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Transport of particulate and gaseous pollutants in the vicinity of a human body

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ABSTRACT

A uniform pollutant concentration in indoor environments can be an inappropriate representation of breathing concentration. This is especially true when local airflow in the vicinity of an occupant is dominant in transporting pollutants. The present study investigates the airflow in the vicinity of a human body, effects of respiration on breathing concentration of particulate and gaseous pollutants, and inhalation exposure in relation to source position and overall airflow patterns. It is based on experiments with a human simulator in a full-scale environmental chamber. Airflow and pollutant concentrations in the vicinity of a thermal manikin are monitored, while varying parameters including breathing, arm/hand movements, and ventilation system. Results show that breathing of a sedentary manikin has a measurable influence on the airflow in breathing zone, whereas it has very small impacts on occupant thermal plume. Also, localized hand motions have insignificant effects on the thermal plume. The results indicate that overall airflow pattern affect the inhaled particle concentrations. With highly mixed airflow in the space, relatively uniform concentration patterns occur in the occupant vicinity. However, with stratified airflow patterns, non-uniform concentration patterns are observed due to the occupant thermal plume. With a particle source at floor level and in near proximity to an occupant, inhaled particle concentrations are up to four times higher than the ambient concentrations. This finding implies that occupant thermal plume may play a significant role in transporting pollutants from floor level to the breathing zone. The non-uniform concentration observed with stratified flow also suggests caution in estimating inhalation exposure using a "well-mixed" mass balance model.

1. Introduction

Previous exposure studies found that concentration measurements at a reference location in a room may not be representative for indoor inhalation exposure [1–3]. These studies have demonstrated that the actual inhaled concentrations of pollutants can be considerably different from the concentrations measured by a stationary indoor monitor. This discrepancy is mainly due to non-uniform distributions of pollutant concentrations in occupied spaces. Previous studies [4–6] showed that the non-uniform distribution of pollutants in the vicinity of an occupant is caused by a thermal plume around a human body, occupant movement and breathing, and the overall airflow pattern in a space.

A thermal plume generated by heat from a human body affects airflow and pollutant concentrations in the vicinity of the occupant. Bjørn and Nielsen [5] and Johnson et al [7] found that buoyant upward flow in the vicinity of an occupant affects pollutant dispersion in breathing zone. The effect of the buoyant thermal plume becomes significant in a space with little or no air mixing, such as a space in which a mechanical ventilation system is not operating or a room with displacement ventilation [8,9].

Occupant activity also affects the local airflow and pollutant concentration in the breathing zone. Welling et al [10] indicated that arm movement influences dispersion of pollutants in the breathing zone and thus should be included in exposure analysis. Bjørn and Nielsen [5] investigated the influence of physical movements of a breathing manikin in a room with displacement ventilation and reported that a larger degree of air mixing occurred in the room with the moving manikin than with the stationary one. Furthermore, the effect of human respiration on local airflow should be considered when studying pollutant transport between occupants and the amount of re-inhaled air after exhalation [4]. Breathing also influences local temperature, airflow and gaseous pollutant concentration in the breathing zone [4,5].

The overall airflow pattern is often responsible for a non-uniform distribution of pollutant concentration in a space [11–13]. Distribution of supply (fresh) air in a space determines airflow patterns and spatial contaminant distribution. Most of the flow patterns in building environments can be characterized as mixing or stratified flow. In a space with mixing flow, air is supplied with

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a large momentum, causing significant air mixing throughout the space. A mixing flow pattern typically exists in an office building where the ventilation supply diffusers provide sufficient and uniform air mixing. However, in a space with temperature stratification, cooler and heavier air is at floor level and is moved upward by buoyancy from heat sources in the space. In some cases strong buoyancy forces can create significant mixing in the space. However, in most buoyancy-driven flows, often present in a room with displacement ventilation or a residential space where mechanical ventilation is not operating, mixing of air is less intensive and pollutant concentration is less uniform than a room with mechanical ventilation.

Different ventilation systems can increase or decrease occupant exposure to airborne pollutants. Lin et al [14] compared mixing and displacement ventilations by measuring carbon monoxide, VOCs, and mean age-of-air in offices, industrial workshops and public places. They concluded that displacement ventilation provides better indoor air quality than mixing ventilation. Qian et al [15] studied infectious droplet nuclei and bacteria in a hospital environment with either mixing or displacement ventilation and reported higher infection risks in the room with displacement ventilation. In addition, Gao and Niu [16] conducted a numerical study to examine inhaled particle concentrations with three different ventilation systems: mixing ventilation (MV), displacement ventilation (DV) and under-floor air distribution (UFAD). They found that the human exposure to particles from 1 to 10 μm from the supply inlet is generally lower with MV and higher with UFAD.

These previous studies provide valuable information on the relationship between local airflow around a human body and pollutant concentrations in the breathing zone. However, most of the previous studies have focused on the transport of gaseous pollutants. To our knowledge, there is lack of studies that show how particulate pollutants distribute in the micro-environment surrounding a human body depending on breathing, source position and ventilation system. For example, Melikov and Kaczmarczyk [4] provided valuable experimental study about unsteady airflow field in vicinity of mouth and quantified concentration of re-inhaled gaseous pollutants; however, no reported study has determined the effect of breathing on inhaled particle concentration.

The objectives of the proposed study are to (1) investigate the airflow in the vicinity of a human body depending on occupant activity, breathing and ventilation system operation; (2) examine the effect of breathing on inhaled particle concentration; and (3) estimate the level of exposure to gaseous and particulate pollutants in relation to source position and overall airflow pattern, either mixing flow or stratified flow. The unique features of the present study include measurements of airflow and particle concentrations in the vicinity of a breathing thermal manikin under the two distinct indoor airflow patterns.

2. Methods

Two sets of experiments were conducted to identify the following:

(1) parameters that affect the occupant thermal plume;
(2) spatial pollutant concentration in the micro-environment surrounding an occupant in relation to breathing, source location and airflow pattern in a room.

The following sections present the experimental apparatus and methods used for the first and second sets of experiments.

2.1. Experimental apparatus

Experiments were conducted in the Indoor Air Quality Laboratory at the University of Texas at Austin. The experimental set-up, as shown in Fig. 1, was developed to investigate the local airflow and occupant exposure to gaseous and particulate pollutants. The set-up includes a $5.5 \times 4.5 \times 2.7$ m^3 environmental chamber equipped with an air handling unit (AHU), thermal manikin and sampling and measurement apparatus. The AHU controlled the air temperature and humidity in the room and gas and particle concentrations in the supply air. Fig. 1a shows a breathing thermal manikin positioned in the central area of the chamber with a low-momentum air supply diffuser at floor level. The manikin, which has a very similar geometry to a real person as shown in Fig. 1b, has the capability to move its arms and control the surface temperature of each part of its body. The total heat flux across the skin surface was adjusted to 85 W, which corresponds to a sedentary occupant having the manikin's surface area (1.5 m^2) [17]. Also, the manikin's breathing system provided realistic airflow associated with inhalation and exhalation.

