Particle transport characteristics in indoor environment with an air cleaner: The effect of nonuniform particle distributions

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Abstract

Air cleaners are expected to improve the indoor air quality by removing the gaseous contaminants and fine particles. In our former work, the effects of the air cleaner on removing the uniformly distributed particles were numerically investigated. Based on those results, this work further explores the performances of the air cleaner in the reduction of two nonuniform particle distributions generated by smoking and coughing. The Lagrangian discrete trajectory model combined with the Eulerian fluid method is employed to simulate the airflow pattern and particle transport in a room. In general, the results show that the particle fates have been resulted from the interaction between the emitting source and the air cleaner. And the position of the air cleaner is a key parameter affecting the particle concentration, for which a shorter distance between the air cleaner and the human body corresponds to a lower concentration. Besides, the air velocity emitted from the human mouth and the orientation of the air cleaner can also influence the transport of particles.

Keywords

nonuniform particle distribution, indoor environment, air cleaner, particle trajectory model

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1 Introduction

Indoor air quality is closely related to human health since most people spend nearly 90% of lifetime in the indoor environment (Klepeis et al. 2001). Both gaseous contaminants and fine particles in the indoor air can pose a threat to human health (Ardkapan et al. 2014; Cao and Meyers 2015). The severe acute respiratory syndrome (SARS) exploded in 2003 was a typical epidemic disease that infects human by the tiny droplets or particles carrying various virus and bacteria (Chen et al. 2010). Some research results even show that the airborne particle concentration is closely associated with human mortality (Dockery et al. 1993; Chen et al. 2013). The problem of indoor air quality may become more severe when the outdoor air pollution intensifies, especially in the days of fog and haze.

In order to reduce the indoor air pollution, more and more air cleaners are used. Obviously, the particle concentration of indoor air is determined by both conditions of the particles (e.g. particle quantity, particle distribution,

etc.) and the air cleaner (e.g. location, airflow rate, flow direction, etc.), which are the source and sink of particles, respectively. Quite a few studies have been carried out to evaluate the performance of the air cleaner (Nelson et al. 1993; Ongwandee and Kruewan 2013; Ardkapan et al. 2014; Zhang et al. 2010; Kang et al. 2008; Chen et al. 2010; Jin et al. 2015; Qian et al. 2010). The investigations indicate that the position of the air cleaner is a key parameter, which influences the airflow patterns and leads to different removal efficiencies (Zhang et al. 2010). According to (Kang et al. 2008), the air cleaner positioning may cause up to three-fold difference in effectiveness. Besides, the direction of airflow ejection is another key parameter for aerosol dispersion control (Chen et al. 2010). In order to have a comprehensive understanding of the key influencing parameters, Jin et al. (2015) numerically analyzed the effects of the position, flow rate and air ejection direction of an air cleaner on the particle transport characteristics. It was found that the flow rate of the air cleaner is a key parameter affecting the particle concentration. The location of the air cleaner plays a

significant role only when the volumetric flow rates are low. Horizontal and upward ejections of the air cleaner have little difference in the removing airborne particles, while they are superior to the downward ejection.

On the other hand, the particle removal efficiency is also influenced by the condition of airborne particles (Nazaroff 2000), especially their distributions. In the literature mentioned above, the contaminant concentration is generally assumed uniform. However, in the case of smoking or coughing, the particles are mainly from the person who stays at a certain part of the room. As a result, the contaminative particles are nonuniformly distributed. There are relatively fewer studies reported on the transport characteristics of the nonuniformly distributed particles in indoor environment with an air cleaner.

This paper evaluates the performance of an air cleaner for the nonuniformly distributed particles caused by smoking and coughing. The evaluation is based on our previous work (Jin et al. 2015), and nonuniform particle distributions are simulated. The influences caused by the particles and the air cleaner are analyzed in detail.

