Experimental and simulated evaluation of airborne contaminant exposure in a room with a modified localized laminar airflow system

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Abstract:

The traditional mixing ventilation is not an energy effective approach to remove indoor air pollutants, maintain breath zone air quality, and control the airborne transmission. This study investigated the potential of a localized laminar airflow ventilation system to alleviate human exposure to pollutants. Breathing thermal manikins with sitting posture and supine posture were used to simulate the human. N_2O was used as the tracer gas to simulate the indoor pollutants emission. The contaminant exposure index (ε_{exp}) and intake fraction index (IF) were used to assess the risk of human pollutant exposure for various supply air velocities given different emission source positions. Enhanced pollutant removal efficiency (E_{ff}) (from the result) showed the qualification and desirability of the localized laminar airflow ventilation system in improving the breath zone air quality. The results showed that the CFD results could fit well with the experimental data, and found out the interaction between thermal plume and supply air. The results also indicated a low ε_{exp} and IF, with the Eff over 90%, all of which were highly correlated with the supply velocity. Human's different breathing methods have little influence on the pollutant exposure so as to the location of the pollution source. This study found that localized laminar airflow ventilation system could efficiently provide fresh air to the breathing zone without sacrificing the thermal environment around human. It can be used for small region air quality control such as that in the bedroom and living room where desired air quality is favored.

Key words: localized laminar airflow system; breathing thermal manikin; pollutant exposure; pollutant removal efficiency.

1. Introduction

Human spend over 80% of their lifetime in the indoor environment (Dodson et al. 2007) and about two-thirds of a day inside their houses or dwellings (Zhang et al. 2009). Nowadays, study on ventilation problems in residential buildings has been conducted (Kyoungbin et al. 2008; Richard et al. 1997; Vernon et al. 1997), but, the some scholars focused on the kitchen space. A more recent study (Cheng et al. 2018) further investigated people's time distribution in residence and found people spend near 85% of their time in the living room and bedroom of which bedroom alone could take up 55% of the time. Thus, people's health risk from the indoor pollutant exposure could be greatly reduced if we can take control over the air quality of the bedroom and living room, which also means an improvement in people's living environment. In addition, there are several critical considerations that make these two environments (i.e., the bedroom and living room) unique: (1) the prolonged period of exposure due to sleeping time, which makes up nearly one third of people's lives in the bedroom (Dodson et al. 2007; Zhang et al. 2009); (2) the potential for higher exposure due to people's closer proximity to the breathing zone (BZ) pollutant sources; and (3) the existence of diversified indoor pollutants such as gaseous-phase contaminants.

Air-conditioning systems were commonly used for the indoor environment control and thermal comfort management in the residential buildings. Ventilation is increasingly becoming recognised as an important component of a healthy residential building, and is the ultimate strategy to control indoor air quality (IAQ) (Dimitroulopoulou, 2012). For the requirements of ventilating flow rates, energy consumption and IAQ would have conflict, and thermal comfort would also be affected by the ventilating flow rates (Kim et al, 2009; Lozinsky et al. 2020). However, traditional air-conditioning systems typically mix the clean, filtered air with the ambient room air and return air. As a result of this mixing effect, the pollutants concentration of the BZ air almost equals to the concentration of the mixed air. Moreover, the strong supply airflow draft could deliver the near-surface pollutants (such as those on/near the furniture surfaces) to the BZ (Spilak et al. 2016), which is another critical air quality consideration of the traditional systems. On the other hand, portable air cleaners (also known as air purifiers) are often used in homes and offices due to their high particle-removal efficiencies, no need of pre-installations and relative low prices (Spilak et al. 2014; Bräuner et al. 2008). However, the filtered air from the portable air cleaner will be mixed with the indoor air in a similar way as that of the traditional heating, ventilation, and air conditioning (HVAC) systems. Hence, the portable air cleaners could have the same BZ air quality considerations as that of the HVAC systems.

