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Dynamic interaction of a downward plane jet and a cough jet with respect to particle transmission: An analytical and experimental study

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ABSTRACT

A cough jet can travel beyond the breathing zone of the source person, and thus, infectious viral- and bacterial-laden particles can be transported from the source person to others in close proximity. To reduce the interpersonal transmission of coughed particles, the objective of this study was to analytically and experimentally investigate the performance of downward plane jets with various discharge velocities. Chamber measurements were conducted to examine the interaction between a transient cough jet (discharge velocities of 12 m/sec and 16 m/sec) and a steady downward plane jet (discharge velocities from 1.0–8.5 m/sec) with respect to the transport of and human exposure to coughed particles. The results show that a relatively high-speed cough can easily penetrate a downward plane jet with a discharge velocity of less than 6 m/sec. A downward plane jet with a discharge velocity of 8.5 m/sec can bend the cough jet to a certain extent. In this study, momentum comparison of the cough jet and the downward plane jet shows that the value of personal exposure to coughed particles depends on the ratio of jet momentums. The results show that when the two momentums are equivalent or if the downward plane jet has a greater momentum, the cough jet is deflected downward and does not reach the breathing zone of the target thermal dummy. Using the ratio of the two momentums, it may be estimated whether the transmission of a cough jet can be controlled. A trajectory model was developed based on the ratio of the two momentums of a cough jet and a downward jet and was validated using the experimental data. In addition, the predicted trajectory of the cough jet agreed well with the results from smoke visualization experiments. This model can be used to guide the design of downward plane jet systems for protection of occupants from coughed particles.

KEYWORDS

Airflow distribution; cough jet; downward plane jet; dynamic interaction; personal exposure

Introduction

The outbreak of severe epidemics such as Severe Acute Respiratory Syndrome (SARS) and Middle East Respiratory Syndrome (MERS) has attracted increasing attention to improved control strategies for reduction of the transmission of respiratory diseases.[1] A number of important infectious diseases (e.g., tuberculosis, influenza, MERS, and SARS) are known or believed to be transmitted via inhalation of aerosols emitted from the respiratory tracts of infected persons.[1] Strong and sufficient evidence exists to demonstrate the association between ventilation and air movement in buildings and airborne transmission/spread of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox, and SARS.[2] Viral- and bacterial-laden particles released from an infected person via coughing or sneezing can spread throughout a room via indoor airflow patterns, thus putting other occupants at risk for inhalation exposure. These airflow patterns are governed in part by the room's ventilation system (e.g., ventilation type, ventilation rate, diffuser design, and discharge velocity) and the occupants (e.g., buoyant thermal plumes and movement patterns).[3] It is important for ventilation systems to control airborne dispersion of infectious disease-carrying particles to minimize the risk of cross-infection. This scenario is especially true for critical indoor environments, such as hospitals and healthcare facilities, in which cross-infection might occur with a higher probability.[4,5]

With respect to personal exposure, doctors, nurses, and health care personnel (HCP) in hospitals are expected

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to exist in close proximity to infected patients on a frequent basis throughout their daily routines. Patients with acute or chronic coughing syndromes might pose a greater threat of expelled disease-carrying particles to staff in hospitals. One early study found that a downward ventilation system might not produce a downward "unidirectional" airflow partner at an air change rate of 4 h^{-1}, as was expected in the design recommended by the CDC.[6] One recent study showed that the use of local air exhaust combined with local cleaning could significantly reduce the exposure risk in hospitals.[7] It was reported that personal exposure was increased to as high as 12 times the fully mixed value when the distance between the source and target manikins was reduced to a distance of 0.35 m.[8,9] One recent study reported that it is possible to decrease the transmission of a tracer gas from one manikin to the opposite manikin by increasing the momentum of a supply downward plane jet, and as such, the risk of personal exposure to aerosols might be reduced.[10]

Current hospital ventilation systems are primarily based on the principle of mixing ventilation or total volume flow rate ventilation. However, if a normal ventilation system is used, the exposure of HCP to potential infectious agents remains high after HCP enter the room. One study found that cough-generated airborne particles spread rapidly throughout the room and that a worker located anywhere in the room could be exposed to potentially hazardous aerosols within 5 min.[11] This study also revealed that personal protective equipment (PPE) might not be sufficient to protect HCP when patients coughed or sneezed and expelled significant quantities of bacterial and viral particles. Moreover, even if HCP wear PPE, the HCP can receive secondary exposure when particles are resuspended from clothing fibers.[12] Hospital isolation rooms are vital for controlling indoor containment from patients (when under negative pressure) and for protecting patients from outdoor airborne infectious agents (when under positive pressure). Such facilities were essential for management of highly contagious patients during the 2003 severe acute respiratory syndrome (SARS) outbreaks and the more recent 2009 A/H1N1 influenza pandemic.[13] However, few effective airflow distribution methods have been reported to reduce the near-field exposure of occupants to airborne particles generated by a human cough.

Current ventilation standards (ASHRAE-170)[14] require a minimum total air changes per hour (ACH) of up to 12 hr^{-1} in health care facilities, except for surgery and critical care spaces. However, the general minimum ACH might have a limited effect on controlling the interpersonal transmission or near-field exposure of airborne particles expelled from respiratory activities such as coughing and sneezing under various conditions.[15–17] These reviews also suggest that the requirement for total minimum ACH can control far-field exposure (FFE) ($>$1.0 m) but fails for near-field exposure (NFE) ($<$1.0 m) because coughing or sneezing jets are too strong to be controlled through regular airflow patterns of typical mixing ventilation systems, even at high ACHs. Far-field exposure is normally caused by the movement of airborne particles (bacterial and viruses) via bulk room airflow, whereas NFE due to respiratory activities might take place when people are located close to each other without the use of protection devices. Therefore, the current ventilation systems for hospital spaces must be improved to prevent NFE to respiratory particles. Cao et al.[10] proposed a push-pull downward jet system, known as protected occupied zone ventilation (POV), to divide a space into two or more "sections." The system reduces the transmission of a pollutant from one section to another through multiple indoor air curtains. A recent study shows that downward plane jets can reduce the peak concentration of coughed particle in the breathing zone of a recipient occupant located 0.7 m away by 20%.(18) Thus far, many unknowns still exist as to how POV can affect cough jets with different discharge velocities, which is especially important for coughs with high discharge velocities, which were reported in a range of 6–28.8 m/sec.[19,20] Additionally, no studies have reported a simple model that can predict the interaction between a high speed cough jet and a thin steady plane jet.