2 Mathematical model

2.1 Turbulent airflow model

The Reynolds averaged Navier–Stokes (RANS) equations combined with Renormalization Group (RNG) k - ε model are applied to model the indoor turbulent flow (Launder and Spalding 1974). The interaction between indoor air and the particles is neglected since the particles are small enough and can hardly affect the airflow distribution (Zhao et al. 2004). The governing equation is (ANSYS 2009):

$$\frac{\partial \varphi}{\partial t} + \nabla \cdot (\vec{u} \varphi) = \nabla \cdot (\Gamma_{\varphi} \nabla \varphi) + S_{\varphi} \quad (1)$$

where ∇ is the gradient of the variable; $\vec{u}$ is the time-averaged velocity; φ may be the time-averaged velocity component (u , v , w), the turbulent kinetic energy k , the turbulent dissipation rate ε , or air enthalpy h in different equations; Γ_{φ} and S_{φ} are the effective diffusivity and source term for each variable, respectively.

Commercial CFD software FLUENT was employed to solve Eq. (1) in the form of discretized algebraic equations with a second-order upwind scheme. The SIMPLE algorithm (ANSYS 2009) was used to couple the pressure and velocity fields. The Boussinesq approximation was also applied to include the influence of the buoyancy effect.

2.2 Particle trajectory model

To obtain the transport characteristic of indoor particles,

the Lagrangian particle tracking method was employed to calculate the average concentration and final fates of the particles. All the particles were treated as solid spheres, and the heat and mass transfer between the particle and fluid were ignored. The particle movement is described by Eq. (2) (ANSYS 2009):

$$\frac{du_p}{dt} = \frac{18\mu}{\rho_p d_p^2 C_c} (u_i - u_p) + g_i \left(1 - \frac{\rho}{\rho_p}\right) + F_a \quad (2)$$

where u_p , d_p and ρ_p are the velocity, diameter and density of the particle, respectively; u_i and ρ are the velocity and density of indoor air; μ is the kinetic viscosity of air. The first term on the right side of Eq. (2) is the specific drag force of the particle (i.e. drag force per unit particle mass). C_c is the Cunningham correction, which can be calculated by (ANSYS 2009)

$$C_c = 1 + \frac{2\lambda}{d_p} (1.257 + 0.4e^{-(1.1d_p/2\lambda)}) \quad (3)$$

where λ represents the molecular mean free path of air and the Reynolds number is defined by Eq. (4) (Zhao et al. 2004):

$$Re = \frac{(u_i - u_p) \rho d_p}{\mu} \quad (4)$$

The second term on the right side of Eq. (2) is the specific gravitational force and the third term includes all the other forces like the pressure gradient force, Basset force, virtual mass force, Brownian force, thermophoretic force and Saffman's lift force, etc. In indoor environment, the pressure gradient force, Basset force and virtual mass force are much less than the drag force (Zhao et al. 2004). Consequently they were neglected. As for the Brownian, thermophoretic and Saffman's lift forces, they were included in the model since their order of magnitudes are comparable to that of the drag force in some zones (Zhao et al. 2004; ANSYS 2009).

2.3 Stochastic tracking model

Besides the time averaged flow field, velocity fluctuations can also affect the particle transport, especially for small particles. The Discrete Random Walk (DRW) model was employed to simulate the velocity fluctuations. During the calculation of the particle trajectory, the DRW model will predict the fluctuating gas flow velocity based on a stochastic scheme. This fluctuating velocity combined with the mean flow velocity will be used in Eq. (2) as the term of air velocity to predict the turbulent effect on the dispersion of particles. The DRW model assumes that the turbulence is isotropic and the random velocity fluctuation follows a Gaussian

probability distribution as (Lai and Chen 2006):

$$u'_i = \varsigma_i \sqrt{u_i'^2} = \varsigma_i \sqrt{\frac{2k}{3}} \quad (5)$$

where ς_i is a normally distributed random number, which maintains constant during the lifetime of a turbulent eddy. However, the isotropic assumption is not suitable in near-wall areas where the turbulent kinetic energy normal to the wall is substantially smaller than the ones parallel to the wall (Lai and Chen 2006). To resolve this problem, the turbulent kinetic energy for the first cells adjacent to the wall was modified by using Eqs. (6) and (7) (Wang and James 1999). Before particle tracking, the kinetic energy near walls was artificially decreased by using the user define functions (UDF) in FLUENT.

$$u'_y = \varsigma_y \sqrt{\frac{2k}{3}} \times f_v \quad (6)$$

$$f_v = 1 - \exp(-0.02 y^+) \quad (7)$$

2.4 Model validation

The numerical model used in this work is the same as that used in our previous work (Jin et al. 2015), which has been compared with investigation of (Lu et al. 1996) and validated by their experimental results. The details of validation can be found in our previous work and will not be repeated here.