Recently, the temperature-controlled laminar airflow (TLA) has been investigated by some researchers as an indoor environment control alternative in the health care systems (Spilak et al. 2016; Pedroletti et al. 2009; Evans et al. 2010). The TLA environment control approach relies on a local downward laminar airflow, which delivers low-speed air via overhead supply nozzles after the air been filtered, cleaned and conditioned. The cooler air supplied by the TLA system flows downward against the upward convection airflows that caused by the thermal plumes of the sitting and/or sleeping person. Since the supply air is delivered locally to the BZ, the mixing effect with the indoor air is greatly reduced, resulting in a significantly lower amount of supply air required by the BZ to achieve the same air quality and/or thermal comfort as required by the traditional HVAC systems or portable air cleaners (Cong et al. 2018).

Nowadays, the laminar airflow (LAF) has been proven by many scholars as an better airflow to maintain clean air compared to the mixing airflow approach, it has been widely applied for the hospitals' air systems to reduce the patients' exposure risk to particles (Lidwell et al. 1982; Memarzadeh et al. 2002; Chow et al. 2004; Oguz et al. 2017; Whyte et al. 1982; Hirsch et al. 2012; Diab-Elschahawi et al. 2011; Fischer et al. 2015). In addition, LAF systems are commonly used to remove airborne microbial particles and other pollutants in hospital operation room or other places where strict indoor environment are required.

Some scholars focused on the efficiency of the TLA system used for diseases risk control and management. In a study, a bedside device using horizontal laminar airflow was introduced to alleviate rhinitis symptoms and daytime somnolence (Morris et al. 2006). Another researcher introduced the TLA system to improve asthma-specific quality of life and ease airways inflammation (Boyle et al. 2016). Some scholars focused on the efficiency of TLA for particles removal. As a study showed, the magnitude of the reduction was more than 99% in every category within 30 minutes by using TLA system (Gore et al. 2015). Another study showed the similar result, The TLA device could remove the 99.9% of the initial particles in a short time and the downward LAF was able to prevent the particles from peripheral zone move into the BZ, keep the BZ air quality isolate from peripheral zone (Spilak et al. 2016). A scholar compared real-person exposure in bed with two different cases, and it obtained the similar results with previous studies (Gore et al. 2015). There was a research considered both decease and particle, TLA system achieved massive reductions in both total particle and cat allergen concentrations in the BZ while subject lying on the bed (Warner et al. 2017). According to these studies, TLA could remove over 99% airborne particles of all sizes, and the concentrations of particles outside the TLA airflow zone did not change, it would have high concentration compared to the BZ (Warner et al. 2017). However, the supply air is supplied directly straight to the people, the thermal plume of the people appears to have a greater effect on velocity field and temperature field in the LAF system than in the traditional mixing ventilation system, the thermal plume may decrease the supply air velocity which may cause the unstable situation in TLA airflow zone, the pollutants might move into BZ. It could increase the exposure of the patient to various indoor airborne pollutants (Guangyu et al. 2019). A previous study taken placed in hospital found that the location of the pollutant source may not be a significant factor to affect the risk of exposure (Guangyu et al. 2019).

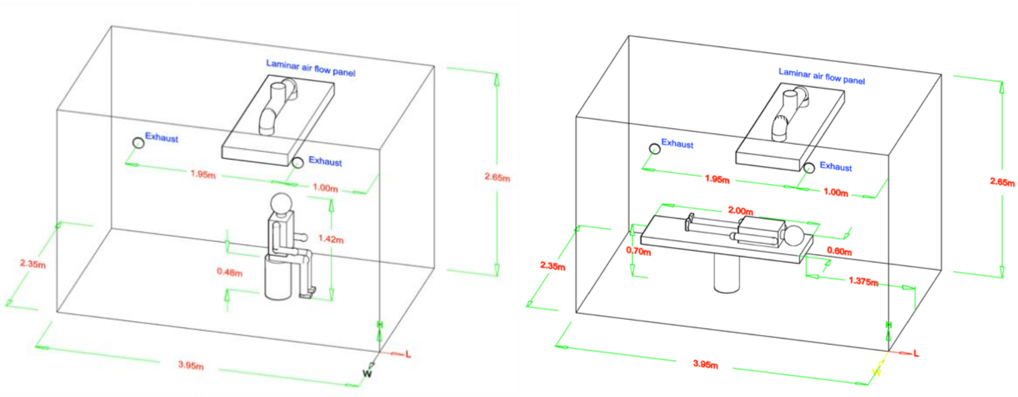
Although the TLA system was showed to be effective in improving the BZ air quality in the hospitals, the environment of the hospital is actually different from that of the residence (with respect to the pollutant source, number of people, and the cost of the TLA system). Thus, it is not reasonable to straightly apply the TLA system used in the hospitals for residences or for ventiate spaces for residential uses. In order to use the TLA system for residential buildings, the regular system used in the hospital may need to be modified. In this study, we draw lessons from past applications of the TLA system, and make a modified and simplified version of TLA which is a localized or personal LAF. And the main objective of this study is to experimentally and simulatively determine pollutants exposure by assessing the risk of pollutants in a room with modified LAF system. To achieve this objective, we i) investigated the impact of ventilation air flow velocities on the pollutants-removal effectiveness in the BZ, ii) compared the impact of different emission sources locations on the pollutants-removal effectiveness in the BZ, iii) investigated the impact of different breathing modes on the E_{ff} in the BZ.

