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TRANSPORT OF GASEOUS POLLUTANTS AROUND A HUMAN BODY IN QUIESCENT INDOOR ENVIRONMENT

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Abstract

"Well-mixed" assumption often leads to inadequate prediction of the human exposure. In spaces that operate with a low air velocity, local airflows generated by occupants play predominant role for pollutant transport. The present study investigates the ability of a human convective boundary layer (CBL) to transport the pollution in quiescent indoor environment. A human body is resembled by a thermal manikin with a body shape and surface temperature distribution of a real person. The objective of the study is to examine the impact of the pollutant location around the human body on the pollution concentration levels in the breathing zone. The results show that the location of the pollution source has a considerable influence of the breathing zone concentrations. This is contributed to the human CBL, as it pulls the pollution emitted close to the human body and transports it to the breathing zone. For different pollutant location studied, the highest breathing zone concentrations are achieved when the pollution is located at the chest, while there is zero exposure for the pollutants emitted from the upper back or behind the chair. The results suggest that understanding of the air patterns around the human body should be recognized in ventilation design practice.

Keywords: Convective boundary layer, Pollutant location, Thermal Manikin, Personal exposure

1 Introduction

Building occupants are exposed to a wide range of airborne pollutants such as gases and particles that affect human health, comfort and work performance. The transport of these pollutants and human exposure has attained a great importance as occupants in developed countries spend around 90% of their time in artificial environments (Spengler and Sexton, 1983).

A human body generates a metabolic heat that is exchanged with the cooler surrounding air creating a human convective boundary layer (CBL). The CBL accelerates and develops into a human thermal plume above the head after it detaches from the body, as described by several researches (Homma and Yakiyama, 1987; Craven and Settles, 2006; Licina et al. 2014a). The human CBL plays two important roles. The first role is its contribution to the convective heat loss from the human body with 29% of the total body heat loss (Murakami et al. 2000). The second role is the transport of particles around the human body that may be entrained from the ambient air or that may be shed from the skin or clothing.

Human beings shed their entire layer of skin every 2-4 weeks in the process known desquamation. The shedding rate is very large and equivalent to 0.2 – 1 billion of skin cells per day (Roberts and Marks, 1980) which makes them a major contributor of dust on indoor environments occupied by humans. These particles are mostly transported towards the breathing zone by the CBL and subsequently disseminated across the room. Some studies reported that the biggest portion of inhaled polluted air for sedentary person originates from the convective boundary layer around the human body (Melikov, 2004; Zhu et al. 2005).

Apart from the one originating from the human body, pollutants may come from surrounding potentially infectious air that can be entrained by the CBL. Therefore, is in necessary to understand the influence of the pollutant location relative to the occupant because its CBL can transport the pollution to the breathing zone. This is especially the case in rooms with low air mixing because the pollution is non-uniformly distributed with concentrations that substantially differ across the space. Rim and Novoselac (2009) found that in the low mixing environment, pollutants located 0.5 m behind the manikin and 0.15 m above the floor had 4 times higher inhaled concentration than the ambient concentration. Parametric analysis conducted by Rim and Novoselac (2010) showed that the pollution can reach 9.3 times higher concentration in the breathing zone than in case of perfect mixing, when the pollution is released at 0.6 m height and at 0.4 m horizontal distance from the chest.

From the literature review it has been established that the human CBL plays important role in air transport around a human body. The results, however, do not show how different pollutant location affects pollutant distribution in the breathing zone and the personal exposure. The objective of the study is to determine pollutant distribution in the breathing zone and the personal exposure levels in a function of the source pollution location.

2 Methods

Measurements were conducted in a climate chamber with the dimensions of 4.7 m x 6.0 m x 2.5 m. The chamber was well insulted with vinyl sheets covering the inner walls. The chamber was ventilated with a low velocity upward piston flow (100% outdoor air) through the floor which was built of a porous sheet with a steel floor grating placed on the top. Most of the air (85%) was supplied through the floor, while the remaining air was introduced via the space between the wall and the vinyl sheet. This kind of construction ensured the room air temperature to be equal to the mean radiant temperature.