3 Case set-up

Due to the heavy haze pollution in China, most of residents tend to close windows to restrain the outdoor particles entering into the room. However, the particles generated by coughing and smoking in the indoor environment can also pose threat to human health. In this case, more and more air cleaners are employed to enhance the indoor air quality. To study the transport characteristics of the nonuniformly distributed particles, caused by smoking or coughing indoors and expected to be removed by an air cleaner, a full-scale room is selected. For a typical apartment, the chair or sofa is usually placed adjacent to the wall. And most of time, people sits on a chair or sofa to rest. To mimic this scenario, the human model was placed against the wall with a sitting posture. Besides, the air cleaner is also usually placed next to the wall so as not to affect human activities. As shown in Fig. 1(a), the height (H), width (W) and length (L) of the room are 2.7 m, 3.2 m and 4 m, respectively. One manikin is assumed to sit at the center of the east wall of the room, whose head and mouth are simplified as a sphere with a diameter of 20 cm and a cycle with a diameter of 2 cm, respectively. Three to-be-evaluated positions of the

air cleaner are illustrated in Figs. 1(a) and (b). Position-1 is symmetrical about the middle line in the x - z plane. In position-2, the distance between the west wall of the room and the west side of the air cleaner is 0.5 m. The distance between the east wall of the air cleaner in position-2 and the west wall of the air cleaner in position-3 is 1 m. Figure 1(c) shows the cabinet type of air cleaner used in households with overall dimensions of height $\times$ width $\times$ length = 1.3 m $\times$ 0.3 m $\times$ 0.6 m. The dimensions of the air intake and outlet are 0.6 m $\times$ 0.5 m and 0.6 m $\times$ 0.3 m, respectively. As for the

Fig. 1 Schematic of (a) the room with air cleaner and manikin, (b) positions of the air cleaner and manikin, (c) air cleaner geometry and (d) ejection orientations

three typical ejection directions of air current from outlet shown in Fig. 1(d), i.e., upward, horizontal and downward, the downward ejection was found to be much less efficient for removing particles as compared with the horizontal and upward ejections (Jin et al. 2015). Besides, the differences between the horizontal and upward ejections are generally insignificant, therefore, only the horizontal ejection is studied in this work.

It is well known that the temperature of the burning cigarette is significantly higher than the ambient environment, which induces a strong buoyancy effect to transport particles upward. During the process of smoking, however, most of the particles are absorbed into the human body and exhaled from the mouth. The amount of particles directly emitted from burning cigarette is comparatively lower. Therefore, we mainly focus on the dispersion of particles exhaled from human mouth in this study. And the smoking process is treated similar to the respiration activity. According to (Hörschler et al. 2010), the periodic respiration could be simplified as a steady exhalation activity. Therefore, a constant exhalation rate of 1.4 m³/h is applied for the human mouth, which is equivalent to a mean velocity during exhalation process. In contrast, the velocity of cough process is much larger, which is assumed to be 20 m/s according to (Zhao et al. 2005). It should be noted that the time of smoking a cigarette may last for a few minutes and most people cough more than once in a cycle of coughing. Therefore, the simulation of the complete process of smoking or coughing may be computational expense and time consuming. In order to simplify the prediction, we only consider smoking process for 5 s and coughing for 0.5 s, which is longer enough to capture the main features of particle transport (Zhao et al. 2005). The time step for calculating the fates of particles is taken as 0.01 s as recommended in (ANSYS 2009), which is small enough to capture the particle transport characteristics.

From the investigation of (Miller and Nazaroff 2001), the diameters of particles generated during smoking range from 0.5 to 1 µm and the total particle emission rate approximates to 370 µg/min. Similarly, the diameter of particles ejected during coughing is about 1 µm and the total number is around 3000 according to (Wei and Li 2015). In this study, 3100 sample particles were injected into the indoor environment during the activity of human smoking or coughing, which is larger enough to represent the mean transport characteristics of particles. The time of injection lasts 5 s for smoking and 0.5 s for coughing (Fig. 2). Moreover, the diameters of particles are all set to a dominant value of 1 µm and the density of particle is 1200 kg/m³.

