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INTERACTION OF CONVECTIVE FLOW GENERATED BY HUMAN BODY WITH ROOM VENTILATION FLOW: IMPACT ON TRANSPORT OF POLLUTION TO THE BREATHING ZONE

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SUMMARY

This study aims to investigate the interaction between the human convective boundary layer (CBL) and uniform airflow from two directions and with different velocities. The study has two objectives: first, to characterize the velocity field in the breathing zone of a thermal manikin under its interaction with opposing flow from above and assisting flow from below; and secondly, implication of such a flow interaction on the particle transport from the feet to the breathing zone is examined. The results reveal that the human body heat transports the pollution to the breathing zone and increases concentration by factor of 5.5. Downward flow of 0.175 m/s does not change airflow patterns and pollutant concentration in the breathing zone, while the velocity of 0.425 m/s offsets the thermal plume and minimizes the concentration. Since the downward flow at 0.30 m/s collides with the CBL at the forehead level, it prolongs particle dwell time and consequently, increases the concentration in the breathing zone by 106%. Adding the assisting flow dilutes the pollution and reduces the concentration compared to case of a pure CBL. Findings that the assisting flow of 0.30 m/s and above reduces the velocity in the breathing zone due to the blocking effect of the chair suggest that furniture should be carefully considered in numerical results predictions and optimal air distribution.

INTRODUCTION

Indoor environment to which building occupants are exposed influences their comfort, productivity and health. In the current ventilation design, complex airflow interactions between ventilation flows and buoyant flows induced by the building occupants are not taken into account which results in inaccurate prediction of human exposure. Understanding this complex airflow interaction is important to provide a comfortable environment and prevent spread of pollution.

At normal activity levels, human body dissipates about 30% of its total heat loss by means of convection (Murakami et al. 2000). Consequently, the convective flow rises around the human body, driven by the temperature difference between the warm body and colder ambient air. This flow enveloping the body is known as a human convective boundary layer (CBL) which develops into a human thermal plume above the head. The airflow induced by the building occupants is important for indoor air quality, occupants' thermal sensation and airborne diseases spread (Craven and Settles, 2006; Zukowska et al. 2008)

Several studies in the past investigated the airflow characteristics around the human body in a calm indoor environment (Homma and Yakiyama 1988, Clark and Toy 1975, Licina et al. 2013). Other studies attempted to examine how the CBL is influenced by the factors such as thermal stratification (Craven and Settles, 2006), body posture, clothing insulation, table and chair design (Licina et al. 2014, accepted). The disturbance of the CBL caused by the surrounding flow generated by the mechanical ventilation has not been studied extensively in the past. This is mostly due to a complex interaction between ventilation and buoyant airflows and experimental difficulties associated with a point-wise measurement technique. Some studies investigated interaction between the CBL and locally supplied airflows (Bolashikov et al. 2011a; Bolashikov et al. 2011b). Manikin exposed to a uniform horizontal airstream from behind (Melikov and Zhou, 1996) or from front (Heist et al. 2003) have also been studied. None of the studies in the past considered airflow interaction between the CBL and assisting flow from below nor opposing flow from above.

It has been reported that the human convection flow plays important role in air transport around a human body (Rim and Novoselac, 2009). This air may be polluted from contaminants at the floor level or and may also carry the bio-effluents produced by the human body. Interaction of the CBL flow with the surrounding airflows generated by ventilation system will modify the human CBL and thus affect pollutant distribution around the human body. It has been known how mixing and stratified indoor environment affect pollutant dispersion in the vicinity of a human body (Rim and Novoselac, 2010); however, how different airflow patterns affect transport of pollutants and the personal exposure has not been studied in details. The first objective of this study is to investigate how the CBL interacts with opposing flow from above and assisting flow from below. The second objective is to investigate the personal exposure levels under the same airflow interaction in regard to the pollution source released from the feet.