A calibrated non-breathing thermal manikin with female body shape of 1.23 m height in the sitting posture was used to resemble a realistic human body. The manikin was positioned in the center of the chamber and it was dressed in the summer attire (t-shirt, trousers, underwear, socks and shoes) with a total heat output of 65 W/m^2. The room was kept at constant temperature of 23 ˚C. The air was introduced to the room at the low supply velocity to minimally disturb natural convection around the thermal manikin. In addition, a horizontal plate (2.0 m x 1.54 m) was placed below the manikin in a way shown in Figure 1 (left). In this way, air movement in the vicinity of the manikin was induced only due to the manikin's body heat since there was no interference between the supply air and the manikin's convection flow (CBL). The velocity measured (SENSOR omnidirectional thermal anemometers; ±0.02 m/s accuracy) at many locations around the unheated manikin was below 0.05 m/s which indicated that quiescent indoor conditions were achieved (Murakami et al. 2000). A low degree of vertical thermal stratification was recorded (0.07 K/m).

The air was exhausted from the chamber through the reduced area of the perforated ceiling (2.4 m x 2.4 m) placed directly above the manikin. This was done to ensure that the rising thermal plume of the manikin does not spread across the room causing additional air circulation in the room, but to be directly exhausted from the chamber.

A pollution source was simulated by tracer gas Nitrous oxide (N_2O) which was injected through a sponge ball of diameter 0.05 m. The gas was supplied isothermally without initial velocity at eleven different locations shown in Figure 1 (right). All the pollutant locations were aligned with the central vertical axis of the manikin, except P8 that was located in the armpits.

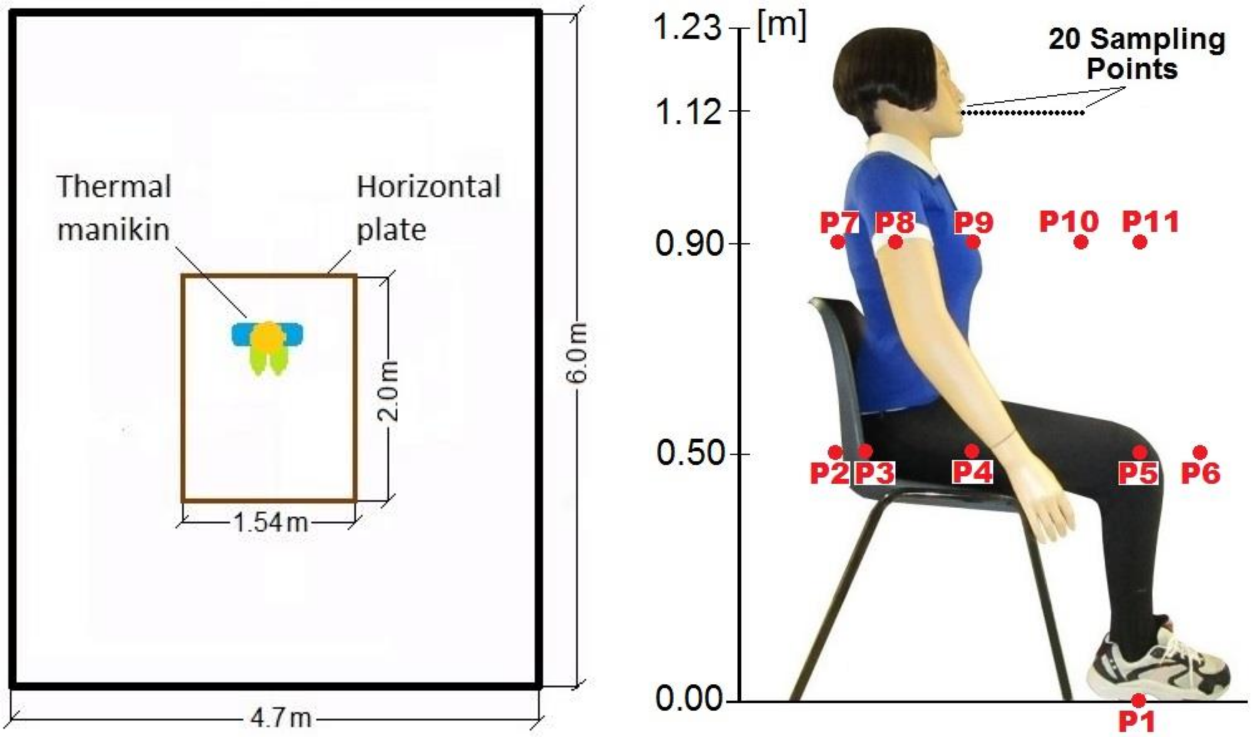

Fig. 1 Top projection of the climate chamber (left) and pollution/sampling location (right).