Meanwhile, the particles are expected to be removed by the air cleaner. The intake of air cleaner is set as a Neumann

Fig. 2 Outlet velocity of the particles in coughing and smoking processes

boundary condition. The filtration efficiency of the air cleaner is defined as the ratio of clean air delivery rate (CADR) to the volume flow rate through the air cleaner Q_v according to (Shaughnessy and Sextro 2006):

$$\varepsilon = \frac{\text{CADR}}{Q_v} \quad (8)$$

where the filtration efficiency is set to 1 so that the Q_v equals CADR. Therefore, the particles captured by the air cleaner intake are regarded as escaping from the domain, and no particles are ejected at the outlet of the air cleaner. Since the filtration approaches for air cleaners mainly consist of fibrous and electrostatic filtration, and the filtration efficiency for particles larger than 1 µm can be as high as 99% (Shaughnessy and Sextro 2006), the number of micron-sized particles escape from the air cleaner is extremely small, justifying the assumption of 100% filtration efficiency in this study. However, the air cleaners cannot effectively remove the submicron particles and the escape phenomena are significant, which will be investigated in our future work.

For the popular air cleaners in the Chinese market, the typical CADR value ranges from 100 to 600 m³/h. For example, the air cleaner made by Blueair Company (product model Blueair-303) has a CADR of nearly 300 m³/h and the geometry is 0.25 m × 0.44 m × 0.635 m (length × width × height), representing a relatively smaller category. While the air cleaner developed by SAMSUNG Company (product model KJ720F-K7586WF) has a CADR of as high as 720 m³/h and the dimension is 0.28 m × 0.36 m × 1.2 m (length × width × height). In this study, the size of the air cleaner is close to that of the SAMSUNG product. As for the CADR value, on one hand, three different values of 260 m³/h, 520 m³/h and 970 m³/h were studied in our previous work

(Jin et al. 2015), which found that the average suspended particle concentration could be reduced much faster by using a larger flow rate. On the other hand, the typical flow rate of air cleaners ranges within $600 \text{ m}^3/\text{h}$. Based on these two considerations, the flow rate of $520 \text{ m}^3/\text{h}$ is investigated in this study, which is large enough to ensure a relatively well air mixing condition of the indoor environment.

Wall functions are applied to the region close to the walls. When a particle collides with the surface, it will be retained without bouncing back. Due to the fact that the heat from human body would produce the buoyancy effect that could change the particle trajectory significantly (Ge et al. 2013), the temperature difference between the human body and indoor environment is included by using the Boussinesq approximation. A constant temperature of 304 K is set to the human body, which is recommended by (Gao and Niu 2004) and the temperature of the room environment is 298 K . Adiabatic boundary conditions are used for the surfaces of the chair and room. For the air cleaner, the rated power is less than 100 W as illustrated in many product introductions. Even one third of the power is converted into heat, the heat release of the air cleaner is about 30 W , which is smaller than the heat release of human body of about 100 W . Besides, the air velocities near the inlet and outlet of the air cleaner are approximate 1 m/s . These airflows significantly disturb the flow field and abate the influence of convection boundary layer of the air cleaner. In order to quantify the influence of heat release from the air cleaner, a simulation is conducted and the thermal boundary of air cleaner is set to 30 W . The flow fields are similar to the cases with adiabatic boundary conditions and the particles exhibit analogous fates. Therefore, the heat release from air cleaner is neglected.

In the process of computations, the unsteady state airflow is obtained by solving the URANS equations and the turbulent kinetic energy in the cells adjacent to walls is modified with Eqs. (6) and (7), so that the particles are tracked in the modified airflow field. The stochastic tracking model (DRW) was used to predict the influence of turbulence on particle dispersion and 5 simulation runs were conducted for each case to eliminate the effect of randomness. The mean value of the 5 runs was applied to represent the transport characteristics of particles. For the sake of computational cost and accuracy, the grid independence tests were carried out for several positions of air cleaner. Three numbers of cells namely 0.4M (case-1), 1.2M (case-2) and 2.0M (case-3) are adopted to check the mesh independence. Figure 3 shows the velocity magnitude at the line-1 (refer to Fig. 1(b)) when the air cleaner locates at position-1. The velocity of case-2 varies little from that of case-3, therefore the 1.2M cells is applied in the simulation.

