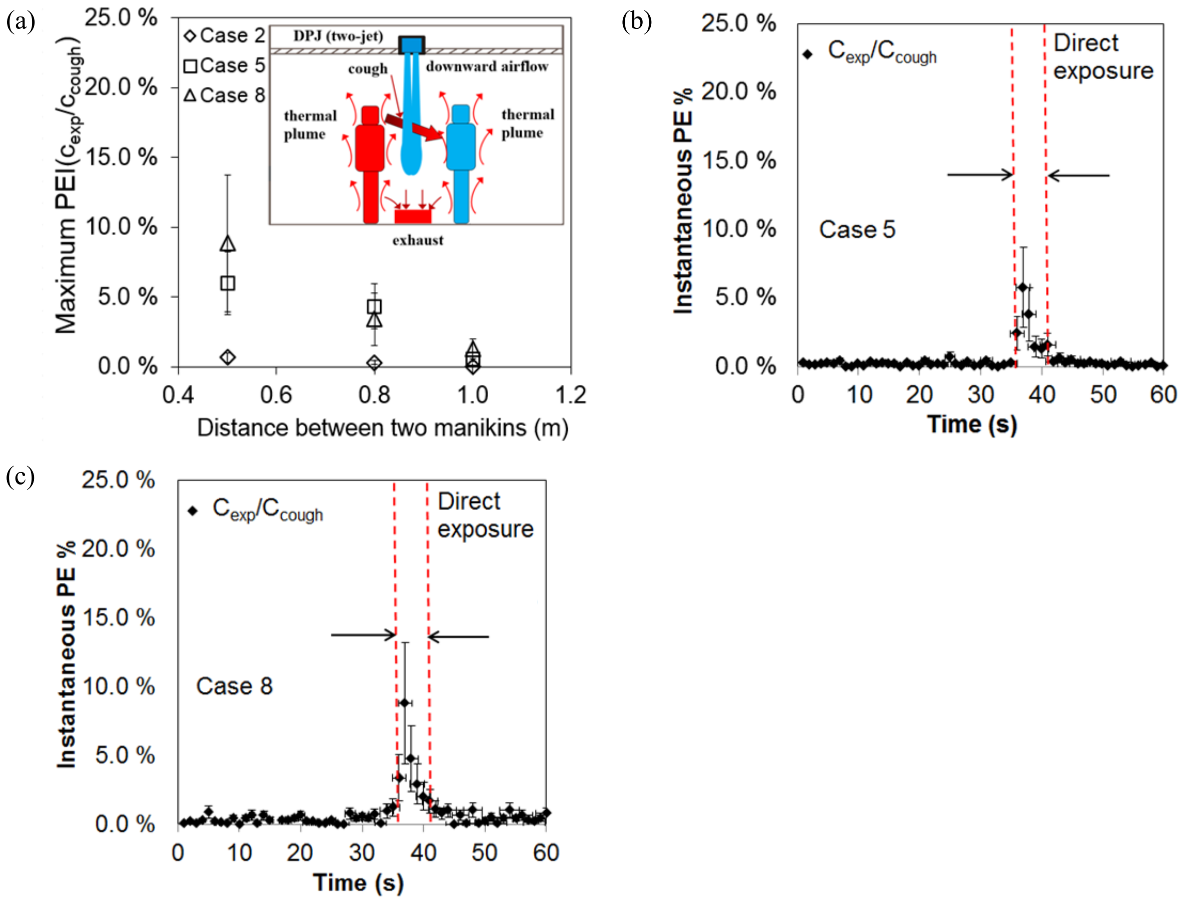

Fig. 5. (a) average personal exposure value of the exposed dummy to a cough from a source dummy with DPJ (two-jet) (b) instantaneous personal exposure value of the exposed dummy to a cough from a source dummy in case 5, (c) instantaneous personal exposure value of the exposed dummy to a cough from a source dummy in case 8.