The tracer gas was simultaneously sampled at 20 locations along the horizontal line in front of the mouth, with a distance between the points 0.03 m (Figure 1, right). The first sampling point was located at the upper lip of the manikin, according to the study performed by Melikov and Kaczmarczyk (2007). The tracer gas was sampled through the sampling tubes and sent to Innova multi-gas sampler and analyzer placed outside the chamber. Total sampling time took three hours which correspond to 45 samples of gas in each point. It was found that 45 samples was a representative number above which variation in the concentration became insignificant (< 5%). A low level of N_2O was found in the supply air due to leakage in ducts which was subsequently deducted from the results to minimize measurement inaccuracy.

3 Results

Figure 2 shows the results of an average pollution concentration distribution in the breathing zone of the thermal manikin for different pollution source locations. Overall, pollution concentration close to the breathing zone (< 100 mm) is notably higher than concentration further from the surface. This decay profile is formed because the human body heat has the ability to pull the pollution towards itself when it is located in a near proximity. As seen, the highest pollutant concentration in the breathing zone is achieved when the source is located in the chest region (P9) peaking at 807 ppm at the mouth (0 mm distance). Moving the pollution source 0.3 m away from the chest (P10) substantially reduced the pollution concentration. In this case, a decay profile was not as steep as when the source originated at the manikin’s body. Moving the pollution additional 0.15 m from the surface (P11) caused more even concentration distribution, as the pollution was more spread within the CBL due to weaker CBL further from the surface. The concentration is the lowest or barely exists for the pollution released at the upper back (P7) or behind the chair (P2). Releasing the pollution at the groins (P4) and the knees (P5) showed a similar concentration profile in the breathing zone that was lower than when the pollution was released at the height of the chest. In general, when the pollution is released from front of the manikin, the concentration is higher for the pollutants released at 0.9 m than when released at 0.5 m. On the other hand, the pollution located at the lower back (P3) causes a higher concentration in the breathing zone than the pollution located on the upper back (P7), which is opposite of effect that occurs in the front of the manikin. This is because the rising pollution from the lower back has more time to mix within the CBL and part of it is able to reach the front side of the manikin.