METHODOLOGIES

An environmental chamber (11.1 x 8 x 2.6 m) equipped with displacement air distribution system was used in this study. Air was introduced to the chamber via 6 low momentum diffusers and exhausted via 6 ceiling mounted grills located at sufficient distance from the manikin to minimize interference between ventilation flow and the CBL (Figure 1, left). A calibrated non-breathing thermal manikin with female body shape of 1.23 m height in the sitting posture was positioned in the centre of the chamber. The manikin 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 and the minimum ventilation rate to provide calm conditions close to the manikin. The velocity measured (Dantec omnidirectional thermal anemometers; ±0.02 m/s accuracy) at 1.2 m distance from the manikin was below 0.05 m/s which indicated calm indoor conditions (Murakami et al. 2000).

An airflow generator with dimensions 1.8 x 1 x 0.2 m (L x W x H) was designed to provide a uniform airflow that interacts with the manikin's CBL. Within the airflow generator, 66 fans were installed and controlled via frequency regulator with a fine tuning. Airflow generator was mounted in two ways: (i) at the ceiling to generate a uniform forced-convection of 0.175, 0.3 and 0.425 m/s that opposes the convection flow of the manikin, and (ii) placed below the manikin to generate a uniform convection of 0.175, 0.3 and 0.425 m/s that assists the manikin's convection flow (Figure 1, right). Prior to experiments the flow uniformity test was performed at 0.7 and 1 m distance from the outlet of the airflow generator and the velocities measured had a low discrepancy, below 10%.

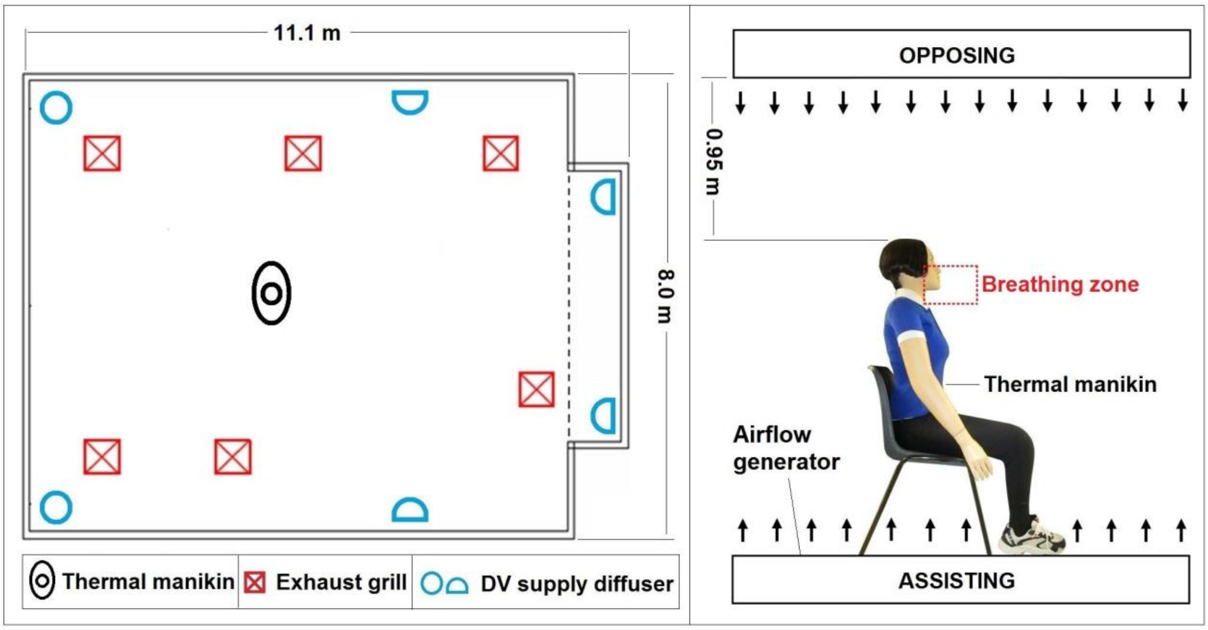

Figure 1. The Environmental chamber (left) and experimental setup (right).