In recent years, few studies have examined protected zone ventilation (PZV) used to protect people from exposure to indoor contaminants by separating the indoor space into protected zones with downward plane jets (DPJs).[10,18,21] Two recent studies showed that DPJs might reduce the exposure risk of a target breathing thermal manikin by one order of magnitude compared with displacement ventilation.[10,22] Because the discharge velocity of human respiration is rather low (less than 4 m/sec), the performance of DPJs might be ineffective when other respiratory activities occur, such as coughing (up to 28.8 m/sec) and sneezing.[19] Liu et al.[18] showed that a DPJ might reduce the exposure value of occupants exposed to a cough with a velocity of 6 m/sec. Although numerous studies have developed analytical models for transient or steady jets in a quiescent fluid, little experimental data are available on the interaction of a thin steady downward plane jet with a transient high speed cough jet.[23]

The primary objectives of this study are: (1) to examine the interaction of a high momentum cough jet (discharge velocities of 12 m/sec and 16 m/sec) with a downward plane jet (discharge velocities of 1.0–8.5 m/sec) through controlled chamber experiments; (2) to characterize personal exposure, including both maximum exposure and instantaneous exposure, to a cough jet with and without a downward plane jet; and (3) to develop a cross-flow trajectory model to predict the trajectory of a cough after impingement with a downward plane jet.

Experimental setup

Test chamber

The experiments were performed in a scaled room chamber (length 2.3 m × width 1.94 m × height 2.1 m) located at Center for Energy and Environmental Resources (CEER) at the University of Texas at Austin (see Figure 1). A DPJ was used to separate the inner space of the chamber into a source zone and a protected zone. Coughs were triggered from the source thermal dummy facing the target thermal dummy (TTD) in the protected zone (see Figure 1). The particle number concentration of a cough was measured inside a cough generator. Additionally, the particle number concentration was also measured at the "mouth" of the target mannequin. Both thermal dummies contained 75 W of heat power to simulate the convective boundary layers.[24]

Measurement conditions

All measurements were conducted in the chamber (see Figure 1), which was positively pressurized at +0.3 (Pa) above the ambient laboratory air to avoid infiltration. The cough source and receptor were positioned at a height of 1.7 m, and the downward plane jet was installed between the cough source and the receptor at a height of 2.1 m. The chamber was ventilated only with a downward jet and without supplementary ventilation. One linear slot diffuser with a slot width of 19 mm was used to produce the downward plane jet, which had lengths of 1.94 m, 1.0 m, and 0.5 m to produce different discharge velocities (see Table 1). Given the setups shown in Figure 1, the visualization test showed that the width of the cough jet was smaller than the width of the downward jet in the cross-section of the two jets. Thus, it was assumed that the width of the DPJ in this study had a negligible effect on the interaction of the DPJ and a cough jet. Each measurement of the particle concentration at the "mouth" of the TTD lasted 60 sec with a sampling interval of 1 sec. A cough jet was triggered after a 30-sec measurement of the background concentration. Each test was repeated three times. The distance between two dummies was maintained at 0.5 m, which represented the distance between two people in conversation. To obtain a thermally stable experimental condition, the ventilation system and the two thermal dummies were turned on for approximately 3 hr before conducting the measurements. The supply air temperature of DPJ remained within the range of 23 ± 0.5°C. Table 1 lists the detailed measurement conditions of each case.

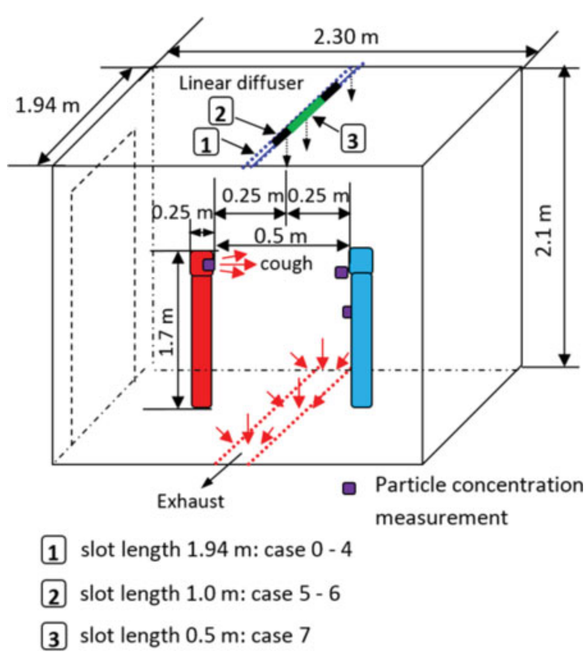

Figure 1. Schematic of the test chamber setup.

Particle-laden cough jet

A cough generator was built to produce a particle-laden cough jet that mimics the discharge of infectious bacteria and viruses from the mouth. The cough generator had dimensions of 0.25 m × 0.25 m × 0.25 m and was supplied with pressurized air. A 3-jet Collision Nebulizer was used to generate cough particles. The same cough generator was used in three previous studies by Liu and Novoselac (2013),[18] Liu et al.,[25] and Cao et al.,[22] and these articles include a more detailed overview of the cough generator and cough particle seeding. The total cough volume had a variation of 0.8–5.0 L/cough.[20,26] In this study, the total cough air volume was 3.26 L/cough with maximum cough velocities of 12 m/secec and 16 m/secec over periods of 0.8 sec and 0.6 sec, respectively. The momentum values of a cough were 0.059 kg/s^2 and 0.104 kg/s^2 with cough velocities of 12 m/secec and 16 m/secec, respectively. The Reynolds numbers of the cough jets with velocities of 12 m/secec and 16 m/secec were 15,200 and 20,266, respectively. Earlier studies showed that the droplets exhaled/coughed by the influenza-infected subjects varied in the range of 0.3–13.5 μm[15,27–29] Another study found that the total average size distribution of the droplet nuclei coughed by human subjects was 0.58–5.42 μm,

Table 1. Measurement conditions.

Case No.	Cough velocity(m/sec)	Average supply air velocity (m/sec)	Slot length (m)	Supply airflow rate (m^3/sec)	Reynolds number at slot	Room temperature (°C)	Momentum flux, kg.m/sec^2 per meter slot
Case 0a	12	0	—	0	0	25.0 ± 1.0	—
Case 0b	16	0	—	0	0	25.0 ± 1.0	—
Case 1a	12	1.0	1.94	0.037	1267	25.5 ± 0.5	0.00144
Case 1b	16	1.0	1.94	0.037	1267	25.5 ± 0.5	0.00144
Case 2a	12	1.5	1.94	0.055	1900	25.5 ± 0.5	0.00324
Case 2b	16	1.5	1.94	0.055	1900	25.5 ± 0.5	0.00324
Case 3a	12	2.0	1.94	0.074	2533	25.5 ± 0.5	0.00576
Case 3b	16	2.0	1.94	0.074	2533	25.5 ± 0.5	0.00576
Case 4a	12	3.0	1.94	0.111	3800	25.8 ± 0.5	0.01296
Case 4b	16	3.0	1.94	0.111	3800	25.8 ± 0.5	0.01296
Case 5a	12	4.5	1.00	0.086	5700	25.8 ± 0.5	0.02916
Case 5b	16	4.5	1.00	0.086	5700	25.8 ± 0.5	0.02916
Case 6a	12	6.0	1.00	0.114	7600	25.8 ± 0.5	0.05184
Case 6b	16	6.0	1.00	0.114	7600	25.8 ± 0.5	0.05184
Case 7a	12	8.5	0.50	0.081	10767	26.2 ± 0.5	0.10404
Case 7b	16	8.5	0.50	0.081	10767	26.2 ± 0.5	0.10404

with 82% centered in the range of 0.74–2.12 μm.[30] In this study, particles with a diameter of 2.5 μm were used to simulate droplets expelled by the influenza-infected subjects. The source particles consisted of polystyrene microspheres with a density of 1.05 g/cm^3.