Measurement apparatus monitored air velocity and temperature as well as tracer gas and particle concentrations around the manikin, as summarized in Table 1. During the experiments, SF_6 tracer gas was used to represent a non-reactive gaseous pollutant, while 0.03 μm, 0.77 μm, and 3.2 μm particles were used to assess transport of different sized particles. The 0.03 μm particles represented ultrafine particles, which can penetrate deeply into the

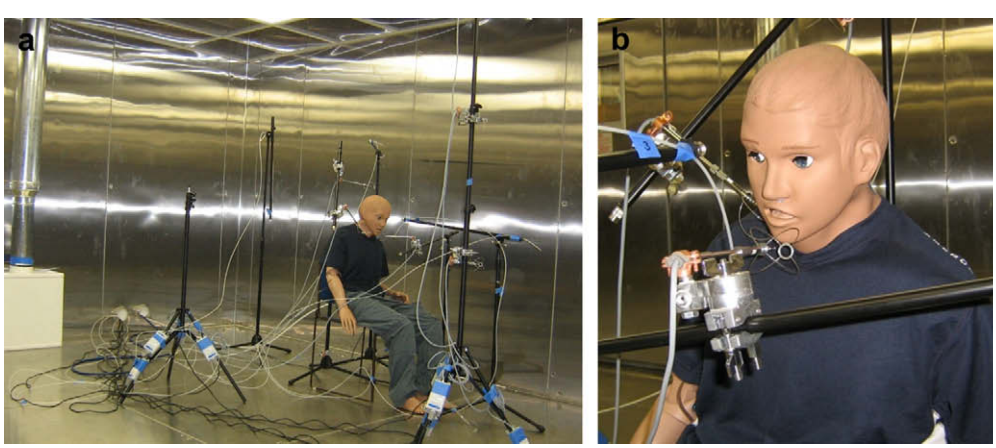

Fig. 1. Experimental setup for measuring airflow, temperature and pollutant concentrations: (a) the chamber with measuring equipments (b) thermal manikin in the chamber.

Table 1
Overview of monitoring devices.

Measurement	Analytical Method	Accuracy (±) and Detection Limit	Logging Interval
Air velocity	Hot-wire Anemometer	±0.02 m/s	0.01 s
Sulfur Hexafluoride (SF_6)	Electron Capture Detector/Gas Chromatograph	±5%	2 min
Temperature	Thermistors	±0.2 °C	30 s
Ultrafine PM (0.03 μm)	Condensation Particle Counter	1/cm^3	10 s
Fine PM (0.77 μm)			
Coarse Mode PM (3.2 μm)	Optical Particle Counter	1/m^3	30 s

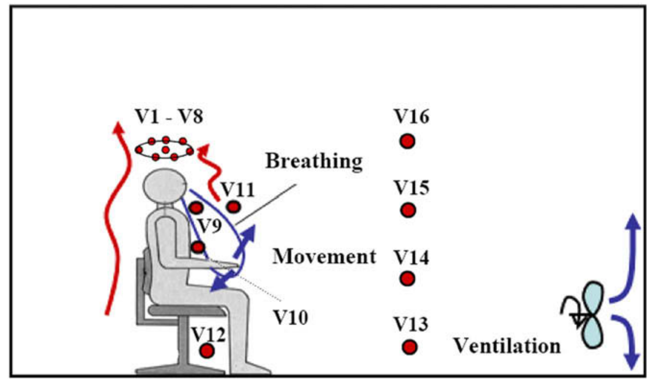

Fig. 2. Velocity monitoring points to examine the effects of breathing, movement and ventilation on the thermal plume.

lungs and blood vessels, causing respiratory and cardiovascular diseases [18,19]. Examples of ultrafine particles are the particles from vehicle exhaust that penetrate to the indoor environment and particles generated from gas stoves. The 0.77 μm particles fall in the fine particle range, which spans 0.1–2.0 μm in diameter. These particles are known to be unlikely to deposit on indoor surfaces, typical residential air filters, or the upper respiratory region [20,21]. An example of fine particles is particles generated in tobacco smoke. The 3.2 μm particles represent coarse mode particles. These particles have large settling velocities and easily resuspend from floor surfaces [22]. Resuspended particles may contain indoor allergens or pollen and can trigger respiratory and allergic symptoms among occupants [23,24]. Using different particle sizes, the similarities and differences in dynamics of ultrafine, fine and coarse particles were investigated.

2.2. Measurements of occupant thermal plume

The first set of experiments was designed to investigate the intensity of the occupant thermal plume associated with breathing, occupant movement and fan operation. To investigate the effect of the thermal plume rising from the manikin, air was supplied with a low-momentum by a displacement ventilation diffuser. The perforated diffuser supply side (with dimensions of 0.53 m × 0.53 m) contained 3200 circular openings with a diameter of 3 mm. The effective surface area of the diffuser was 0.0225 m^2, which was 8% of the diffuser supply side. The velocity measured directly at the small openings at various locations ranged from 2.0 to 2.3 m/s with higher values in the upper part of the diffuser. The turbulence intensity ranged from 10 to 15%. Because of the small effective diffuser surface area, the initial air velocity decreased dramatically, reducing the diffuser jet momentum. Air speed measured 0.05 m away from the diffuser (at a height of 0.20 m) decreased to 0.15 m/s. The supply air temperature was 18 °C, and the only heat source in the chamber was the thermal manikin. The temperature at the exhaust was 1.3 °C higher than the supply air temperature and the air was thermally stratified in the vertical direction.

The airflow velocity was then measured at 16 positions inside and outside the boundary layer of the manikin's thermal plume, as shown in Fig. 2. The airflow velocity measurements at V1–V8 covered a circular area of 0.25 m above the head with a diameter of approximately 0.25 m (Fig. 2). The average of velocities at the 8 positions (V1–V8) above the head was selected to represent the upward thermal plume because the velocity intensity inside the thermal plume was the largest in this region. This area-averaged measurement (V1–V8 in Fig. 2) was conducted to avoid inaccuracy due to the steep velocity gradient of the thermal plume which can be deflected by the human activity or room airflow. By observing the changes in the averaged velocity in the circular area above the head, the effects of (1) breathing, (2) occupant movement, and (3) mechanical ventilation on the thermal plume were analyzed.