2. Methods

2.1. Test room and experimental setup

The experiment was conducted in a small climate chamber, with a dimensions of 3.95m×2.35m×2.65m (L×W×H) as shown in Fig. 1. The air was supplied from a 0.50 m × 0.50 m laminar air panel in the middle of the room positioned 2.2 m above the floor. Compared with the traditional localized laminar systems used in hospitals, the nozzle outlet of the diffuser in this experiment was equipped with honeycomb flow straighteners (Ø4 mm) to straighten the flow and to reduce the turbulence intensity. In addition, the system dimension was much smaller. The air was exhausted through two exhaust outlets with opening areas of 0.0256m^2 located on the sidewall (Fig.1). During the test, the room temperature was kept at 23.0 ± 0.5°C and frequently checked by the temperature measurements from a TSI VelociCalc 9565-P multi-function ventilation meter in the middle of the chamber with a height of 1.5m.

This study used the matured manikins model which were fully used in the Department of Energy and Process Engineering (EPT) of Norwegian University of Science and Technology (NTNU) (Guangyu et al. 2018; Aganovic et al. 2019; Cheng et al. 2019; Guangyu et al. 2019). The geometry of the manikins in the computational fluid dynamics (CFD) simulation were kept the same with the experiment entities (see section 2.3). A cuboid-shaped room was used in the simulation, the size of which was also kept the same with the small climate chamber. There were two exhaust openings on the wall and a laminar air flow panel above the manikin's head, as indicated by the experiment setup.



(a) (b)

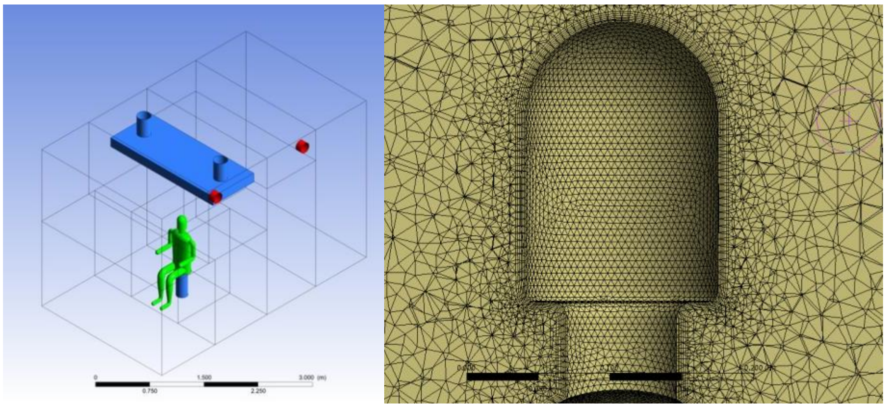
Figure 1 Schematic diagrams of the full-scale experiment ward (a)sitting case (b) supine case