Aerosol sampling instrumentation

Particle concentration was measured using two types of particle measurement instrumentation: 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). Table 2 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 target TTD, and the OPC was used to monitor the particle concentration

Table 2. 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	GTX116 Digital Transmitter	± 3.0% of supply air
Pressure	DG-500 Digital Pressure Gauge (Micromanometer)	± 1% of reading from −1250 to +1250 Pa
Particle concentration	Aerodynamic Particle Sizer Spectrometer (APS)	1,000 particles/cm^3 at 0.5 μm with less than 2% coincidence and 1000 particles/cm3 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)

inside the cough generator before triggering of a cough jet. Prior to measurement, the OPC and APS were calibrated side-by-side.

Exposure metrics

The concentration of cough particles was measured in the cough generator and near the "mouth" of the TTD. The dimensionless exposure index is used to express the risk of personal exposure (PE) to coughed particles as follows:

$$PE = C_{exp}/C_{cough}. \tag{1}$$

The total particle number concentration was used to calculate the personal exposure value. Because the generated monodispersed-particles were of a known size of 2.5 μm, background particles with dominant sizes smaller than 2.5 μm had a minimum effect on the sampling accuracy of coughed particles. The index of the cough exposure period (CEP) is defined as the duration of the exposure period to a cough in which the personal exposure (PE) value remains approximately 15% higher than the average exposure value of each case, in, which it may vary due to small variations in background concentration.

Visualization experiments

The interactions among the cough jet, the downward plane jet, and thermal plumes were studied using smoke visualization in eight conditions, namely Case 2a, Case 2b, Case 4a, Case 4b, Case 6a, Case 6b, Case 7a, and Case 7b, as described in Table 1. Smoke was generated by a smoke machine Model EF-1000 (Eliminator Lighting, Los Angeles, CA, USA) with normal unscented water-based fog machine fluid, which had a density of 1.043 × 10^3 kg/m at 23.0°C. The size distribution (0.3–20 μm) of the smoke was measured with the APS. Measurement results showed that over 99% of the particles were less than 2.5 μm in aerodynamic diameter. The initial cough velocities were 12 and 16 m/secec with cough periods of 0.8 and 0.6 sec, respectively. The TTD of 0.5 m from the source thermal dummy represented the condition of exposure that occurs from two people talking to one another.

Empirical model

The interaction between a cough jet and downward plane jet is complex, especially if it is located in the vicinity of a person. Figure 2 shows the bent trajectory of a cough jet that collides with the downward plane jet. The convective boundary layer rising up from the thermal dummy has a relatively low velocity of 0.16 m/sec.[31] Because the impingement between the cough jet with discharge velocities of 12 m/sec and 16 m/sec and the thermal dummy took place in a notably short period, the effect of the rising boundary layer on the cough jet was negligible. This study assumed that the change in trajectory was determined by the magnitudes of the momentum between the cough jet and the downward plane jet. This study also assumed that the interaction of the downward jet and the cough jet occurred in a manner similar to that of a cross-flow. In addition, this study assumed that the trajectory of the cough jet crossing the plane jet could be modeled using the extended model of classic cross-flow phenomena. These assumptions were verified by the smoke visualization experiments, as described in the Results section.

For the jet velocity, the decay of the centerline velocity of a plane jet in the developed region is represented by the following:[32]

$$U_m/U_0 = K/\sqrt{y/h}, \tag{2}$$

where h is the slot width, which is 19 mm in this study.

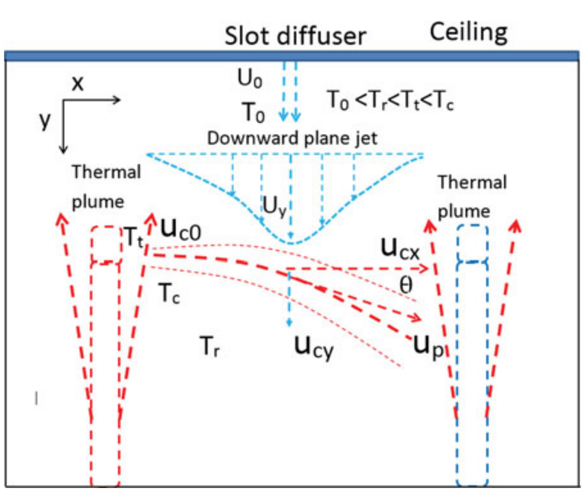

Figure 2. Schematic of the interaction of a cough jet with downward plane jet.

Rajaratnam[32] recommended a value of 2.47 for K. A value of 2.4 was used in certain other studies, including those of Chen and Rodi[33] and Kulmala et al.[34] In this study, a value of 2.4 was used to calculate the maximum velocity decay. For the velocity decay of the cough jet, the centerline velocity can be expressed as follows:[35]

$$U_{cm}/U_{c0} = k(x/d)^{-1}. \tag{3}$$

Due to the temperature difference between the cough jet and room temperature, the Archimedes number was defined to describe the buoyancy effect on the cough jet flow:[36]

$$Ar = \frac{\beta g \sqrt{a_0 \Delta T_0}}{U_{c0}^2}. \tag{4}$$

In this study, the Ar values were 3.2×10^{-5} and 1.8×10^{-5} in the cases with cough velocities of 12 m/sec and 16 m/sec, respectively. According to another study, the effect of buoyancy due to the temperature difference between the cough jet and room air can be neglected in this study due to the small Archimedes number.[37]