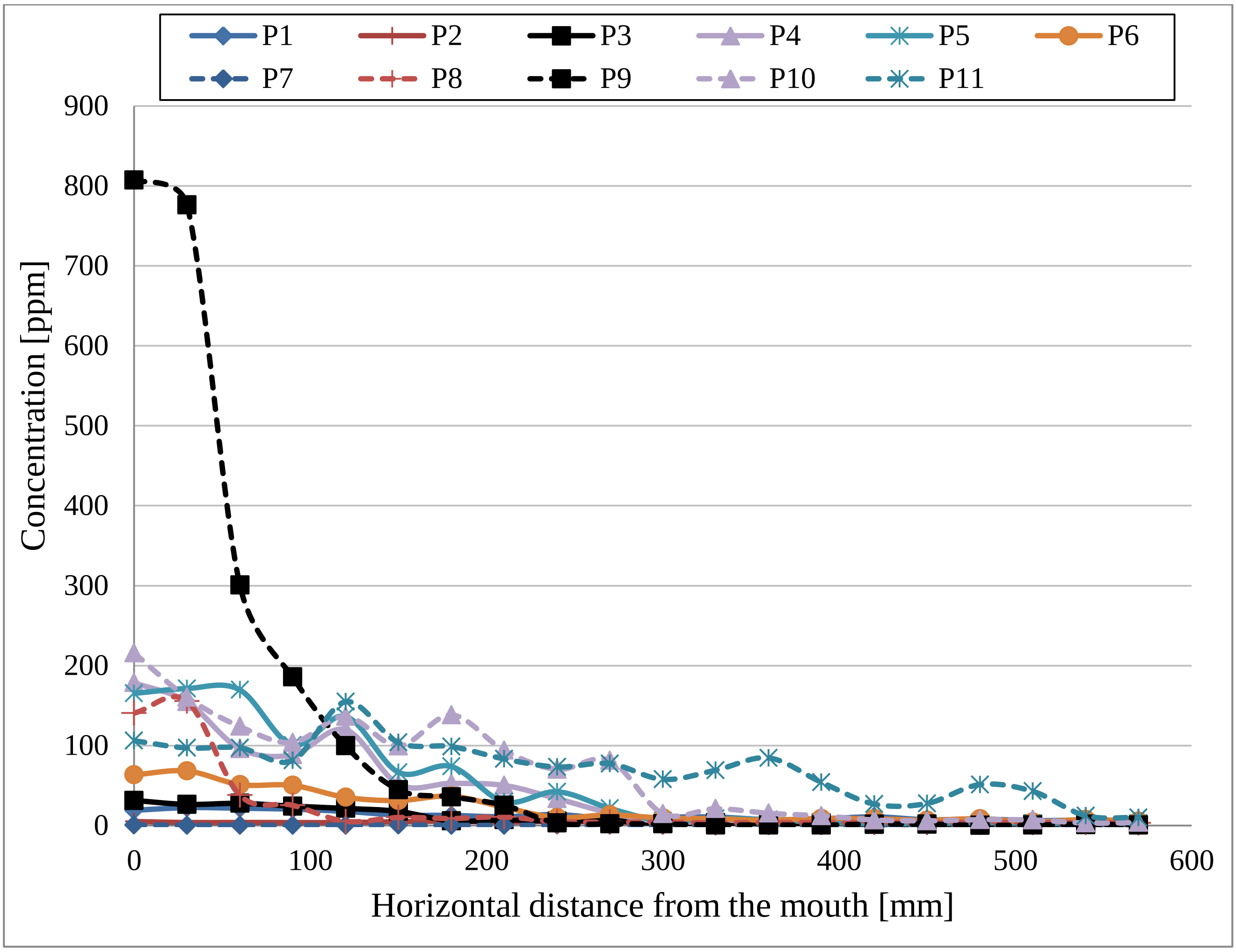

Fig. 2 Concentration of tracer gas in the breathing zone for different pollution locations studied.

The influence of source location on the normalized personal exposure values (at 0 mm distance from the surface) is shown in Figure 3. The results were normalized with respect to the mean concentration at the mouth obtained when the pollution was located at the chest. The standard deviation of the personal exposure values was generally very high, which suggest that the flow in the breathing zone was highly unsteady. As seen, personal exposure decreased 73% when the pollution source was moved from the chest (P9) to the location 0.3 m in front (P10), and 87% when in was moved additional 0.15 m (P11). This reduction is contributed to the distance between the source and the mouth and due to a weaker CBL further away from the body that highly dilutes the pollution. Pollution released from the groins (P4) and the knees (P5) was transported upward towards the breathing zone; however, the personal exposure level was five times lower compared to the source located at the chest (P9).