2.2. Simulation setup

CFD simulations were performed with Ansys Fluent 19.1 (ANSYS, Inc.) using *k-ε RNG* turbulence model. The buoyancy force was obtained by Boussinesq approximation, air density was treated to be constant during the calculation. No slip and fixed temperature condition were given as the boundary condition for the body surface and wall. The gravitational acceleration (*g*) and the thermal expansion coefficient (*β*) were 0.00333k^{-1} and -9.8m/s^2 respectively. Surface temperature of manikin's head was assigned to be 31 °C while other parts were 26.6 °C. Environmental temperature was designed by defining floor, ceiling, wall, bed and chair temperature, which was given as 23 °C. The density of surface of manikin was 1200kg/m^3, specific heat capacity and thermal conductivity were 3300j/kg/k and 0.34w/m/k respectively. Density, specific heat capacity and thermal conductivity of the insulation wall were 1200kg/m^3, 970j/kg/k and 0.17w/m/k respectively. The supply air velocity was different in two different posture. For sitting model, the magnitude of velocity was 0.25m/s, 0.30m/s and 0.35m/s, for supine model, the magnitude of velocity was 0.15m/s, 0.25m/s, and 0.35m/s. K and Epsilon was 0.0001 and 0.00001 respectively. The exhaust was pressure outlet.

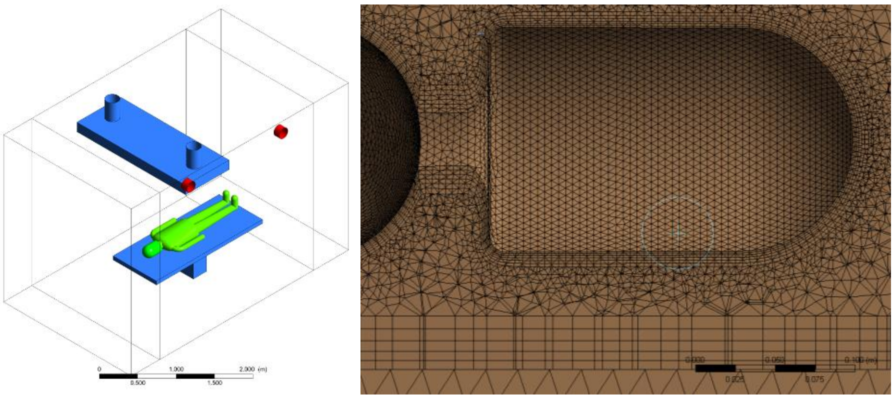
SIMPLE scheme was adopted for Pressure-velocity coupling Method. Power law scheme was adopted for momentum equation and energy equation discretization. PRESTO！ scheme was adopted for pressure interpolation schemes. Second-order upwind differential was adopted for others. Parallel computing was conducted to accelerate the calculation.

Calculation domain was divided into different parts for the mesh generation. Fine grid was generated for the zones around human body and laminar air flow panel to insure sufficient grid for the simulation need of thermal plume and supply air. The size of the grid was from 2mm to 45mm. Moreover, size function was defined to refine the grid on human body surface, laminar air flow panel and exhausts. For manikin, first layer size in contact with body surface was 0.9mm considering a growth ratio of 1.1 with a total number of 6 layers. For other surfaces, first layer size was 4mm considering a growth ratio of 1.1 with a total number of 8 layer. In sitting case, the totally 4.4 million grids were defined for the calculation. In supine case, the totally 4.2 million grids were defined for the calculation.



(a) (b)

Figure 2 Simulation model (sitting posture) (a)Chamber; (b)Mesh of manikin



(a) (b)

Figure 3 Simulation model (supine posture) (a)Chamber; (b)Mesh of manikin

2.3. Breathing thermal manikins

Previous study showed that the use of the thermal manikins is a practical and effective approach method to study the interaction between thermal plumes and the downward laminar airflow (Guangyu et al. 2018). To simulate the human subject, a breathing thermal manikin with a complex body shape was used. Two thermal manikins with performing an specific breathing function are used during the experiments. The supine manikin was a 1.85m tall man while the sitting manikin was a 1.7m woman. The female manikin dressed in shirt and jeans with an insulation value of approximately 0.8clo and was seated on a cylinder which had a height of 0.48m to minimize the impact of the chair on airflow distribution. The male manikin was placed on a 0.7m height and 0.6m width bed covered with the cotton-type sheet as the supine position covered with thin quilt below laminar air flow panel.