In this study, a strong cough jet with a velocity of up to 16 m/sec was injected and lasted for 0.6 sec. In addition, because it took less than 1 sec for the cough jet to arrive at the TTD, the cough jet can be considered as a steady jet with characteristics of a starting turbulent jet.[38] This study assumed that the interaction of the strong cough jet with the DPJs was quite short and that the buoyancy effect on the cough jet was neglected during the interaction process due to the small Archimedes number. This assumption was supported by the smoke visualization experiments. The flow field of a constant jet in cross-flow was reportedly influenced primarily by the effective velocity ratio r, which accounted for the density difference between the jet and the cross-flow:[39]

$$r = \left(\frac{\rho_{cj} U_{c0}^2}{\rho_{dj} U_m^2}\right). \tag{5}$$

Broadwell and Breidenthal[40] used similarity theory to treat the jet exit as a point source of momentum and concluded that the global length scale in the flow was rd in the region away from the jet exit. This length scale is used to scale the trajectory as follows:

$$\frac{x}{rd} = A\left(\frac{y}{rd}\right)^B, \tag{6}$$

where A and B are constants, i.e., $A = 2.05$ and $B = 0.28$.[39,41] Margason[39] offered a list of experimental values for A and B, namely $1.2 < A < 2.6$ and $0.28 < B < 0.34$. In this study, the coordinates are defined in Figure 2, where y is the vertical direction and x is the horizontal direction, and the trajectory of the cough jet flow can be rewritten as shown in Equation (7):

$$y = rd\left(\frac{x}{rdA}\right)^{-B}. \tag{7}$$

The empirical equations (Equations (1–7)) model a perpendicular uniform cross-flow interacting with a steady round jet. This study assumes that the trajectory of the cough jet crossing the downward plane jet might be expressed using equations similar to those of steady-state cross-flow but with different coefficients due to the quick dispersion of the momentum of the transient cough jet. This assumption was supported by the smoke visualizations. As estimated from the smoke visualization experiments, the values of A and B can be derived using Equation (5). From the visualization results, this study chose values of 4.2 and 0.43 for A and B, respectively. The values of A and B obtained in this study differed from the values used in early studies[39] because this study used a transient cough jet, whereas previous studies examined a constant round jet flow.

Results and discussion

Visualization of the interaction of a cough jet with a downward plane jet

Figures 4 and 5 show smoke visualizations of the interaction between a cough jet and a downward plane jet. When the velocity of a cough is increased to 16 m/sec, the downward jet with a velocity less than 6 m/sec only marginally affects the travel of the cough jet. The cough jet might directly impinge on the "mouth" area of the TTD. The downward jet with a velocity of 8.5 m/sec might bend the cough jets downward, and thus, the cough jet cannot directly impinge on the "mouth" area of the TTD.

Predicted trajectory of the cough jet

The visualization results prove the hypothesis that the interaction of the downward jet and the cough jet performs in a manner that is similar to that of a cross-flow. The trajectory of a cough jet crossing a plane jet predicted using Equation (7) agrees well with the visualization results. Figure 3 shows the trajectory of a cough jet predicted using Equation (5). The dashed lines represent the centerlines of cough jets with initial velocities of 12 m/sec and 16 m/sec and show that the cough jet is bent slightly when the downward plane jet velocity is less than 4.5 m/sec. This result means that the cough jet might directly approach the "mouth" area of the TTD. The predicted trajectory of the cough jet matches the smoke visualization quite well and might depend on the quality of the smoke visualization. Figure 3h shows how the distance between the source of the cough jet (i.e., the "mouth" of the source thermal dummy in this study) and the downward plane jet affects the trajectory. This figure indicates that when the cough source is located farther from the downward jet, the downward jet is able to prevent the transmission of cough particles from the source person/zone to the target person/zone.

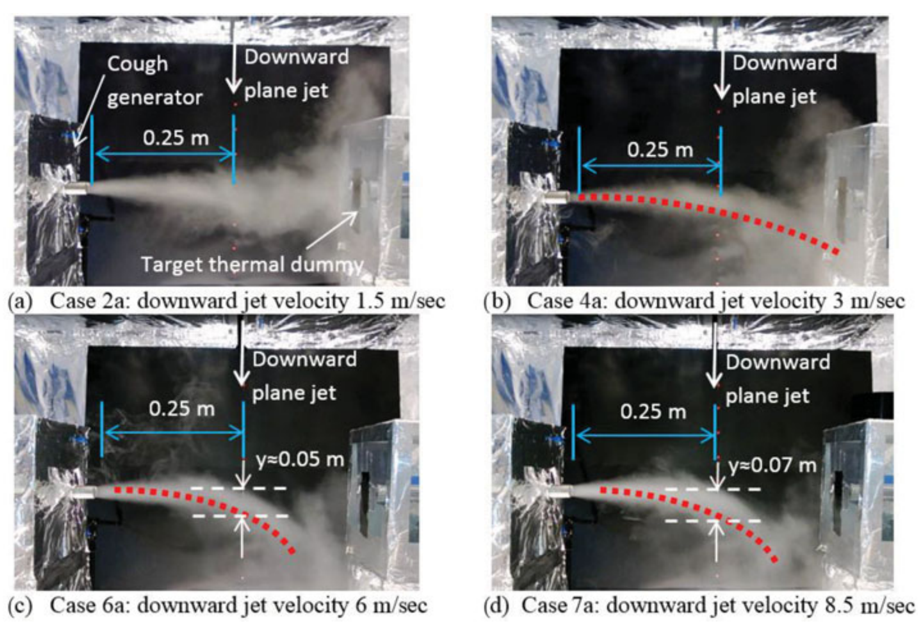

Figure 3. Photos of smoke visualization of a cough jet with an initial velocity of 12 m/s with a distance of 0.5 m between two thermal dummies under different conditions: (a) Case 2a: downward jet velocity 1.5 m/sec; (b) Case 4a: downward jet velocity 3 m/sec; (c) Case 6a: downward jet velocity 6 m/sec; (d) Case 7a: downward jet velocity 8.5 m/sec.