Airflow interaction in the breathing zone of the manikin was examined using Particle Image Velocimetry (PIV). The PIV equipment includes dual laser (190 mJ and wavelength 532 nm), synchronizer, 2MP CCD camera (1600 x 1200 pixels) and the computer. The laser sheet was aligned with a central vertical axis of the manikin to illuminate seeding particles that were discharged from the airflow generator. Seeding particles were generated in Six Jet Atomizer (TSI Inc.) with extra virgin olive oil (Bertolli) as an aerosol generating material. To obtain instantaneous images of the flow field, the camera (28 mm lens) was positioned perpendicularly to the laser sheet at 0.48 m distance, which yielded target image area of 20 x 15 cm. In total, 540 image pairs were averaged and analyzed that corresponds to 54 s of the flow. More details about experimental setup and procedure are presented in the separate paper (Licina et al. 2014, accepted).

Atomizing the same olive oil generated passive pollution with zero initial momentum released between the feet of the manikin to simulate particles re-suspended from the floor or pollution due to smelly feet. Pollutant release time was set to 2 min. A calibrated aerosol spectrometer (Grimm 1.108) with 16 size channels (from 0.3 μm to 20 μm) was used to measure a real-time aerosol concentration in the breathing zone of the manikin. Aerosol spectrometer had a sampling rate of 1.2 L/min and a sampling frequency of 1 Hz. Analysed particle size was within a range 0.5-0.65 μm because particles smaller in size are proven to be more severe compared to larger particles. Sampling time was 2 min during the pollutant release, plus 1 min after termination of release (in total 3 min). Pollution source generated concentration level several orders of magnitude above the initial background concentration. Nevertheless, one minute prior to pollutant release the background concentration was recorded and subsequently deducted from results to minimize measurement inaccuracy duo to initial background concentration.

RESULTS AND DISCUSSION

The results of the PIV measurements describe the CBL in a calm indoor environment and its interaction with mutually opposing and assisting flow at three different velocities. The results are presented in the form of averaged velocity contours with vectors where the length of an arrow is proportional to the velocity magnitude (Figure 2 and 3) and the velocity profiles as a function of the horizontal distance from the mouth (Figure 4). The results of Grimm particle concentration measurements are obtained under the same scenarios and compared to the case of a non-heated manikin under calm indoor conditions.