Fig. 3 Grid independence test by comparing the velocity magnitude at line-1 for case-1, case-2 and case-3

4 Results and discussion

4.1 Particles from smoking

Figure 4 shows the evolutions of the number of suspended sample particles in the room during the process of smoking. For all the three positions, the particle number decreases when the running time of the air cleaner increases. Since the distances between the air cleaner and the human body are in the order of position-1 > position-2 > position-3, it is clear that the shorter the distance, the faster the reduction of the particle concentration. In detail, the number of the suspended particles in the case of position-1 is conspicuously larger than the other two cases during most part of the statistic time except for the initial stage (within $\sim 40 \text{ s}$). Also, when the air cleaner is placed at position-3, which is the nearest position to the human body, the number of suspended

Fig. 4 Evolution of average suspended particle concentration in the room for various positions of the air cleaner (the particles are generated by smoking)

particles decreases much quicker than that in the other two positions. It should be noted that the particle concentrations have been conspicuously reduced during 0–900s. Then the air cleaner can be manually or automatically switched to a smaller CADR value to maintain the particle concentration at a lower level and reduce the energy consumption. This kind of operation strategy is widely adopted by commercial air cleaners.

The different results indicated above are related to the various airflow patterns as shown in Fig. 5. The airflow field in plane-1 (refer to Fig. 1(b)) for the case of position-1 is given in Fig. 5(a), in which two clear vortices can be found. One of the vortices generates near the floor and the sitting man, which can be attributed to the combined effects of the buoyancy force and the flow ejected from the air cleaner. In addition, the air current exhaled from the human mouth

bends towards the body, under the effect of the air cleaner, inducing the particles of smoking cluster around the body at the initial stage. As for the draft generated by the air cleaner, it will influence the thermal comfort of human body. For the three positions investigated in this study, position-1 is right in front of the human body, which might have a severe thermal comfort problem. However, as illustrated in Fig. 5, the air velocity at the area next to the human is smaller than 0.3 m/s, which will not lead to obvious discomfort.

For the case of position-2, the airflow pattern in plane-2 and plane-1 are shown in Figs. 5(b) and (c). On plane-2, which is perpendicular to the air cleaner, the airflow field is similar to that of Fig. 5(a). However, obvious differences appear in the airflow pattern in plane-1. As a result of buoyancy effect, the airflow direction near the human body

Fig. 5 Airflow patterns at the time of 5 s for the case of smoking with (a) plane-1 when air cleaner is at position-1, (b) plane-2 when air cleaner is at position-2, (c) plane-1 when air cleaner is at position-2, (d) plane-3 when air cleaner is at position-3, (e) plane-1 when air cleaner is at position-3

is upward. Comparatively, the region near the air cleaner is dominant by the momentum ejected from its outlet which leads to a more turbulent airflow pattern. Furthermore, the particles generated by smoking, which are not suffered from the directly blowing by the air cleaner, disperse more quickly comparing with the case of position-1.

Similar to the flow patterns in the case of position-2, the airflow field in plane-3 and plane-1 for the case of position-3 are shown in Figs. 5(d) and (e). However, the air mixing effects in this case are stronger than the other two cases. Moreover, particles are easily transported to the region near the air cleaner due to the relatively shorter distance, which enhances the probability of particles captured by the cleaner.

The diameter of the particles investigated in this study is 1 μm , for which the Stokes number is very small, so the particles will follow the airflow tightly. Figures 6(a) and (b) show the location of sample particles at the statistic time of 5 s and 20 s after their generations for the case of position-1. Since the airflow from the air cleaner blows directly to the human, it causes many particles to gather around the human body and increase the probability of particle collision with the body surfaces. As a result, a large number of particles deposit on the human body (refer to Table 1), and the number of suspended particles is lower at the initial period

of statistic time. That is probably the reason why the number of suspended particles in the case of position-1 decreases faster than the other two cases within the initial 40 s, as indicated in Fig. 4.