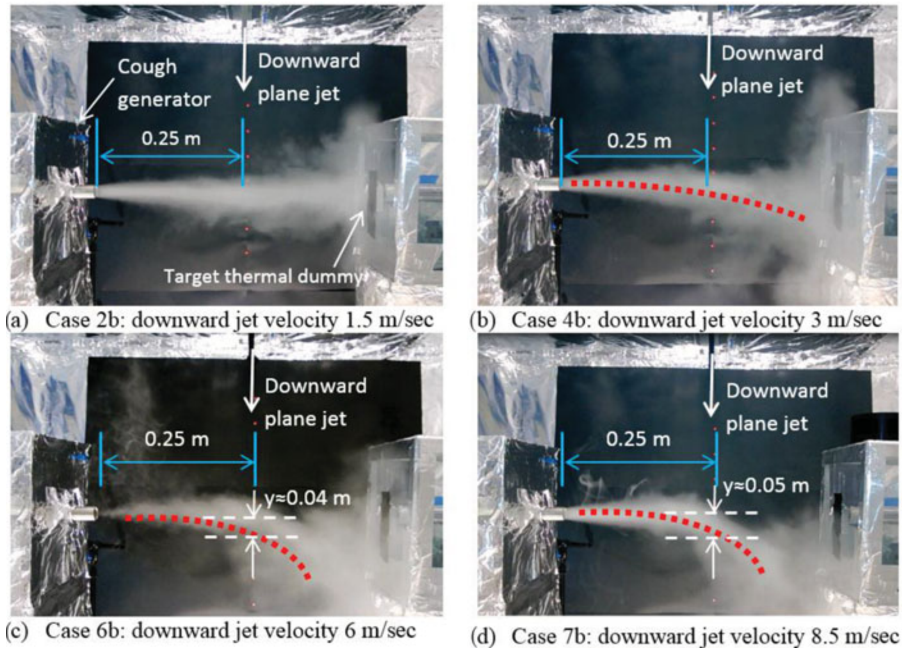

Figure 4. Smoke visualization of a cough of 16 m/s between two thermal dummies with various downward plane jet velocities: (a) Case 2a: downward jet velocity 1.5 m/sec; (b) Case 4a: downward jet velocity 3 m/sec; (c) Case 6a: downward jet velocity 6 m/sec; and (d) Case 7a: downward jet velocity 8.5 m/sec.

Effect of jet velocity on exposure

Maximum personal exposure value

Figures 6 and 7 show the measured maximum PE values for a cough jet interacting with a downward plane jet (velocity varies from 1.0–3.0 m/sec). The maximum PE for a cough of 12 m/sec is reduced by a factor of three with a downward plane jet with velocity greater than 3 m/sec. A downward jet with a discharge velocity greater than 3 m/sec might not reduce the PE value further to that of a cough of 12 m/sec and 16 m/sec. Figure 7 shows the measured maximum personal exposure values for a cough jet with a downward plane jet (velocity varies from 4.5–8.5 m/sec). The maximum PE decreases as the velocity of the downward plane jet increases. The effect of cough velocity (from 12–16 m/sec) on the PE value for the given setup becomes negligible when the discharge velocity of the downward plane jet reaches 8.5 m/se. The trend in Figures 6 and 7 shows that when jet velocity is greater than 3 m/sec, PE does not reduce significantly which may indicate that the velocity, 3 m/sec, of a downward jet seems critical to reduce the personal exposure to a cough jet.

Instantaneous exposure value

Figure 8 shows the instantaneous personal exposure and CEP with a cough velocity of 12 m/sec at a distance of 0.5 m between two thermal dummies with various velocities of the downward plane jet. The PE value for a cough of 12 m/sec is 3 times lower when the downward plane jet velocity increases from 1 m/sec to 4.5 m/sec. From Case 1a to 4a, the results indicate that increasing the downward jet velocity from 1 m/sec to 3 m/sec might not decrease the PE value significantly. Figure 8h shows that the instantaneous maximum PE drops to 1% when the downward plane jet velocity increases to 8.5 m/sec. By comparing the momentum flux of a cough jet and a DPJ, the downward plane jet in Case 2a has a momentum of nearly 0.0032 kg.m/sec^2 per meter of the slot jet, which is much smaller than the momentum of the cough jet, i.e., 0.059 kg.m/sec^2 and 0.104 kg.m/sec^2. For Case 7a, the plane jet has a momentum of 0.104 kg.m/sec^2 per meter of the slot jet, which is larger than the momentum of the cough jet of 12 m/sec and similar to the momentum of the cough jet of 16 m/sec. The momentum comparison of the cough jet and the DPJ shows that the value of PE depends on the ratio of the two momentums in this study. The results show that when the two momentums are equivalent, or if DPJ has greater momentum, the cough jet is deflected downward and does not reach the breathing zone of the TTD. Using the ratio of the two momentums, one might roughly estimate whether the transmission of a cough jet can be controlled.

From Case 0a to Case 5a, the CEP value lies between 7 and 12 sec, which is longer than the values of 3–4 sec in Cases 6a–7a. The reduction of the CEP might indicate that the possible personal exposure risk decreases only when the velocity of the downward plane jet reaches a certain level. In this study, the CEP does not change much when