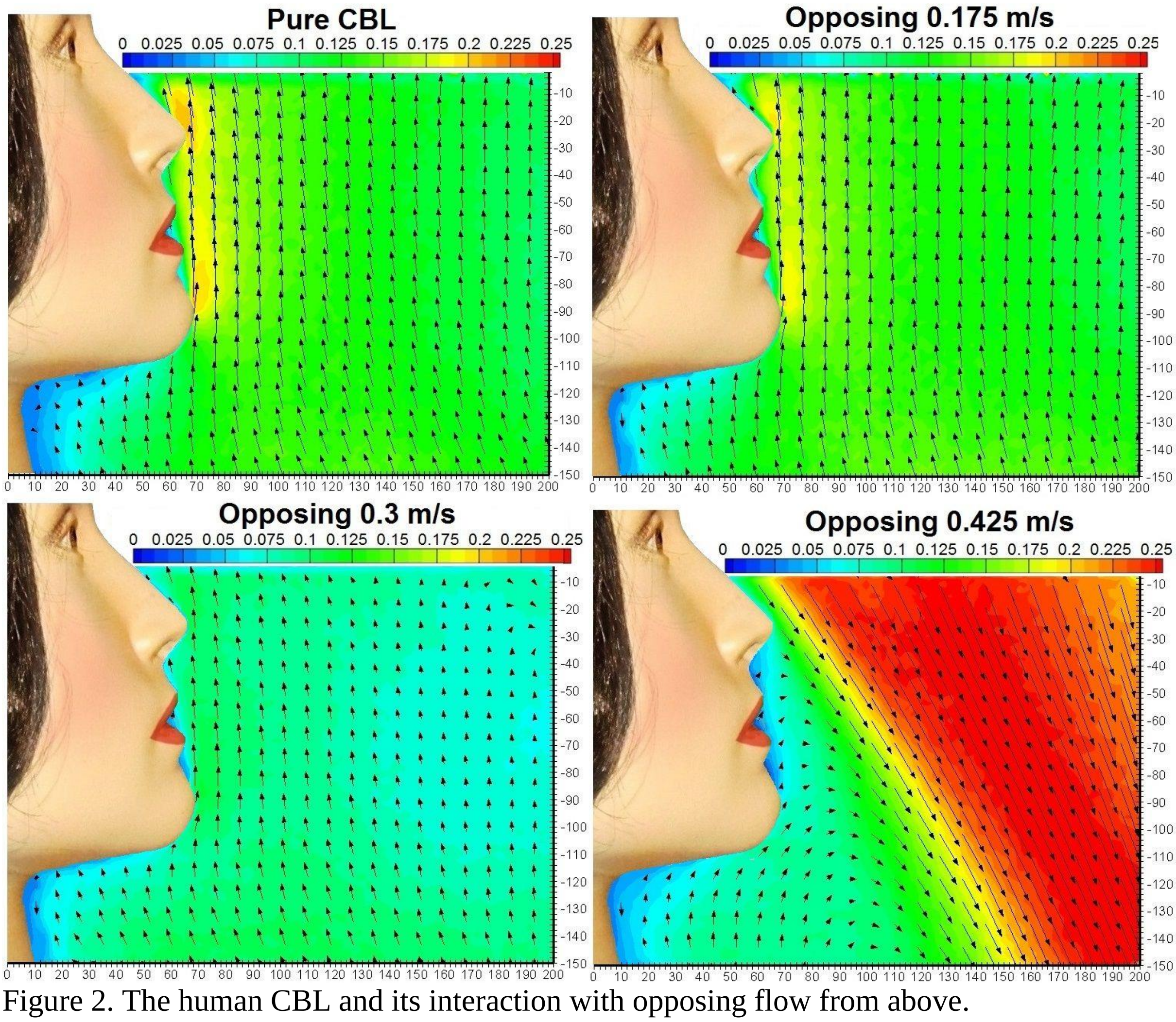

Figure 2. The human CBL and its interaction with opposing flow from above.

Figure 2 presents the mean velocity contours in the breathing zone of the CBL in a calm indoor environment (denoted as Pure CBL), and its interaction with the downward flow from above at the velocities of 0.175, 0.30 and 0.425 m/s. In addition, Figure 4 shows the change of the mean velocity as a function of the distance at level of the mouth for the same scenarios. In case of a calm indoor environment, the manikin generated the peak velocity in the mouth region of 0.185 m/s at 14 mm distance from the surface that steadily decreased to 0.095 m/s at 150 mm distance. The results indicate that the downward velocity of 0.175 m/s created insignificant effect on the velocity profile in the breathing zone, as it was not able to penetrate the thermal plume. Manikin's thermal plume exposed to a uniform downward flow at 0.30 m/s was neutralized at the level of the forehead at 150-200 mm distance. In this case, the peak velocity in the mouth region decreased from 0.185 m/s to 0.10 m/s (Figure 4). Downward velocity of 0.425 m/s was able to completely break away the human CBL. Only the region below the chin maintained upward air movement, as it was protected by the physical contours of the head.