The *breathing* of the manikin consisted of consecutive 2-s inhalation and exhalation periods through the nose with a short pause of half-second between them. The frequency and flow rate of the breathing were adjusted to those of a typical sitting adult. The number of exhalations was 12 per min (with the same number of inhalations) and the flow rate was adjusted to provide an exhalation jet with the maximum velocity of 0.60 m/s at a distance of 4 cm from the nose, which is similar to that of a real occupant. The velocities at the monitoring points were measured during two phases of breathing operation: breathing ON and breathing OFF.

Large and small hand motions of the manikin simulated the activity of a sitting person in typical indoor environments. The large motion was a periodic rotation of the entire arms back and forth within ±30°, whereas the small motion was a periodic up-and-down rotation of the elbow within ±10°. The large motion represents active hand movements such as filing activity; the small motion indicates limited hand movements such as typing. During the hand movements, velocity sensors recorded the disturbances of the thermal plume by measuring velocities at characteristic points.

The effect of *mechanical ventilation* on the manikin's thermal plume was examined using two ventilation fan operation modes: fan ON and fan OFF. The power and position of the fan were adjusted to provide forced convection flow, which is typical for a space with mixing ceiling diffusers. The average air speed in the central spaces ranged from 0.15 to 0.25 m/s with the fan ON, while the air in the bulk flow region (1.5 m away from the manikin) was stagnant (lower than 0.06 m/s) when the fan was OFF. The fan operation was intermittent with several minutes of ON and OFF periods. This periodic schedule is typical for operation of a residential air-conditioning system and provides information on the dynamics of airflow in a space with intermittent operation of the ventilation system.

2.3. Measurements of pollutant concentrations

The second set of experiments was designed to examine occupant exposure to pollutants in relation to breathing, source location and overall airflow pattern. Fig. 3 illustrates the five monitoring positions at which the SF_6 gas and particle concentrations were monitored. Sampling position 1 (S1) was 0.25 m above the head. Sampling position 2 (S2) was in front of the mouth at a distance of 0.05 m. The sampling locations were based on a previous study concluding that the inhaled air concentration can be accurately measured only if the sampling tube is located within 0.15 m of the

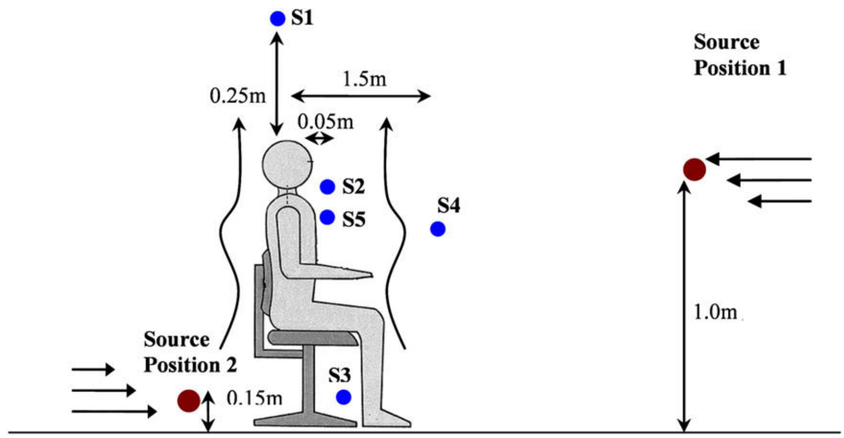

Fig. 3. Positions of pollutant sources (Source Position 1 and Source Position 2) and air sampling points (S1, S2, S3, and S4) in the vicinity of the manikin.

front of the face of the manikin at its upper lip [4]. Sampling position 3 (S3) was 0.2 m above the floor close to the legs. Sampling position 4 (S4) was located 1.5 m from the right side of the manikin to measure the concentration in ambient bulk air region. Sampling position 5 (S5) was in front of the chest at a distance of 0.03 m. At every sampling point, the air samples were simultaneously collected and then analyzed. The measurements at S5 (chest) are not reported, as will be shown in later sections, given that the differences in the observed concentrations between S2 (mouth) and S5 (chest) were maximum 6%.

The SF_6 and particle concentrations were measured using two source positions in Fig. 3. Source Position 1 was placed 1.6 m in front of the manikin face to simulate pollutant moving toward an occupant, such as air approaching an occupant after someone sneezed. On the other hand, Source Position 2 was located 0.5 m behind the manikin and 0.15 m above the floor to simulate particle resuspension from the floor. Fig. 3 also shows the overall direction of air movement with respect to the manikin and the two sources. At the two source positions, SF_6 gas and each of the three sizes of particles were injected. The SF_6 source had a constant emission rate of 10 mL/min of 0.1% SF_6. The sources of 0.03 μm, 0.77 μm, and 3.2 μm particles, which were mixtures of water, alcohol and particles, had particle concentrations of 7.0×10^{12}/mL, 8.0×10^7/mL and 2.0×10^5/mL, respectively. Each set of mono-disperse particles had a density of 1.05 g/cm^3. The mono-disperse particles were separately seeded using a Collison Nebulizer with a seeding flow rate of approximately 18 mL/s. The average face velocity of the liquid/gas jet measured using a low velocity hot-wire anemometer was 0.15 m/s and the jet head reached approximately 0.25 m in front of the injection point. The particle sources created concentrations several orders higher in the space than initial background concentrations, thereby reducing the measurement inaccuracy caused by the background concentration.

2.3.1. *Effect of breathing on occupant exposure*

Using the experimental set-up presented in Fig. 3, the effect of breathing on inhaled concentrations of 0.77 μm and 3.2 μm particles were measured with the following procedure. Steady-state thermal-fluid condition was achieved and then the particles were injected separately at each of the two source locations: Source Position 1 and Source Position 2 (Fig. 3). The Collison Nebulizer provided steady-state particle emission, and after particle concentration in the space is stabilized, particle concentrations in air samples were monitored for 20 min without any breathing activity. Afterwards, the breathing mechanism was activated and the particle concentrations were monitored for another period of 20 min. For both particle sizes, the experiments were repeated 3–5 times until consistent concentration patterns were observed.