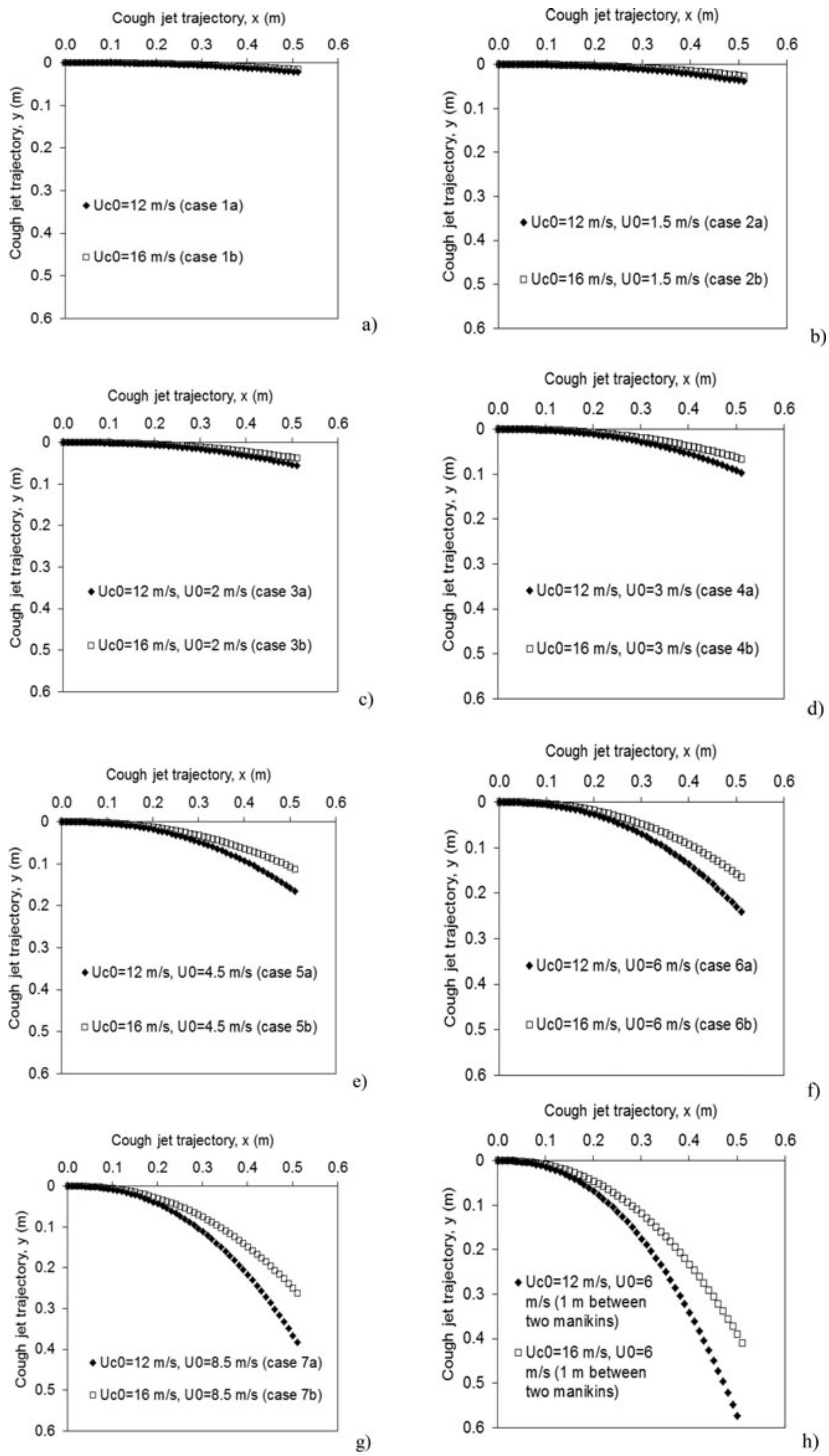

Figure 5. Predicted trajectory of the cough jet penetrating a downward plane jet with various velocities.

the velocity of a downward plane jet is less than 4.5 m/sec (see Figures 8 and 9). When the velocity of the plane jet reaches 8.5 m/sec, the CEP is only one-third of the value in Case 0a and Case 0b.

Figure 9 shows the instantaneous personal exposure and CEP for a cough velocity of 16 m/sec and illustrates that the PE value drops to one-third of the former value, from 9% to 3%, when the downward jet velocity increases up to 4.5 m/sec. The PE value remains in the range of 3–4% when the velocity of downward plane jet increases from 2 m/ecs to 4.5 m/sec. The PE becomes quite low when the downward plane jet velocity increases to 6 m/sec or 8.5 m/sec, possibly indicating that the downward plane jet produces better performance in reducing the personal

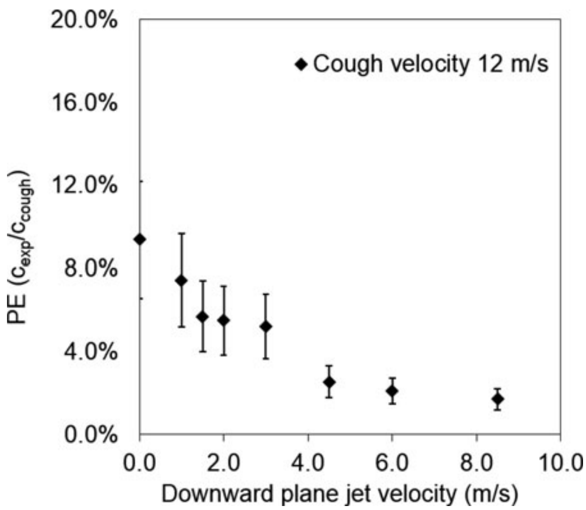

Figure 6. Measured maximum personal exposure value with a cough velocity of 12 m/sec. (The error bar stands for the mean ratio of standard deviation (SD) to the peak PE, 30%.).

exposure to a cough when a higher discharge velocity is used.

Practical limitations

A few practical limitations in this study should be considered in further studies. The smoke visualization tests might not give a truly accurate illustration of the dynamic behavior of a cough due to size differences between the smoke particles and respirable particles of a real human cough, and temperature differences exist between the coughed airflow and ambient air. In addition, use of a stationary cylindrical dummy to represent a human being might neglect the effect of human activities and body geometries on the performance of the DPJ. However, this

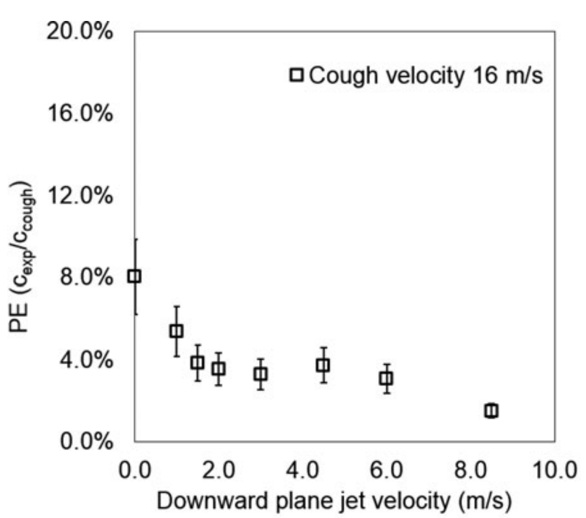

Figure 7. Measured maximum personal exposure value with a cough velocity of 16 m/sec. (The error bar stands for the mean ratio of standard deviation (SD) to the peak PE, 22%.).

approach offers an economical and practical way to visualize the cough for qualitative analysis.

Normally, the height in either hospital or office rooms is over 2.5 m, which is greater than in the chamber used in this study. Because the downward plane jet was installed at the ceiling level, the volume flow rate of the downward jet must be larger to maintain the same velocity when interacting with the cough jet. The change in the installation height might affect the maximum velocity distribution and thus affect the performance of the downward plane jets. The size of bacterial- and virus-laden particles and droplets from a real human cough might vary from 0.05–500 µm, with possible velocities ranging from 6–22 m/sec. This study only studied respirable particles, which have a size of 2.5 µm or lower, and used particles with a size of 2.5 µm for coughs of 12 m/sec and 16 m/sec.

Because the centerline velocity of the cough jet decays with distance, personal exposure decreases if a coughing person stands a bit farther from the downward plane jet. Moreover, a real cough might have a higher peak velocity that could penetrate the downward plane jet to a greater extent than the simulated cough with a flat flow rate profile and the low maximum flow rate used in this study. Further experimental measurements must be conducted to validate the calculation. In addition, the results suggested that a downward plane jet with a velocity of 8.5 m/sec might be used to prevent direct transmission of coughed particles. However, the velocity could be quite high with respect to the energy efficiency of the system. Because the phenomena of coughing and sneezing are unpredictable and accidental, other places such as open-plan offices and multiple workstations, where a higher chance of cross-infection exists, must be investigated further with respect to the discharge velocity of the downward plane jet.