On the contrary, the particles transport smoothly away from the human body in the cases of position-2 and position-3, for the restraints caused by the direct airflow from the air cleaner are relatively weaker, as illustrated in Figs. 6(c)–(e). At the time of 20 s, the particles in the case of position-2 transport to the region near the air cleaner, as shown in Fig. 6(d). Meanwhile, owing to a shorter distance, the particles in the case of position-3 have already arrived at the region in front of the air cleaner where the particles follow the airflow field tightly to move toward wall-2, as shown in Fig. 6(f).

To account for the particle fates, Table 1 lists the number of sample particles deposited on the interior surfaces and captured by the air cleaner for the three cases. For position-1, up to 20% of the sample particles are deposited on the surfaces of the human body, which is obviously larger than that of position-2 and position-3. This discrepancy has been associated with the airflow patterns as mentioned before. Besides, the number of particles intaked by the air cleaner at position-1 is also the highest, which may reasonably be attributed to the face-to-face layout of the air

Fig. 6 Distribution of sample particles when the air cleaner is at the position and time of (a) position-1, 5 s, (b) position-1, 20 s, (c) position-2, 5 s, (d) position-2, 20 s, (e) position-3, 5 s, (f) position-3, 20 s

Table 1 Statistic results of escaped and deposited sample particles in the case of smoking at the time of 900 s

Case	Deposited							Air cleaner-wall	Total deposited	Intake	Suspended*
	Wall-1	Wall-2	Wall-3	Wall-4	Ceiling	Floor	Body				
Position-1	175	189	115	118	127	3	620	150	1497	1515	88
Position-2	67	220	142	810	240	2	66	106	1653	1412	35
Position-3	106	484	63	65	83	27	72	998	1898	1193	9

* Suspended = 3100–Deposited–Intake

cleaner and the human. For position-3, the total number of the eliminated particles (deposit + intake) is the highest, of which the number of deposited particles is also the highest, while the number of intake is the lowest. As discussed previously, position-3 is close to the human, therefore the particles may follow the airflow of the outlet more tightly and obtain higher velocities, which leads to more particles colliding with different surfaces in the room. As for the case of position-2, the results fall in between the cases of position-1 and position-3.

These results reveal that position-3 can obtain a lower number of suspended particles. However, instead of intaking by the air cleaner, a large part of particles are deposited onto the surfaces, which may have a risk of re-suspension. Therefore, position-3 is a good choice when the requirement is lowering the number of the suspended particles as soon as possible. But if the target is to capture more particles by the air cleaner, the location of position-1 is preferred.

4.2 Particles from coughing

The evolutions of suspended particles generated by coughing are illustrated in Fig. 7. Analogous to the cases of smoking, the number of suspended particles in position-3 drops faster than the other two cases. However, the number of suspended particles in position-2 remains higher than that in position-1, which is an obvious distinction from the results of smoking process (refer to Fig. 4). Furthermore, for position-1, the variation of the particle number during the initial 40 seconds is much smoother in the coughing process, while there is a sharp drop for the corresponding case in the smoking process. These differences are resulted from the airflow patterns and the initial larger momentum produced by coughing.

The airflow patterns for the three cases are illustrated in Fig. 8. Generally the airflow patterns in the process of coughing are analogous to those in smoking, while notable differences exist near the human mouth. Since the process of coughing is pulse, it can produce an air current with large momentum. This high-velocity current will disturb the airflow field near the human mouth and carry the

Fig. 7 Evolution of average suspended particle concentration in the room for various positions of the air cleaner (the particles are caused by coughing)

particles to a relatively longer distance than in the smoking process. Nevertheless, the influence of the air current generated by coughing will diminish within a few seconds, and then the airflow field will be dominated by the intaking and ejecting processes of the air cleaner.

For position-1, as shown in Fig. 8(a), the direction of air current caused by coughing is more parallel to the direction of the ejected airflow from the air cleaner, as compared with the situation in the smoking process. In this way, the particles of coughing tend to join the circulating airflow of the air cleaner, and consequently may be removed by the air cleaner with higher possibility.

For the case of position-2, the particles of coughing travel a longer distance as demonstrated in Figs. 8(b) and (c). However, since the momentum of the air current of coughing fades way within a very short time and there is still a comparatively longer distance between the particles and the air cleaner, the particles tend to stay a longer time in the room. Therefore, at the same statistic time, there are more particles for the case of position-2.