2.3.2. *Overall airflow pattern and pollutant concentrations*

Using the breathing thermal manikin, experiments were repeated with two different airflow regimes: mixing flow and stratified flow. The mixing flow and stratified flow were simulated by positioning air supply at ceiling and floor level, respectively. A circular wall opening with a diameter of 0.2 m at the ceiling level supplied the air with an average discharge velocity of 2.7 m/s. Due to the flow profile in the duct, the face velocity at the opening was non-uniform. The elbow of the supply duct generated the maximum velocity of 5.0 m/s at a position 0.05 m from the bottom side of the opening. The turbulent intensity measured at the opening was approximately 10%. This strong momentum of the supply jet produced a mixed convective flow, and an air exchange rate typical for office environments (4.5 h^{-1}). In this condition, the airflow velocity magnitude in the central area of the chamber including the manikin's vicinity ranged from 0.12 to 0.28 m/s. In the case with stratified flow, the previously described low-momentum jet from a displacement ventilation diffuser generated stratified flow and the air exchange rate of the room was 3 h^{-1}. In this case, the mean air speed in the vicinity of the manikin ranged from 0.05 to 0.25 m/s due to the thermal plume around the manikin, whereas the air speed was less than 0.06 m/s in the bulk flow region. In both cases, fresh air was supplied to the space without air recirculation.

The monitored SF_6 and particle concentrations were integrated over the measurement period to exclude the bias from the instantaneous effects of turbulent eddies caused by the manikin's thermal plume and breathing jets. The time-integrated concentrations were normalized by the concentration at reference point S1 (above the head), given the more consistent particle concentration pattern compared to other sampling locations. The ratio of standard deviation to mean of the measurements at S1 was approximately 10% for the different source positions and ventilation systems, which was smaller than those at other sampling points. The goal of the normalization was to quantitatively determine the concentration pattern in the vicinity of an occupant on relative basis. The errors due to measurement and normalization were estimated using the average and standard deviation of the observed concentrations in repetitive tests, which were conducted under identical thermo-fluid conditions. In conjunction with the experiments, detailed directions of airflow and pollutant transport from a source were analyzed with Computational Fluid Dynamics (CFD) simulation. CFD software FLUENT [25] was used to analyze the causes of non-uniform pollutant concentrations measured in experiments. To simulate accurately the effect of the manikin's thermal plume, convective and radiative portions of the manikin heat flux (totaling 85 W) were calculated based on the surface emissivity and temperatures of the manikin and walls. The convective flux of 45 W was equally distributed across the surfaces of the manikin, and the radiative portion of 40 W was distributed along the chamber surfaces. To provide accurate boundary conditions for particle dynamics modeling, the measured particle jet from the Collison Nebulizer (0.15 m/s) was integrated into the boundary conditions of particle tracking models. The particle trajectories were determined based on the airflow field and by solving particle momentum equations. Numerical parameters such as grid size and number of particles are based on recommendations for particle modeling in indoor environment [12].

3. Results and discussion

The following sections provide results on (1) sensitivity analysis of thermal plume, (2) effect of breathing on inhaled particle concentration, and (3) occupant exposure with different ventilation flow patterns and pollutant source positions.

3.1. Thermal plume sensitivity analysis

This section presents the analysis of the first set of experiments. Fig. 4 shows the velocity profiles measured at the characteristic points with the three parameters: breathing, arm/hand movements and mechanical fan operation.

Fig. 4a shows the *effect of breathing* on velocity profiles observed above the head (average of V1–V8) and breathing zone (V9) during the two phases of breathing operation: breathing on and breathing off. Fig. 4a indicates that the breathing jets directly affect the airflow in the breathing zone and in the region above the head, although the effect of the breathing jets is more significant in the former than the latter. During the breathing activation, the airflow velocity at breathing zone (V9) dramatically increases, whereas the change in the mean velocity above the head (average of V1–V8) is negligible. Regardless of the breathing, periodic oscillation in the velocity profile above the head exists, indicating that the thermal plume generates turbulent fluctuation of airflow and influences the air velocity above the head. The average airflow velocity above the head was around 0.20 m/s with breathing and 0.21 m/s without breathing. This implies that the breathing jet of a sedentary person does not significantly affect the buoyant thermal plume.

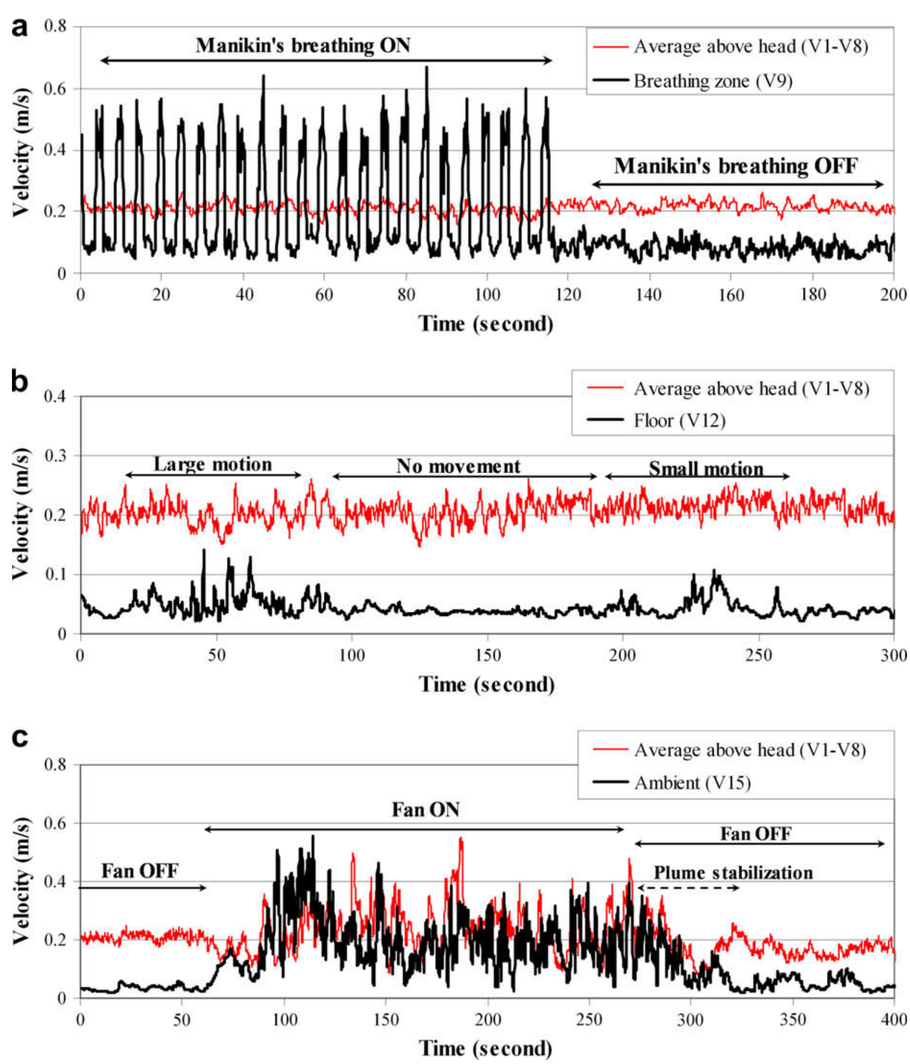

Fig. 4. Velocity profiles at characteristic sampling points with changing parameters: breathing, hand movement and mechanical fan operation: (a) velocity profiles at two sampling points (25 cm above the head and 5 cm in front of the mouth) with and without breathing, (b) velocity profiles at two sampling points (10 cm above the floor and 25 cm above the head) with three different activity modes: no movement, large motion and small motion and (c) velocity profiles at two sampling points (25 cm above the head and room corner) with two fan operation modes: fan ON and fan OFF.