Furthermore, the dynamic response of the aerodynamic particle sizer (APS) used to study the particle concentrations at the target manikin might underestimate the peak values of PE and CEP because the duration of the coughs is less than the time resolution of the APS. However, the particle concentration was measured in the breathing zone of the recipient dummy (located 0.5 m from the discharge opening) in which the jet velocity decayed greatly. The particle concentration in this location did not vary as rapidly as in the high air velocity regions. Each case was measured three times, and the standard deviation of the particle concentration was calculated and reported to account for the uncertainties that might be caused by "minor shifts in the time." The concentration of cough particles was measured in the cough generator and near the "mouth" of the TTD. The dimensionless personal exposure (PE) was calculated by dividing the particle concentration reported by the APS at each time point by the concentration within the cough

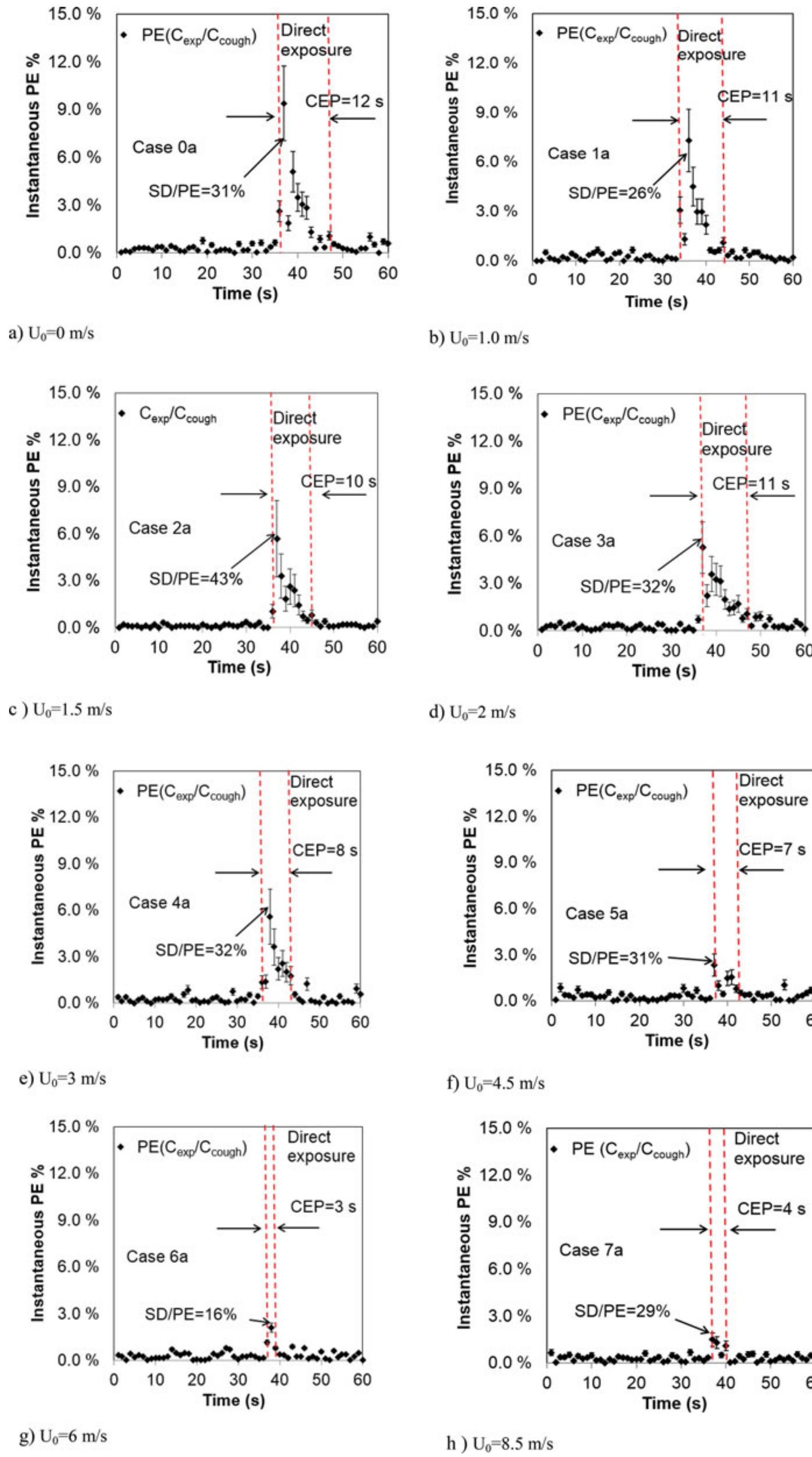

Figure 8. Measurement results of instantaneous personal exposure to a cough of 12 m/sec with various downward jet velocities: (a) case 0a no ventilation; (b) case 1a $U_0 = 1.0$ m/sec; (c) case 2a $U_0 = 1.5$ m/sec; (d) case 3a $U_0 = 2$ m/sec; (e) case 4a $U_0 = 3$ m/sec; (f) case 5a $U_0 = 4.5$ m/sec; (g) case 6a $U_0 = 6$ m/sec; and (h) case 7a $U_0 = 8.5$ m/sec. (The error bar stands for the ratio of standard deviation (SD) to the peak PE varies from 16–43%.).