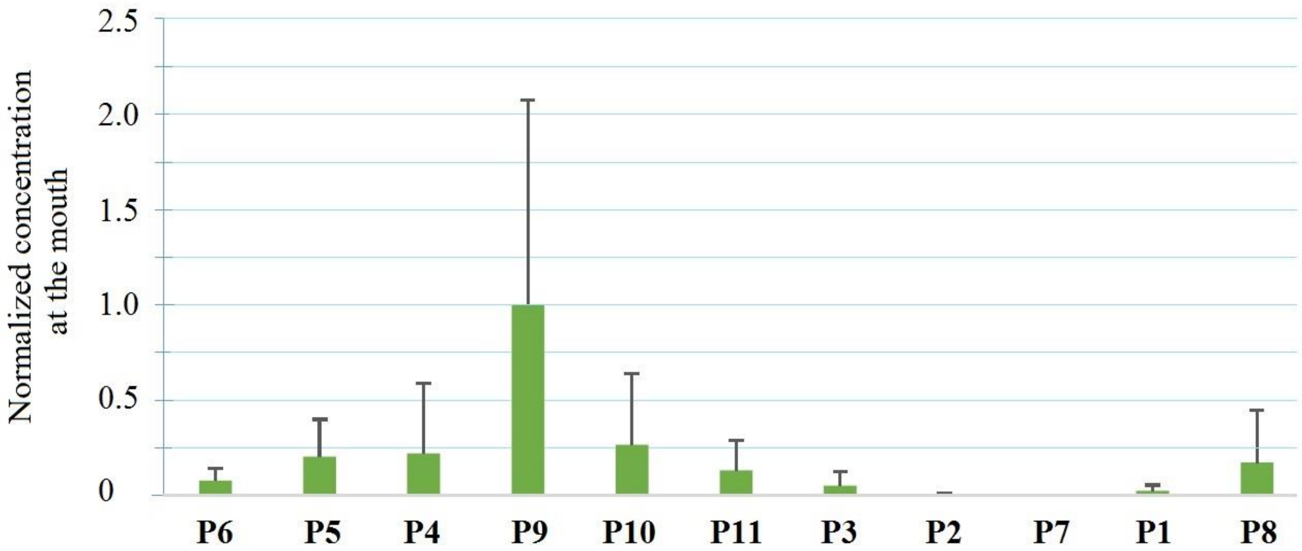

Fig. 3 Normalized values of the personal exposure for different pollution locations studied.

Figure 4 shows the impact of the pollutant location on the thickness of the concentration boundary layer in the breathing zone. The thickness of the concentration boundary layer indicates how much pollution spreads around the human body. It was assumed that the thickness of the concentration boundary layer in the breathing zone extents to a distance where the concentration of the tracer gas reaches 10% of the maximum concentration for each source pollution location. Thickness for the pollutant locations P1, P2 and P7 was not determined because of their low concentration in the breathing zone. From Figure 4 it could be observed that the thickness of the CBL depends on the source location. When the pollution was released at 0.9 m height the narrowest thickness of the concentration boundary layer (0.127 m) in the breathing zone occurred for the pollutants originating from the body, i.e. at the groins (P8) and the chest (P9). Increasing the distance of the source from the chest to 0.3 m (P10) increased the thickness of the concentration boundary layer more than 2 times, i.e. more than 4 times (0.546 m) when the pollution was located at P11. When the pollution was located at 0.5 m height in front of the manikin it was spread more within the CBL with a higher thickness compared to the source location emitted at 0.9 m height.