Fig. 4b illustrates the *effect of occupant movement*. The velocity profiles above the head (V1–V8) and 20 cm above the floor (V12) were observed along three different activity modes: no movement, large motion, and small motion. Fig. 4b shows that the velocity at V12 (20 cm above the floor) is significantly affected by physical activity of the manikin. Conversely, the effect of the physical activity on the average velocity above the head appears to be small, given the minor change in the average velocity profile above the head (V1–V8) with the large motion. This result indicates that localized hands motion of a sitting person does not have a large influence on the upward thermal plume. The effect of the occupant's localized motion on the thermal plume appears to be relatively small compared to the effect of a moving person. Bjørn and Nielsen [5] indicated that a moving person walking by a seated person creates strong air movements due to the wake behind the walking person. These air movements are enough to destroy the thermal plume around a seated person.

Fig. 4c represents the *effect of mechanical ventilation*. Fig. 4c shows the velocity profiles above the head (V1–V8) and at an ambient location (V15) with the two fan operation modes: fan ON and fan OFF. When the fan is OFF, the airflow velocity at the ambient location (V15) is negligibly small, indicating that the airflow in the bulk flow region is not affected by the occupant thermal plume. The monitoring point V15 (ambient region) was located at the distance of approximately 60 cm from the manikin. This is consistent with the review of Gao and Niu [26] that the thermal boundary layer around a manikin surface was about 5 cm thick at foot level and 19 cm deep around the neck. When the fan is OFF, the average velocity above the head (thermal plume) and at V15 (ambient stagnation zone) are 0.20 m/s and 0.05 m/s, respectively. After the ventilation fan is ON, the difference between airflow velocities above the head and at the ambient location decreases, as shown in Fig. 4c. It appears that following the activation of the ventilation fan, a significant air mixing occurs and the mixing flow disrupts the thermal plume. Fig. 4c also shows that the duration of the transient period between the two operation modes (fan ON and fan OFF) is approximately 1 min. This short transition time implies that the airflow around an occupant in building environments is either mixing flow or stratified flow depending on the fan operation [27].

The results of the first set of experiments show that breathing has a measurable influence on the airflow in the breathing zone whereas it has very small impacts on the occupant thermal plume. The disruption of the upward thermal plume due to localized hand motion is negligible. The results also show that operation of a ventilation fan generates mixing airflow, causing fairly uniform air velocity distribution in the space. Based on these results, the following sections focus on the effects of breathing and overall airflow pattern in a room on inhaled air quality.

3.2. Effect of breathing on inhaled particle concentration

Fig. 5 shows the particle number concentrations measured at S1 (0.25 m above the head) and S2 (mouth), with and without breathing mechanism. Fig. 5a and b (0.77 μm particles) present the same information as Fig. 5c and d (3.2 μm particles) except the different sampling frequencies due to the different measurement techniques. The results on Fig. 5 indicate that the breathing affects particle concentrations above the head and at the mouth. The change in particle concentration associated with breathing activity varies with source position and particle size. For example, after the breathing activation, the particle concentrations in the breathing zone decreased with the source at Source Position 1, whereas they increased with Source Position 2. The changes in particle concentrations after the breathing activation are approximately 30% for 3.2 μm particles and 15% for 0.77 μm particles. Consequently, effect of breathing is likely more important for evaluating exposure to larger particles. The study by Melikov and Kaczmarczyk [4] also

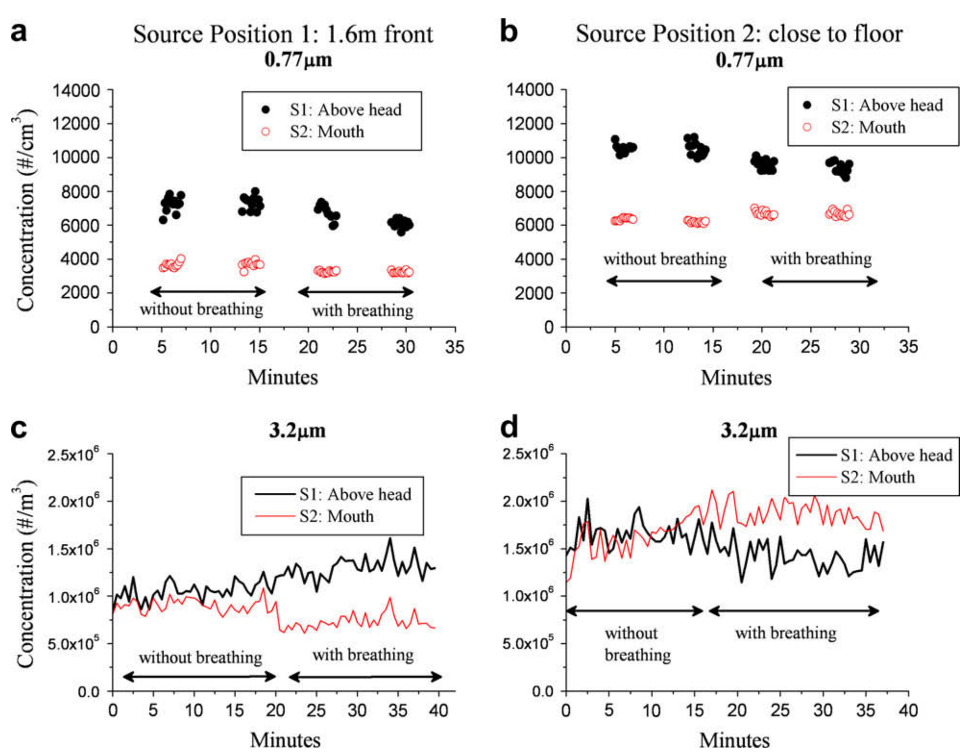

Fig. 5. Concentrations of 0.77 μm (a, b) and 3.2 μm (c, d) particles with and without breathing with two source positions: Source Position 1 (1.6 m in front of the head) and Source Position 2 (0.15 m above the floor and 0.5 m behind the manikin).