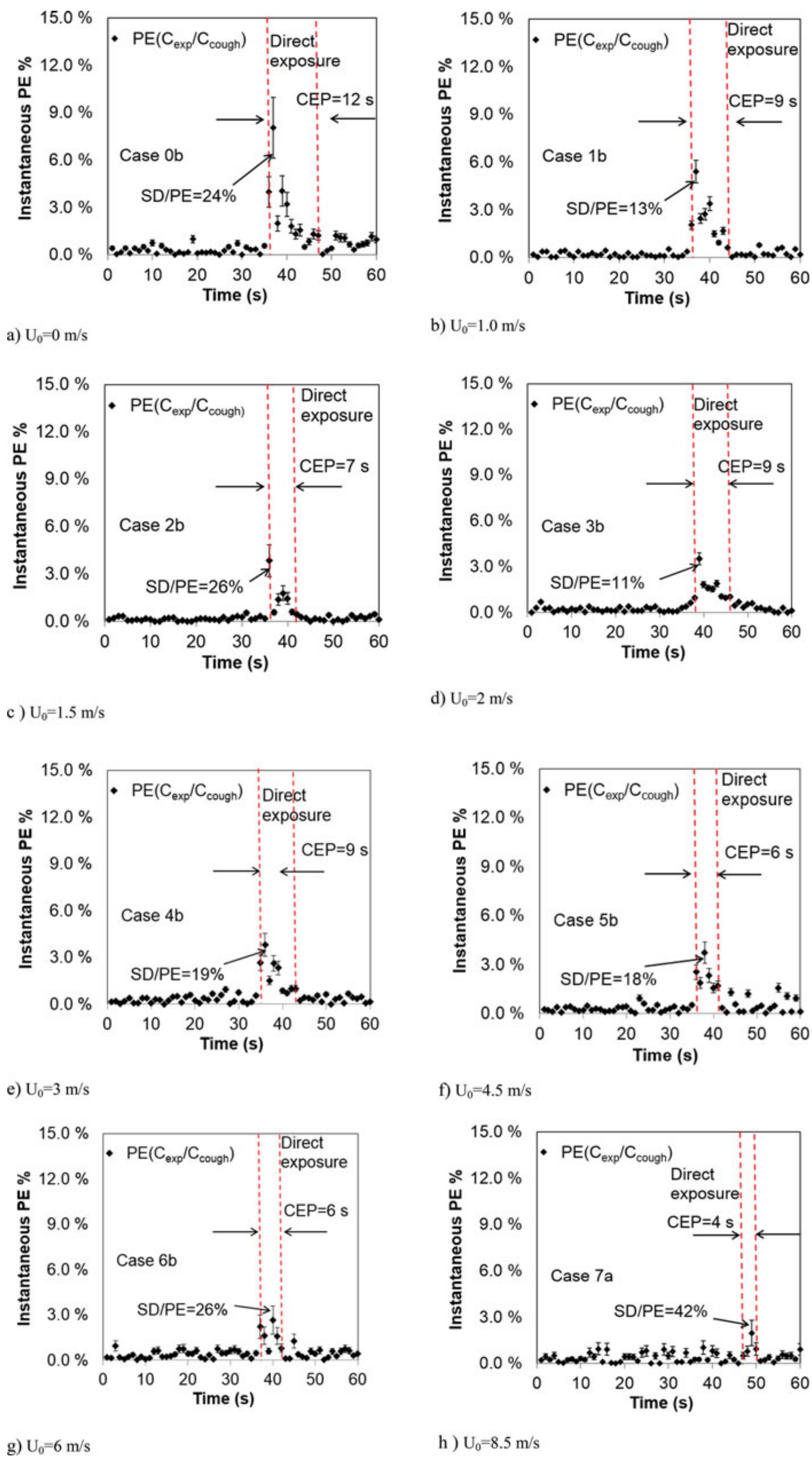

Figure 9. Measurement results of instantaneous personal exposure to a cough of 16 m/sec with various downward jet velocities: (a) case 0b no ventilation; (b) case 1b $U_0 = 1.0$ m/sec; (c) case 2b $U_0 = 1.5$ m/sec; (d) case 3b $U_0 = 2$ m/sec; (e) case 4b $U_0 = 3$ m/sec; (f) case 5b $U_0 = 4.5$ m/sec; (g) case 6b $U_0 = 6$ m/sec; and (h) case 7b $U_0 = 8.5$ m/sec. (The error bar stands for the ratio of standard deviation (SD) to the peak PE varies from 11–42%.).

simulator as reported by an optical particle counter. This method might be dependent on obtaining an accurate measurement of the peak concentration, which is difficult when the time resolution of the instrument is longer than the length of the cough.

The coefficients of the model were validated only for a few conditions with a transient cough jet, and therefore, they should be used to predict the trajectory of a cough jet under similar conditions. The empirical model was originally derived from the interaction of a constant round jet with a plane jet. The new coefficients of the model were not validated for all conditions of a transient cough jet. Further experimental studies are required to validate these coefficients under various conditions. Additionally, the empirical trajectory model was derived from conditions that were selected for a perpendicular uniform cross-flow interacting with a steady round jet. New coefficients must be determined for extension to different conditions, such as different slot widths of the DJP or the distance between the cough jet and the centerline of the DPJs. Additional studies might be required to validate the model with specific values for A and B. The format of the empirical models might also change if the number of slot-producing DPJs changes.

Conclusions

The cross-flow phenomenon of a cough jet with a downward plane jet is complex with respect to the dynamic behavior of the instantaneous cough jet and the thermal environment near the occupants in a room. An empirical model of the trajectory of a cough jet impinged with a cross-flow was developed and validated by smoke visualization. This study also characterized the exposure to coughed particles (diameter of 2.5 µm). The predicted trajectory for the cough jet agreed well with the smoke visualization results. The trajectory of the cough jet interacting with the downward plane jet can be described using the theories of classic cross-flow.

Both the smoke visualization and particle measurement results showed that increasing the momentum of the downward plane jet deflected the cough jet downward, thus decreasing the transmission cough particles from the source thermal dummy to the target thermal dummy positioned 0.5 m away. The value of the PEs reported in this study could be determined using the ratio of the momentum of the cough jet and downward plane jet. When the two momentums are equivalent, or if DPJ has greater momentum, the cough jet can be deflected downward and does not reach the breathing zone of the TTD. Using the ratio of the momentum flux, one can roughly estimate whether the transmission of a cough jet can be controlled. The downward plane jet could likely reduce the risk of airborne cross-infection between two people at the same height. The results suggest that downward plane jets might be used to reduce the exposure of people in a protected zone to respiratory pollutants emitted in a source zone. The experimental work and analytical model in this study could be useful as a guide for ventilation design of PZV for hospitals and relevant health care facilities (that primarily use mixing ventilation) and might also help to reduce the risk of cross-infection and minimize NFE to infectious particles. The results might be also used to guide the design of PZV for rooms, i.e., reception, patient rooms, and waiting rooms, in the hospital that can be separated by downward plane jets to better separate HCP and patients with limited cross-transport of cough particles.

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Nomenclature

A	a constant in the equation of cough trajectory
Ar	Archimedes number
a_0	the area of the "mouth" to expel a cough, (m^2)
B	a constant in the equation of cough trajectory
C_{exp}	particle number concentration measured in the breathing zone of the target dummy, count of particles/cm^3

C_{cough} particle number concentration measured in the cough generator, count of particles/cm^3
d the nozzle diameter of the cough generator (m)
g gravitational acceleration (m/s^2)
h the slot width (m)
K a dimensionless constant of the downward plane jet, 2.4 is used in this study
k a dimensionless constant of a cough jet, 6.2 is used in this study, which is obtained from measured cough velocities
PE the personal exposure to coughed particles (%)
PE_{bkg} the personal exposure to background particles (%)
r effective velocity ratio
U_0 the initial velocity of a downward jet (m/s)
U_{cm} the local maximum jet velocity at a distance of x (m) downstream from the cough generator (m/s)
U_{c0} the cough discharge velocity (m/s)
U_m the local maximum centreline velocity of a downward jet (m/s)
x the horizontal distance downstream from the cough generator (m)
y the vertical distance of downstream from the slot (m)
β the coefficients of thermal expansion 3.4×10^{-3} (1/K)
ρ_{cj} the air density of a cough jet (kg/m^3)
ρ_{df} the air density of a downward jet (kg/m^3)
ΔT_0 the temperature difference between a cough jet and the background air in the chamber (°C)