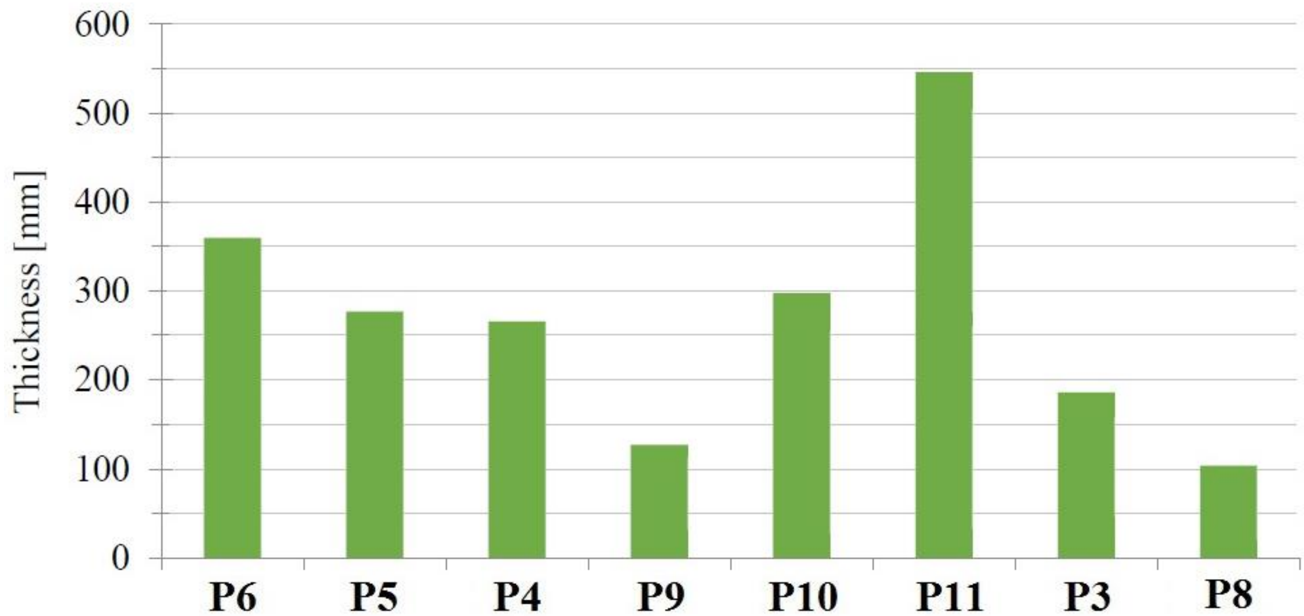

Fig. 4 Thickness of the concentration boundary layer for different pollution locations studied.

4 Discussion

Among all the pollutant source locations studied, pollution emitted from the chest has the highest contribution to the breathing zone concentrations. This result is in a general agreement with the simulation results reported by Rim and Novoselac (2010). These results clearly suggest that the CBL is able to transport the pollution upwards and increase the level of exposure when the pollution is located close to the occupant, as similarly found by Licina et al. (2014b). This is important to consider in rooms with low air mixing because the pollution is non-uniformly spread across the room with concentrations in the breathing zone far higher than those in the surrounding air. In practice, where the worker is exposed to the source located at the surface of the skin\clothes, especially in the chest region the exposure can be maximized. As seen, removing the polluting further from the surface reduces concentration which suggests that this could be a possible way to reduce the exposure. If this is impossible, other control strategies to reduce the exposure to airborne pollutants can be introduced such as blocking the rising CBL with the table (Licina et al. 2014a), removing the CBL with the personalized ventilation (Bolashikov et al. 2010) or by local exhausting of the pollution before it spreads across the room (Yang et al. 2013). The same techniques could be applied for other pollutant locations originating at the human body.

Another important point to consider is the horizontal distance between the pollution source and a human body. This distance directly affects the thickness of the concentration boundary layer which is an important factor not only for the personal exposure, but also for the cross-infection among occupants. As shown in the results section, when the pollution is released close to the body surface, the thickness of the concentration boundary layer in the breathing zone is considerably smaller compared to the pollution emitted further away. This suggests that pollutants originating from the human body itself will spread less across the room, compared to the pollution originating at some distance from the body. Pollutants from the human body are likely to be transported upwards via the thermal plume where they can be exhausted by the ventilation system. On the other hand, pollutants located at some distance from the body could stimulate the cross-infection among building occupants because they can mix with the CBL of a neighboring people and end up in their breathing zone. These findings could be crucial to consider in densely occupied spaces (hospitals, cinemas, offices, public transport), where people dwell close to each other. Furthermore, pollutant emitted at the lower part of the body are likely to increase the probability of cross-infection because they spread more compared to pollutants emitted at the upper part of the body. In addition, pollutants emitted from the back side of the occupant are not very important to consider for the personal exposure (unless emitted from the lower back), but could be very important for the cross-infection, especially in the case P2.

5 Conclusions

The experimental investigation of the ability of the human CBL to transport gaseous pollutants in a quiescent indoor environment reveals the following:

- The location of the pollution source in the vicinity of a human body has a considerable influence on the breathing zone concentrations. The CBL has the ability to transport the pollution to the breathing zone and increase the personal exposure.
- For all studied cases, the highest personal exposure occurred when the pollution source was located at the chest. Pollution located at the upper back of the manikin or just behind the chair is not transported towards the breathing zone.
- The horizontal distance between a human body and pollution location considerably affects the personal exposure and the thickness of the concentration boundary layer. For the gaseous pollution released close to the body surface, the thickness of the concentration CBL will be considerably reduced compared to the pollution emitted further away. In addition, pollutants

emitted at the lower height spreads more and increase the thickness of the concentration boundary layer.

- The study provides a relationship between the source location and the breathing zone concentrations which can be used to estimate the exposure in quiescent indoor spaces; however, in the future it is necessary to investigate the same phenomena under different airflow distributions.

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