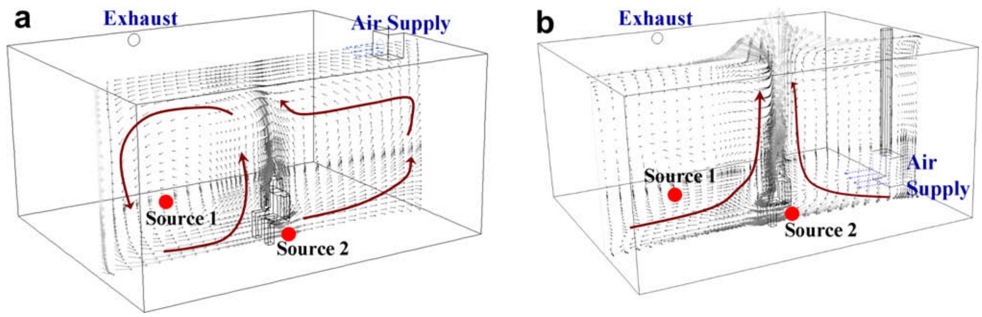

Fig. 6. Room airflow distribution simulated with forced-convection air supply at ceiling level (a) and low-momentum air supply at floor level (b).

reported that breathing is correlated with the temperature and gas concentrations in spaces with mixing or displacement ventilation. The study also recommended proper simulation of breathing in assessing perceived inhaled air quality. Our study found the notable changes in particle concentrations after the breathing activation. Considering the results of our study and the study conducted by Melikov and Kaczmarczyk [4], the experiments in the following section measured occupant exposure to gas and particles with the manikin's breathing.

3.3. Pollutant concentration patterns associated with airflow and source position

Fig. 6 provides CFD results that illustrate the airflow distribution in the test chamber during the experiments with the two studied airflow patterns. Fig. 6a presents air mixing that occurs with forced-convection air supply at the ceiling level, while Fig. 6b shows stratified flow developed with low-momentum air supply at the floor level. The following section presents concentration distributions of SF_6 gas and particles in the vicinity of a breathing thermal manikin with the two airflow patterns in Fig. 6.

3.3.1. Mixing flow regime

Fig. 7 illustrates the SF_6 and particle concentrations measured at four sampling positions including S1 (head), S2 (mouth), S3 (feet), and S4 (bulk air region) with the breathing thermal manikin under a mixing flow regime. As shown in Fig. 6, the concentrations were measured with two source locations: Source Position 1 (1.6 m in front of the face) and Source Position 2 (0.15 m above the floor and 0.5 m behind the occupant). Fig. 7a and b illustrate the SF_6

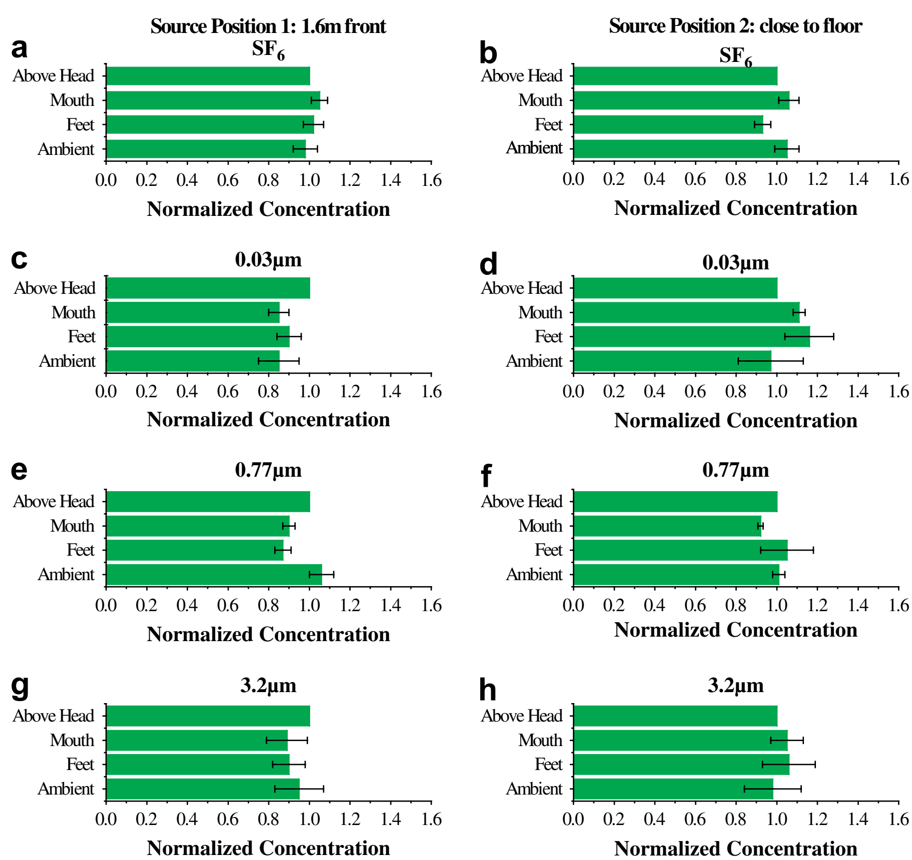

Fig. 7. Concentration of SF_6 gas, and 0.03 µm, 0.77 µm and 3.2 µm particles around a breathing thermal manikin observed with Source Position 1 (a, c, e, and g) and Source Position 2 (b, d, f, and h) using steady source emissions under mixing ventilation.

concentrations observed with the source located at Source Position 1 and Source Position 2, respectively. Fig. 7a and b show that the SF_6 concentrations at all the sampling points in the manikin's vicinity are similar to the ambient concentration, regardless of the source location. This trend can be explained by the fact that the highly mixed convection flow produces relatively uniform gaseous concentration in the space. It seems that the forced convection flow disrupts the manikin's thermal plume and in this case the effect of the buoyant airflow on transport mechanism is negligible.

Fig. 7 (diagrams: c, d, e, f, g, h) presents concentrations of 0.03 μm, 0.77 μm, and 3.2 μm particles in the vicinity of the manikin with mixing airflow in the space. Results indicate that the particle concentrations in the vicinity of the manikin are generally similar to the ambient concentration. The difference between the inhaled particle concentration and ambient concentration is less than 10% for all measured particles. In addition, the source location and particle size make insignificant differences in particle concentration.

Overall, the results in Fig. 7 demonstrate that under the mixing flow regime relatively uniform concentration patterns of gaseous and particulate pollutants occur in the occupant vicinity. This result implies that it is reasonable to apply "well-mixed" mass balance model to evaluate inhalation exposure in environments in which intensive air mixing by forced convection flow is dominant.