Table 1 Summary of the experiments with different parameters

Parameter	Conditions	Details/comments
Ambient	23±0.5°C	-
Manikin heat output	113W	33-34°C
	80W	
Body posture	Sitting	Upright
	lying	

Clothing	Thick loose clothing	Tight jeans, thick loose long-sleeve shirt
	Wig	Short hair wig, slightly below the ear level
Chair	Cylinder	0.48m height
Bed	Sheet	0.7m height and 0.6m width
Breathing	Mouth Nose	See Table 2

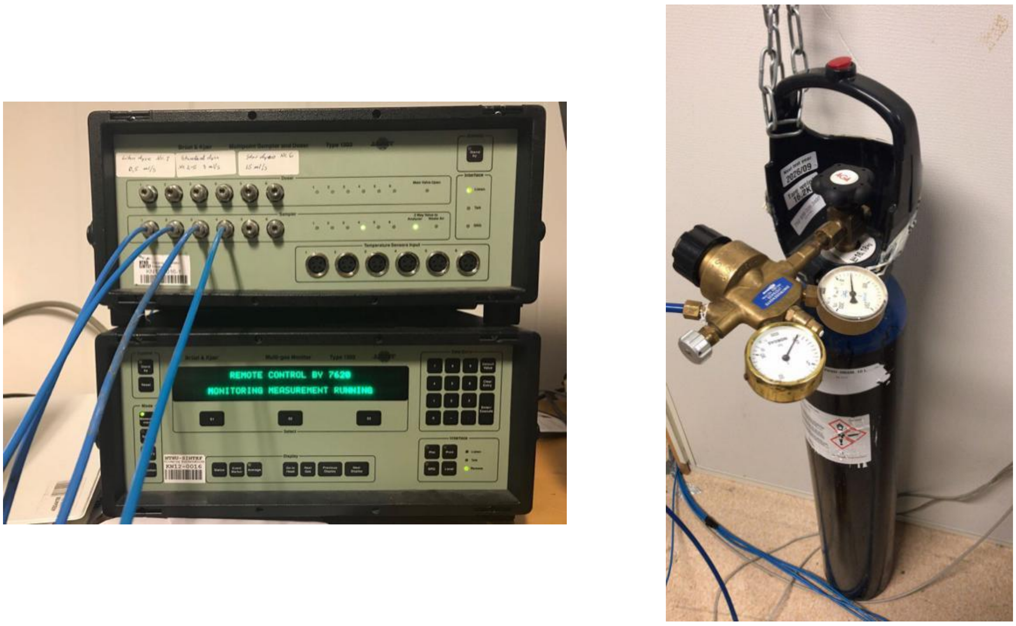
The manikin's breathing system can simulate the realistic airflow associated with the human inhalation and exhalation. The detail information of the exhalation orifices and breathing function was shown in Table 2. The maximum exhalation air velocity is 3.7m/s at the mouth, and the temperature of the exhalation air is around 26°C. The use of artificial breathing device in the manikin was not used during the non-breathing measurements.

Table 2 Respiration parameters of the breathing thermal manikin.

Frequency of breathing (time/min)	air flow (L/min)	Mouth area (cm^2)	Nose area (cm^2)
17.5	8.61	1.20	0.70

2.4. Tracer gas (N_2O) setup and instruments

Nitrous oxide (N_2O) was used as the tracer gas to simulate the pollutant. During the experiment, the N_2O was continuously released by a tube (Ø33 mm) with the gas flowrate of controlled at 0.40L/min. The tracer gas was successively sampled by four plastic tubes placed at 4 different locations (in the BZ, at the supply air panel, and at the two exhausts). The sampled tracer gas was then sent to a pre-calibrated Innova 1303 multi-gas sampler and doser (Brüel & Kjær, Ballerup, Denmark) coupled to an Innova 1302 photo-acoustic monitor.