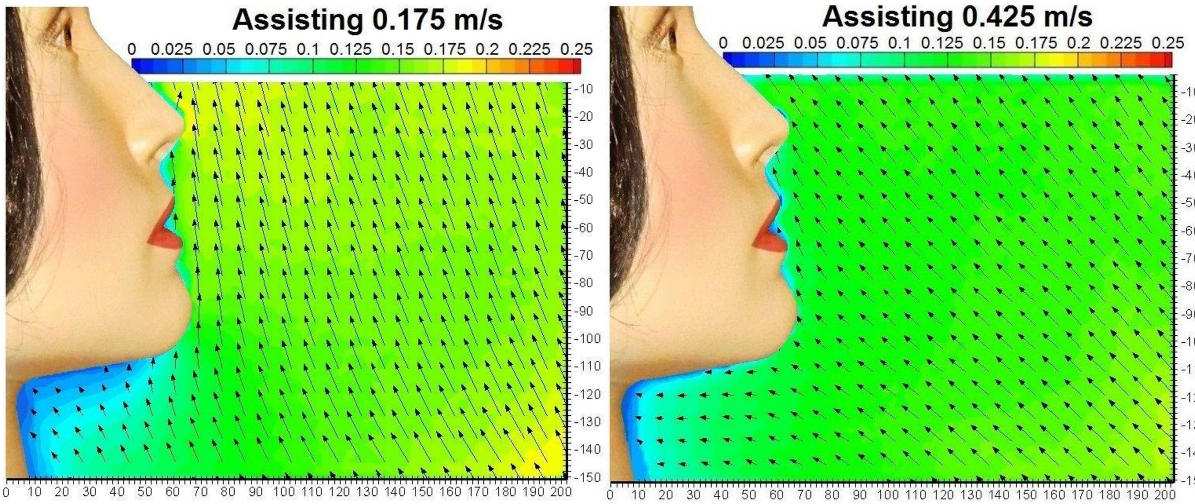

Figure 3. Interaction between the human CBL and assisting flow from below.

Figure 3 shows the mean velocity contours of the manikin exposed to a uniform upward air movement at velocity of 0.175 and 0.425 m/s. Figure 4 shows the mean velocity profiles along the horizontal distance from the mouth when the CBL is interacting with mutually assisting flow at velocities of 0.175, 0.30 and 0.425 m/s. As expected, interaction between the pure CBL and mutually assisting flow at 0.175 m/s resulted in increased velocity in the breathing zone, compared to the case of the pure CBL (see also Fig. 2). This suggested that two flows had a mutually confluent character. Unexpectedly, upward flow velocities of 0.3 m/s (Figure 4) and 0.425 m/s (Figure 3 and 4) reduced the velocity in the breathing zone and tilted the velocity vectors 45˚ towards the manikin's face. This effect occurred because of a blocking effect of the chair and the separation of the assisting flow from the edge of the chair at the higher velocities.