Note that the intensity of mixing depends on the airflow rate and the locations of the supply diffuser and exhaust. Thus, a space with a low airflow rate might have a non-uniform concentration pattern in the occupant vicinity. Future studies should also examine the effects of low airflow rate and positions of supply diffusers in measuring breathing concentrations.

3.3.2. Stratified flow regime

Due to the non-uniform pollutant concentrations in the space with stratified flow, concentrations in the vicinity of the occupant depend on source position and air distribution in the space. Fig. 8 presents CFD simulation results provided to show pollutant flow pattern and support the experimental results. Fig. 8 shows detailed directions of particulate pollutant transport with stratified flow for the two setups used in the test chamber experiments. The results illustrate transport of 0.77 μm particles from the two source positions with respect to the manikin. Fig. 8a shows that when the source is at Source Position 1 (1.6 m in front of the face), pollutants are moved toward to the manikin face by the overall airflow. Fig. 8b also illustrates pollutants transported into the vicinity of the manikin by the occupant thermal plume with the source at Source Position 2 (15 cm above the floor and 0.5 m behind occupant). The general transport directions with respect to the manikin are similar for SF_6 gas and the three sizes of particles, even though the differences in diffusion exist among these pollutants.

Using the results from CFD analysis on general direction of pollutant transport around the manikin, the experimental results were analyzed along with the pollutant transport mechanism. The paragraphs below explain the non-uniform pollutant distributions presented in Fig. 9. They discuss the pollutant distribution in the vicinity of the manikin with the two characteristic source positions: the pollutant approaching the manikin's face (*Source Position* 1) and the pollutant released in proximity to the manikin's legs (*Source Position 2*).

Fig. 9a, c, e and g illustrate the effect of the thermal plume on pollutant transport when the source is located at *Source Position 1* (1.6 m in front of the occupant's face). Fig. 9a suggests that when SF_6 gas approaches the occupant's face, concentration is relatively high above the head and in the ambient region, compared to near the mouth and feet. The tracer gas was moved toward the occupant's face by overall airflow, trapped by the manikin's thermal plume and then driven to upper region, causing a high concentration above the head (Fig. 9a). It seems that the occupant thermal plume provides a protective air layer, keeping the SF_6 gas from moving inside the thermal boundary layer and resulting in lower SF_6 concentration in breathing zone than ambient air. This illustration also helps understand the results of particle distribution around the human body for these two sources. Fig. 9c and e show that the inhaled concentrations of 0.03 μm and 0.77 μm particles are 30–50% lower than the ambient concentrations. This concentration pattern also suggests that the manikin's thermal plume reduces the occupant exposure to 0.03 μm and 0.77 μm particles by generating a protective air layer. The concentration patterns of 0.03 μm and 0.77 μm particles in the vicinity of the manikin appear to be similar to that of SF_6 gas, even though ambient concentration is larger for 0.03 μm particles than 0.77 μm particles. This trend may be due to the turbulent diffusive transport to the ambient region that is more effective for 0.03 μm particles than 0.77 μm particles. Fig. 9g shows that the normalized concentration of 3.2 μm particles is the lowest at the mouth, approximately 20% lower than the ambient concentration. The increased concentration of 3.2 μm particles observed at the floor level is likely due to relatively large settling velocity of 3.2 μm particles.

The measured data for SF_6 and the three sizes of particles consistently show that the inhaled concentration is lower than the ambient concentration with the source at *Source Position 1.* These results suggest that when a pollutant is moving toward the occupant's face in stratified flow the occupant thermal plume plays a significant role in preventing pollutant transport into the breathing zone. This effect remains consistent even after taking into account the small disruption of the thermal plume due to the manikin's breathing. Similarly, Gao and Niu [26] stated that the occupant thermal plume may have a positive effect on inhaled air quality as long as the plume is not broken by other invading flow.

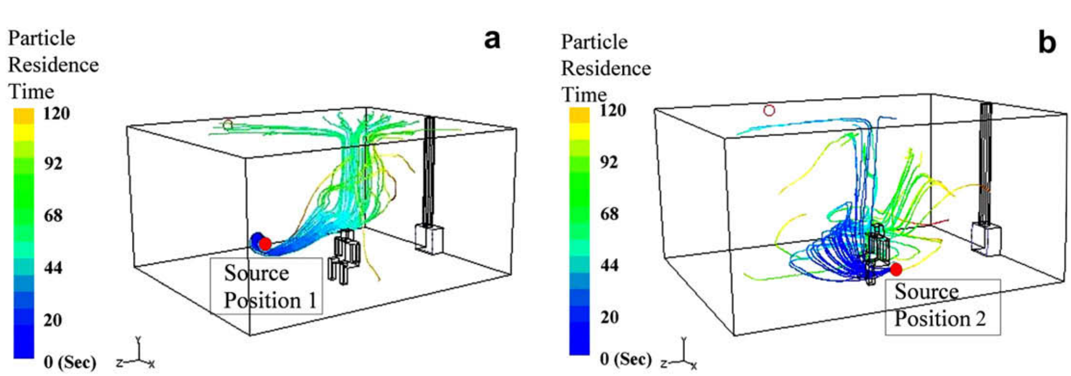

Fig. 8. Trajectory and residence time of 0.77 μm particles in stratified flow with the source at two positions: (a) transport from Source Position 1 and (b) transport from Source Position 2.