Figures 8(d) and (e) give the particle distributions for the case of position-3. Since the distance between the human

Fig. 8 Airflow patterns at the time of 0.5 s for the case of coughing with (a) plane-1 when air cleaner is at position-1, (b) plane-2 when air clean is at position-2, (c) plane-1 when air clean is at position-2, (d) plane-3 when air clean is at position-3, (e) plane-1 when air clean is at position-3

and the air cleaner is shorter than that in position-2, the particles are close to the air cleaner when the momentum of the current fades away. As a result, the particles tend to enter into the circulating airflow of the air cleaner, and are removed by the air cleaner more quickly.

Figure 9 shows the particle distributions in the coughing process at the time of 0.5 s and 20 s for the three different positions of the air cleaner. At the time of 0.5 s, particles ejected from the human mouth by coughing exhibit similar distributions for the three cases, as indicated in Figs. 9(a), (c) and (e). While at the time of 20 s, the particle distributions are much different from each other. For the case of position-1, the particles are near the floor and moving towards the inlet of the air cleaner. Besides, the number of particles deposited on human body is much less than that in the case

of smoking due to the larger momentum of coughing that brings particles to a farer place. For the case of positions 2 and 3, the faster emitting velocity of particles in coughing make them disperse more quickly than the corresponding cases of smoking.

The number of the particles deposit on interior surfaces and intaked by the air cleaner are listed in Table 2. Due to the flow patterns and particle distributions mentioned above, the particles are more likely captured by the air cleaner for the cases of position-1 and position-3. As for the case of position-2, since the particles travel for longer time and distance, the chance of collision with walls, ceiling and floor are much higher. Therefore, half of the eliminated particles in the case of position-2 are deposited, which is much higher compared with the other two cases.

Fig. 9 Distribution of sample particles when the air cleaner is at the position and time of (a) position-1, 0.5 s, (b) position-1, 20 s, (c) position-2, 0.5 s, (d) position-2, 20 s, (e) position-3, 0.5 s, (f) position-3, 20 s

Table 2 Statistic results of escaped and deposited sample particles in the case of coughing at the time of 900 s

Case	Deposited							Air cleaner-wall	Total deposited	Intake	Suspended*
	Wall-1	Wall-2	Wall-3	Wall-4	Ceiling	Floor	Body				
Position-1	132	185	78	59	108	4	185	59	810	2191	99
Position-2	23	150	155	563	128	10	142	224	1395	1394	311
Position-3	87	100	126	121	37	27	79	67	644	2414	42

* Suspended = 3100–Deposited–Intake

5 Conclusions

The modified discrete phase model, which combines the Eulerian fluid model, has been used to study the transport characteristics of nonuniformly distributed particles caused by smoking and coughing in the indoor environment with an air cleaner.

For the smoking process, the velocity of the air current from the human mouth is relatively lower, which causes very limited influence to the indoor airflow pattern. In this scenario, the position of the air cleaner plays an important

role to determine the indoor particle concentration. The shorter the distance between the air cleaner and the smoking man is, the lower the particle concentration exhibits in the room. On the other hand, the orientation of the air cleaner also has impact on its performance. More particles are removed by the air cleaner when it is placed at position-1, which corresponds to a face-to-face layout.

For the coughing process, the lowest particle concentration is also achieved when the air cleaner is placed at the nearest position. However, due to the relatively higher velocity in coughing, the particles from the human mouth

travel a longer distance. Moreover, when the air cleaner is placed opposite to the human, the particles of coughing tend to join the main flow of the circulating airflow of the air cleaner, and consequently may be removed by the air cleaner with higher possibility.