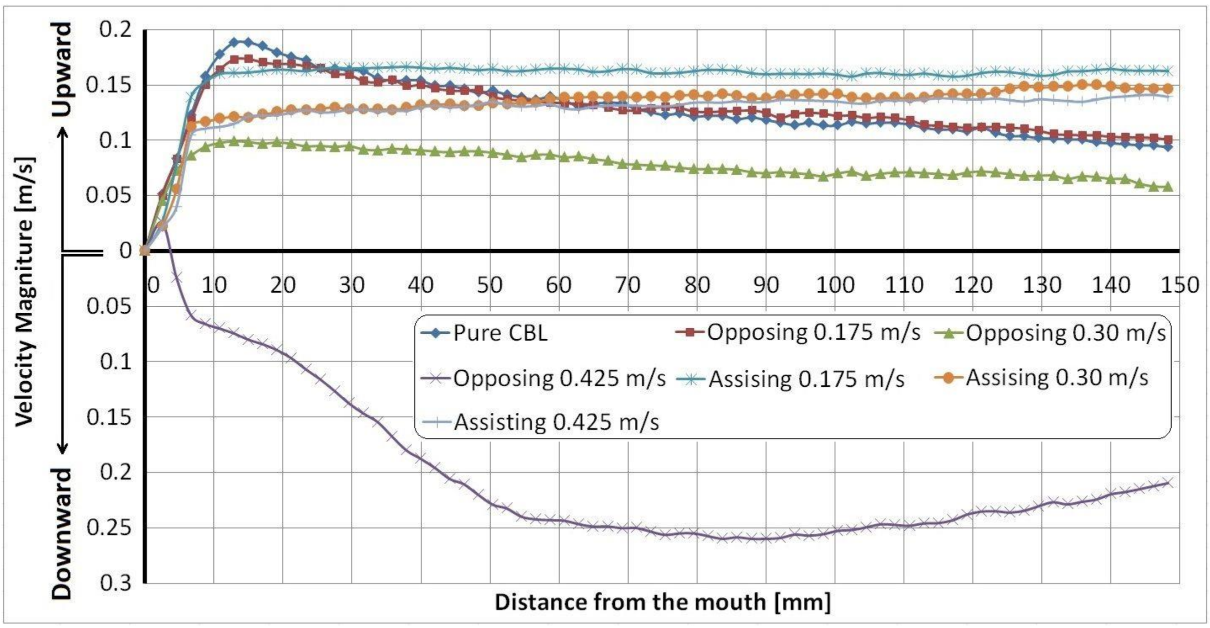

Figure 4. Mean velocity in front of the mouth: Impact of the opposing and assisting flow.

Figure 5 shows the results of concentration measurements in the breathing zone of the manikin when the pollution source is located between the feet. The results clearly show that the CBL of the manikin is able to pull the pollution from the feet to the breathing zone resulting in concentration of $4.4x10^5$, which is approximately 5.5 time higher compared to the case with no body heat. This increase in the personal exposure is contributed to the manikin's body heat that lifts the particles from the feet and transports them to the breathing zone. This finding is in line with several studies in the past that showed increased particle concentration in the breathing zone compared to perfectly mixed concentration, when the pollution source is located close the manikin (Rim and Novoselac 2009; 2010).

For opposing flow configuration (Figure 5, left), downward velocity of 0.175 m/s has insignificant effect on airflow characteristics and therefore, it was reasonable to expect concentrations similar to those in case of the pure CBL (denoted as Manikin On). Increased velocity of downward flow to 0.30 m/s induced the maximum concentration level is the breathing zone of $9.2x10^5$, which is about 106% above the pure CBL scenario. This is due to collision between the downward flow and the manikin's CBL in the forehead region that maximizes the pollutant dwell time and therefore, the concentration in the breathing zone. Thermal plume of the manikin exposed to uniform downward flow at 0.425 m/s was completely offset which decreased pollutant concentration in the breathing zone by factor of 13.5, compared to the pure CBL scenario. In this case particles originating at the feet level were pushed aside by the downward invading flow.

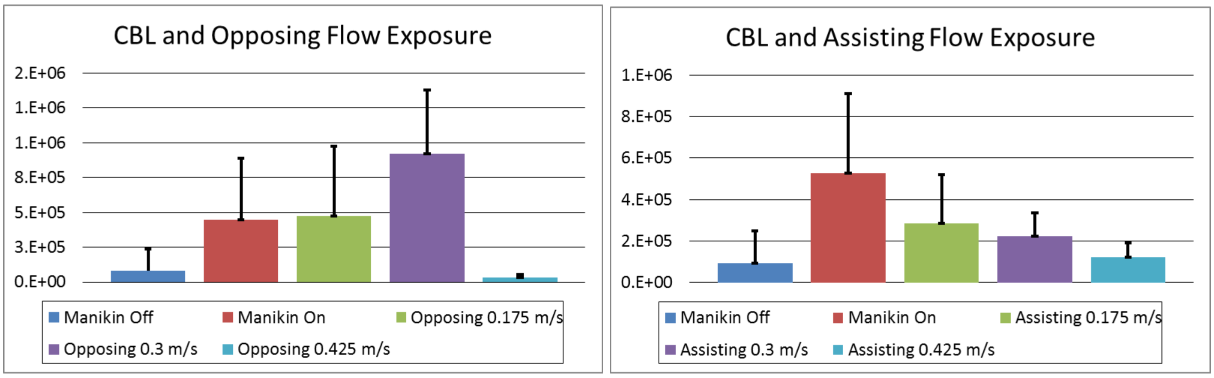

Figure 5. Particle concentration in the breathing zone as a result of particle transport due to the CBL and mutually opposing (left) and assisting flow (right).