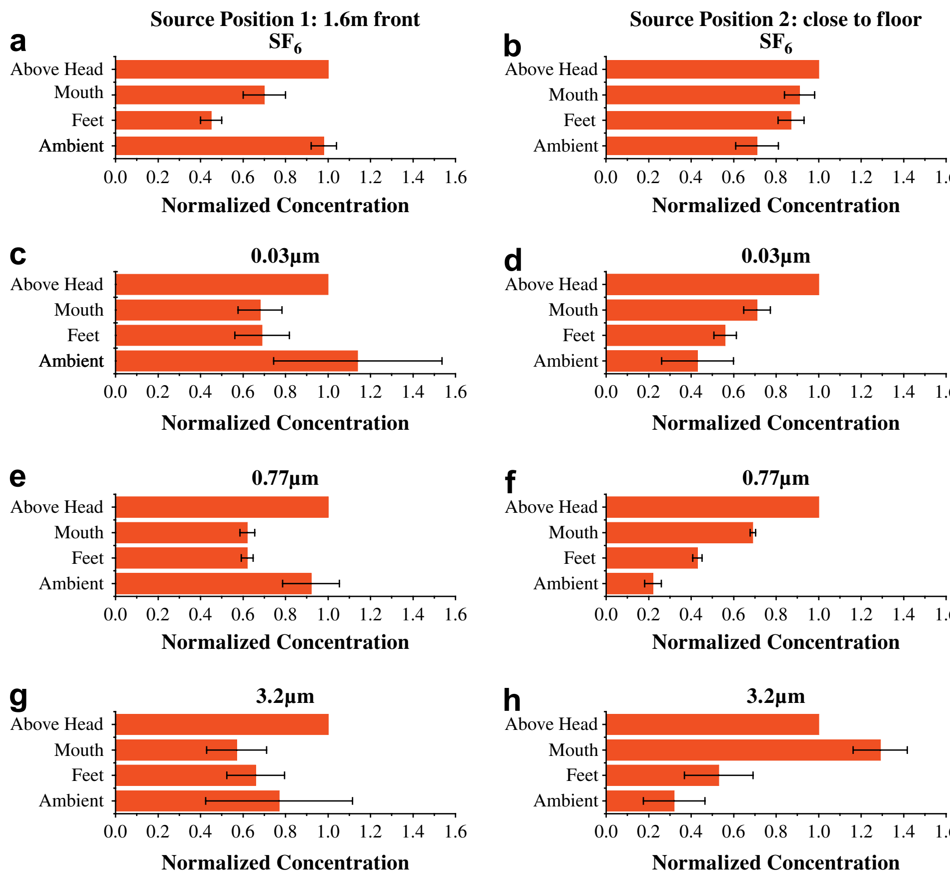

Fig. 9. Concentration of SF6 gas and 0.03 µm, 0.77 µm and 3.2 µm particles around a breathing thermal manikin observed with Source Position 1 (a, c, e, and g) and Source Position 2 (b, d, f, and h) using a steady source emission under a natural convection flow regime.

Both, this investigation and the paper of Gao agree on the beneficial role of the buoyant thermal plume in reducing exposure to pollutants released at breathing plane in the space.

Fig. 9b, d, f and h present concentration patterns in the manikin's vicinity observed with the source at *Source Position 2*. Fig. 9b shows that the SF_6 concentration in the manikin's vicinity increases with height. This pattern is due to the thermal plume, which transports the SF_6 gas to the upper region of the occupant's vicinity. The SF_6 concentration at the mouth is approximately 20% higher than the ambient concentration. Fig. 9d and f illustrate the normalized concentration of 0.03 µm and 0.74 µm particles. The concentration patterns of these particles are similar to that of SF_6 tracer gas, showing increased concentration with height and higher concentration in the occupant's vicinity than on the ambient region. This trend suggests that 0.03 µm and 0.74 µm particles behave similarly to SF_6 tracer gas. However, the increase in concentration with height is more apparent for particles than for SF_6. This difference may be due to the diffusivity of gas being larger than the particles. In case of the particles, the convective thermal plume, which gradually develops in the vertical direction, seems to be dominant over diffusion, being a primary particle transport medium in the manikin's vicinity. Therefore, the upward drag force caused by the thermal plume is likely the most effective force exerted on the 0.03 µm and 0.74 µm particles. Fig. 9 h shows that for 3.2 µm particles, the concentration is the highest at the mouth, at approximately four times the ambient concentration. In this case, the gravitational force exerted on the particles is larger than that exerted on the 0.03 µm and 0.74 µm particles. This effect seems to cause the longer residence time of 3.2 µm particles in the breathing zone of the manikin.

The results with the source at *Source Position 2* show that when the source exists close to an occupant at floor level, such as with particle resuspension, larger inhaled concentrations of gaseous and particulate pollutants compared to ambient concentration occur. This finding complements the studies by Ferro et al [1] and McBride et al [2] which report the source proximity effect. Both of these papers reported that particles resuspended from human activity contribute to the "personal cloud" effect and significantly increase personal exposure by up to several orders of magnitude. The results from this study imply that occupant thermal plume transports pollutants from floor level to the occupant's vicinity, resulting in increased inhalation exposure.

In this investigation, the difference between inhaled concentrations and ambient concentrations is larger for particles than gases. Among the tested particles, the highest inhalation exposure compared to ambient level was observed for the coarse particles (3.2 µm). The coarse particles are most likely to be resuspended by human activity, such as walking and vacuuming. Therefore, it seems reasonable to conclude that thermal plume is one of major contributors to inhalation exposure to resuspended particles in a space with stratified flow.

It should be noted that this study is different from the previous studies that investigated particle deposition rate on indoor surfaces in a ventilated room [16,28]. This study mainly focused the particle concentrations in the micro-environment surrounding a breathing thermal manikin and evaluated an actual inhaled concentration relative to ambient concentration in the bulk air region. However, one limitation of the present study is the measurement of concentrations at single points. Although the single point measurements give valuable information on pollutant transport around an occupant, it is hard to draw a general conclusion about the percent change in an occupant's breathing concentration. Future studies should also include volume-averaged or area-averaged concentration measurements, which can provide more useful information than single point measurements. The results of ambient and inhaled concentrations obtained from this study imply that airflow distribution and source location are important parameters for estimating occupant exposure. Further study should investigate correlation between inhalation exposure and indoor air quality parameters including mixing efficiency or air-change effectiveness. This correlation will help to use representative indoor air quality factors in studies that promote healthy environments in building design phase.

4. Conclusions

This study examines the influences of occupant breathing, movement and mechanical fan operation on the local airflow in the vicinity of an occupant. Breathing has a measurable influence on the airflow in occupant breathing zone. Localized hand motion of a sitting manikin does not disrupt significantly the upward thermal plume. Depending on mechanical fan operation, overall airflow in an occupied space is mainly either mixed convection flow or stratified flow.

Considering the pollutant concentrations at the two characteristic points in the vicinity of a seating thermal manikin (in front of the mouth and at the chest), this study shows that breathing can significantly affect inhaled particle concentrations, even though the influence varies with source position and particle size. Relatively uniform concentration patterns of gaseous and particulate pollutants occur in the vicinity of the occupant in an environment with mixing flow, while non-uniform concentration distributions are present with stratified flow. For example, larger inhaled concentrations than the ambient concentration occur when the source is close to an occupant at floor level. In this condition, the upward thermal plume plays a significant role in transporting pollutants from floor level to the breathing zone, increasing the occupant exposure. This finding implies that the occupant thermal plume is important in transporting resuspended particles, such as indoor allergens, to the breathing zone in stratified flow. Specifically, coarse mode particles showed the highest inhaled concentration, which is up to four times lager than the ambient level. In addition, the non-uniform concentration with stratified flow also implies that applying well-mixed mass balance models to environments where stratified flow is dominant may lead to inaccurate estimations of inhalation exposure.

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