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References

- ANSYS (2009). ANSYS FLUENT 12.0 Theory Guide. Canonsburg, PA, USA: ANSYS Inc.
- Ardkapan SR, Afshari A, Bergsøe NC, Nielsen P (2014). Evaluation of air cleaning technologies existing in the Danish market: Experiments in a duct and in a test room. *Indoor and Built Environment*, 23: 1177–1186.
- Cao S-J, Meyers J (2015). Fast prediction of indoor pollutant dispersion based on reduced-order ventilation models. *Building Simulation*, 8: 415–420.
- Chen C, Zhao B, Cui W, Dong L, An N, Ouyang X (2010). The effectiveness of an air cleaner in controlling droplet/aerosol particle dispersion emitted from a patient's mouth in the indoor environment of dental clinics. *Journal of the Royal Society Interface*, 7: 1105–1118.
- Chen Y, Ebenstein A, Greenstone M, Li HB (2013). Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. *Proceedings of the National Academy of Sciences (PNAS)*, 110: 12936–12941.
- Dockery DW, Pope CA, Xu X, Spengler JD, Ware JH, Fay ME, Ferris BJ Jr, Speizer FE (1993). An association between air pollution and mortality in six U.S. cities. *The New England Journal of Medicine*, 329: 1753–1759.
- Gao N, Niu J (2004). CFD study on micro-environment around human body and personalized ventilation. *Building and Environment*, 39: 795–805.
- Ge Q, Li X, Inthavong K, Tu J (2013). Numerical study of the effects of human body heat on particle transport and inhalation in indoor environment. *Building and Environment*, 59: 1–9.
- Hörschler I, Schröder W, Meinke M (2010). On the assumption of steadiness of nasal cavity flow. *Journal of Biomechanics*, 43: 1081–1085.
- Jin X, Yang L, Du X, Yang Y (2015). Particle transport characteristics in indoor environment with an air cleaner. *Indoor and Built Environment*, doi: 10.1177/1420326X15592253.
- Kang SY, Siegel J, Novoselac A (2008). Effective positioning of portable air cleaning devices in multizone residential buildings. In: *Proceedings of Indoor Air*, Copenhagen, Denmark.
- Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann WH (2001). The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*, 11: 231–252.
- Lai ACK, Chen F (2006). Modeling particle deposition and distribution in a chamber with a two-equation Reynolds-averaged Navier–Stokes model. *Journal of Aerosol Science*, 37: 1770–1780.
- Launder BE, Spalding DB (1974). The numerical computation of turbulent flow. *Computer Methods in Applied Mechanics and Engineering*, 3: 269.
- Lu WZ, Howarth AT, Adam N, Riffat SB (1996). Modelling and measurement of airflow and aerosol particle distribution in a ventilated two-zone chamber. *Building and Environment*, 31: 417–423.
- Miller SL, Nazaroff WW (2001). Environmental tobacco smoke particles in multizone indoor environments. *Atmospheric Environment*, 35: 2053–2067.
- Nazaroff WW (2000). Effectiveness of air cleaning technologies. In: *Proceedings of Healthy Buildings 2000*, 8th International Conference on Indoor Air Quality and Climate, Espoo, Finland.
- Nelson PR, Sears SB, Heavner DL (1993). Application of methods for evaluating air cleaner performance. *Indoor and Built Environment*, 2: 111–117.
- Ongwandee M, Kruewan A (2013). Evaluation of portable household and in-car air cleaners for air cleaning potential and ozone-initiated pollutants. *Indoor and Built Environment*, 22: 659–668.
- Qian H, Li Y, Sun H, Nielsen PV, Huang X, Zheng X (2010). Particle removal efficiency of the portable HEPA air cleaner in a simulated hospital ward. *Building Simulation*, 3: 215–224.
- Shaughnessy RJ, Sextro RG (2006). What is an effective portable air cleaning device? A review. *Journal of Occupational and Environmental Hygiene*, 3: 169–181.
- Wang Y, James PW (1999). On the effect of anisotropy on the turbulent dispersion and deposition of small particles. *International Journal of Multiphase Flow*, 25: 551–558.
- Wei J, Li Y (2015). Enhanced spread of expiratory droplets by turbulence in a cough jet. *Building and Environment*, 93: 86–96.
- Zhao B, Zhang Y, Li X, Yang X, Huang D (2004). Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method. *Building and Environment*, 39: 1–8.
- Zhao B, Zhang Z, Li X (2005). Numerical study of the transport of droplets or particles generated by respiratory system indoors. *Building and Environment*, 40: 1032–1039.
- Zhang T, Wang S, Sun G, Xu L, Takaoka D (2010). Flow impact of an air conditioner to portable air cleaning. *Building and Environment*, 45: 2047–2056.