Figure 5 (right), compares the concentration levels in the breathing zone when the manikin was exposed to a uniform upward flow at 0.175, 0.30 and 0.425 m/s. As seen, all three velocities caused the concentration reduction, compared to the case without surrounding flows (Manikin On). This lower concentration was attributed to increased dilution by the upward flow to which the pollution source was exposed to. Thereby, higher velocity from the airflow generator further reduced the concentration levels in the breathing zone. Upward flow at the velocities of 0.175, 0.30 and 0.425 m/s reduced the concentrations respectively by 46%, 58% and 77%, compared to the case of no surrounding flows. These results are somewhat in compliance with the previous findings that in rooms with higher air mixing, the breathing concentration depends less on the source location and it is closer to the average room concentrations (Rim and Novoselac, 2010).

Ventilation systems that create flows opposing or assisting the CBL are commonly found in residential and non-residential buildings. Some examples of downward approach are ceiling mounted grills that supply a uniform downward airflow, ceiling mounted personalized ventilation or ceiling fan. Examples of upward approach are upward piston flow, displacement or underfloor air distribution principle and locally supplied assisting personalized ventilation. This study has shown that vertical downward approach at 0.425 m/s is the most efficient in terms of preventing the pollution from the feet to reach the breathing zone. Offsetting the thermal plume is also useful in regard to an optimal design of ventilation with a vertically downward air distribution that is aimed to deliver a clean air to the breathing zone. On the other hand, increasing the downward velocity poses an additional energy penalty and increases the risk of thermal discomfort, as the velocity of 0.425 m/s exceeds the comfortable velocity range (ASHRAE 55, 2010).

The results of interaction between the CBL and assisting flow from below at 0.30 and 0.425 m/s reveal the importance of furniture arrangement on the airflow distribution in the indoor environment. The velocity reduction in the breathing zone created by the blocking effect of the chair is similar to phenomenon created by joined legs, as observed in numerical study by Li et al. (2013). Other studies also showed that table arrangement can largely affect airflow characteristics in the breathing zone (Bolashikov et al. 2011a; Licina et al. 2014, accepted) and in the manikin's thermal plume (Zukowska et al. 2012). These studies and the present study suggest that the furniture design and arrangement should be taken into account in numerical results prediction and for designing an environment with optimal air distribution. In terms of pollutant concentration level in the breathing zone of the manikin placed in a uniform upward airflow, the results substantially differ from the ones when the manikin is exposed to a downward flow. These results emphasise the importance of the body orientation relative to the invading airflow direction and magnitude.

The limitation of the current study is that it does not take into account a human respiratory cycle which needs to be investigated in the future. In addition, it should be emphasized that the results of this study are valid only at the room air temperature of 23 ˚C. Furthermore, other airflow directions generated by the ventilation systems should be considered because they create different air patterns. Different room air temperatures and air distribution around the human body may alter pollutant concentration levels in the breathing zone.

CONCLUSIONS

This study examines interaction of convective flow generated by human body with mutually assisting/opposing airflow and investigates its impact on transport of pollution from the feet to the breathing zone. Occupant's orientation relative to the direction and magnitude of invading flow from the surroundings considerably modifies air patterns, and thus pollutant concentration in the breathing zone. The experimental results reveal that a heated manikin placed in a calm environment is able to transport the pollution from the feet to the breathing zone and increase the concentration by factor of 5.5, compared to the case of unheated manikin. Downward flow with velocity of 0.175 m/s does not change airflow patterns in the breathing zone and thus pollutant concentration, while the velocity of 0.425 m/s peels off the thermal plume and minimizes the concentration. Due to its collision at the forehead level, downward flow at 0.30 m/s maximizes the concentration in the breathing zone. The manikin exposed to the assisting flow at 0.30 m/s or higher has a lower velocity in the breathing zone due to the collision of the upward flow with the chair. This emphasizes the importance of the furniture arrangement around the human body for consideration in numerical predictions and optimal ventilation design. Adding the assisting flow to the CBL decreases the concentration in the breathing zone due to a dilution effect which is increased at the higher velocities.

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