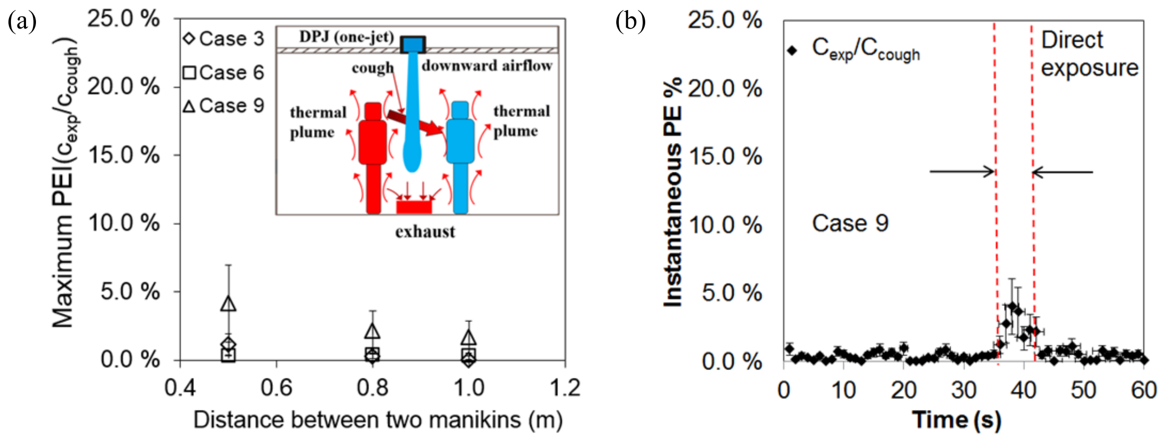

Fig. 6. Maximum PE and instantaneous PE, (a) maximum PE of the exposed dummy to a cough with DPJ (one-jet), (b) instantaneous PE with a distance of 0.5 m between two dummies in case 9.

downward jet velocity with one-jet vertical downward plane jet is 5 times and 2 times lower than with ceiling-attached horizontal jets and two-jet vertical downward plane jet, respectively. It may indicate that DPJ (one-jet) has better performance to reduce the personal exposure to a cough than CAHJs and DPJs (two jets).

The measured instantaneous personal exposure is very low in case 3 and Case 6, which means the one-jet vertical downward plane jet may prevent the transport of coughed particles from the source dummy to the exposed dummy with higher supply airflow rates. Fig. 6(b) shows that instantaneous personal exposure with a downward plane jet of 1.1 m s^{-1}.

Personal Protection Efficiency (PPE)

When the distance of the two dummies is 0.5 m, comparing with using horizontal airflow, vertical downward plane jet (one-jet) has high PPE values, 96.0%, 98.8%, when the initial momentum is higher. Two-jet airflow only has a higher PPE, 95%, when the momentum is higher. In other words, the exposure risk is significantly reduced by about 20–80 times comparing with ceiling-attached horizontal jets by using downward plane jet (one-jet) with higher initial momentum. One-jet airflow shows the great potential to prevent the direct exposure to a cough. In fact, most of the latex particles were transported within a short distance from the coughing person in the first 30 s and then could be transported to the entire space with a uniform droplet distribution in 4 min (Gupta *et al.*, 2011). As the source location significantly affects the pollutant transport within an aircraft cabin (Yan *et al.*, 2009), the use of downward plane jet to separate the space into a few sub zones may minimize the transport of respirable particles of a cough from the source.

CONCLUSIONS

Respirable particles from a cough can disperse throughout a room, which may cause a risk of higher personal exposure in the indoor polluted micro and macro environment. Downward plane jets discharged from commercial linear diffusers, which separate a room into two zones, may reduce dispersion of coughed particles by blocking a particle source in one of the two zones. The direct exposure of an exposed dummy in the protected zone to a cough from the source zone is significantly reduced by using a high momentum downward plane jet as compared with ceiling-attached horizontal jets generated by traditional overhead diffusers. The rising thermal boundary layer around the human body, which is generated by the thermal dummy, may also affect the dispersion of coughed particles close to the breathing zone. The momentum of the uprising thermal plume is smaller than that of the downward plane jet, and thus, has a weaker impact on the transport of the coughed particles. Due to the complex thermal boundary conditions, the air distribution pattern is more important than the airflow rate supplied to a space with regard to the determination of the local personal exposure to a cough jet.

The dynamic interaction of a transient cough jet and a steady downward jet is complex. The personal exposure to a transient cough jet becomes dynamic instead of steady exposure due to the presence of the thermal boundary layer around the human body. The personal exposure value to coughed particles with ceiling-attached horizontal jets is much higher (over 50 times) than in conditions using downward plane jets. In other words, the exposure risk can be reduced significantly comparing with ceiling-attached horizontal jets when the distance is only 0.5 m between two dummies. Personal protection efficiency by using downward plane jets may be improved by increasing the initial momentum of the jets, when the distance between two dummies is 0.5 m. The measurement results indicate that with a higher initial momentum the supplied downward jet may prevent the transport of virus- or bacteria-containing particles after coughing, which may have effects on either the local micro-environment close to the cough source or the entire environment due to the mixing airflow in a space. While ceiling-attached horizontal jets are used mainly for mixing ventilation, downward plane jets may be used for protected zone ventilation. The results may be used to guide the design of an efficient downward plane jet method for different applications. Future work may cover the optimization of the initial momentum of downward plane jet, sneezing via nose/mouth, field measurements, impact of human movement on airflow and concentrations close to a human proximity.

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SUPPLEMENTARY MATERIALS

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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