(a) (b)

Figure 4 Tracer gas system (a) Trace detector (b) Gas cylinder

The performance of the anemometer system are shown in Table 3. The air velocity measurement system was "AirDistSys5000 (Sensor-electronic inc.). The system has 3 part: (1)a pressure sensor which is used to correct the anemometer readings according to the barometric pressure, (2)five omnidirectional anemometer probes, (3)a wireless transmitter transmitting the readings to a USB interface which is connected to a computer and to a power supply.

Table 3 Parameters of the air velocity measurement system.

Model	Measuring variable	Range	Accuracy	Resolution
SensoAnemo5100LSF	Velocity	0.05-5m/s	±0.02m/s or ±1.5% of readings	0.001m/s
SensoAnemo5100LSF	Temperature	-10°C-50°C	±0.2°C	0.1°C
SensoBar 5301	Pressure	500-1500hPa	±3hPa	1hPa

2.5. Contamination distribution indices

To investigate the pollutant remove efficiency of the modified LAF, only considering the efficiency is not enough. To make sure that the modified LAF system is functioning for residential purposes, in this study, exposure index is also considered.

The exposure to contaminants in the BZ of the manikin was determined using the local relative contaminant exposure index ε_{exp}. This indice has been used in a similar approach in previous studies (Cao et al. 2015; Berlanga et al. 2017; Olmedo et al. 2012). The contaminant exposure index ε_{exp} is defined as:

$$\varepsilon_{exp} = \frac{C_l - C_s}{C_{exh} - C_s} = \frac{C_l}{C_{exh}} \quad (1)$$

Where C_l is the average tracer gas concentration in the inhaled air of the receiving manikin and C_s and C_{exh} are the average tracer gas concentrations in the supply and exhausts respectively. The N_2O concentration of the supply air was assumed to be zero as the background concentration of N_2O was extremely low. A low contaminant exposure index means a low concentration of airborne pollutants in the experimental measurement point.

To investigate the intake risk, the intake fraction (*IF*) index (Laverge et al. 2014) was introduced. Its value is obtained as:

$$IF = \frac{\int Q_b C dt}{\int E dt} \tag{2}$$

Where *IF* is intake fraction, Q_b is the breathing rate of manikin (L/s). Where C is the concentration of the pollutant at the sampling site, which is equal to the C_l in equation 1. Being E the emission rate of the pollutant (L/s).

$$E_{ff} = \frac{C_{mix} - C_l}{C_l} \tag{3}$$

Where C_{mix} is the pollutant concentration in breathing zone with mixing ventilation, E_{ff} is the efficiency of removing the pollutant. In this equation, the modified localized laminar airflow system was regarded as a type of air cleaner, the E_{ff} is the same with the "Reduction effectiveness index" which was used to estimate the overall effectiveness of the air cleaners (Miller-Leiden et al. 1996; Spilak et al. 2016).

2.6. Investigated cases

The study consists of 5 experimental cases, based on the different supply air velocity and location of pollutant source, separated in 15 groups. Every group has two experiments, mouth breathing mode experiment and nose breathing mode experiment. The measurements are repeated in each group for three different velocities of the supply airflow: 0.15, 0.25 and 0.35 m/s for lying manikin, and 0.25, 0.30, 0.35 for sitting manikin. The ventilation rate is from 5.4ACH to 12.8ACH with the supply air velocity is from 0.15m/s to 0.35m/s. All cases are summarized in Table 4. The placements of the sampling and the pollutant source are shown in Fig. 5.

Table 4 Cases studied in this investigation.

groups	posture	Supply air(m/s)	Pollutant source location
1		0.25m/s	1m in front of the manikin (case 1)
2		0.30m/s	
3		0.35m/s	
4		0.25m/s	1m side away from the manikin (case 2)
5	Sitting	0.30m/s	
6		0.35m/s	
7		0.25m/s	Close to the back wall (case 3)
8		0.30m/s	
9		0.35m/s	
10		0.15m/s	1m in front of the bed (case 4)
11		0.25m/s	
12		0.35m/s	
13	Supine	0.15m/s	0.5m away from the end of the bed (case 5)
14		0.25m/s	
15		0.35m/s	

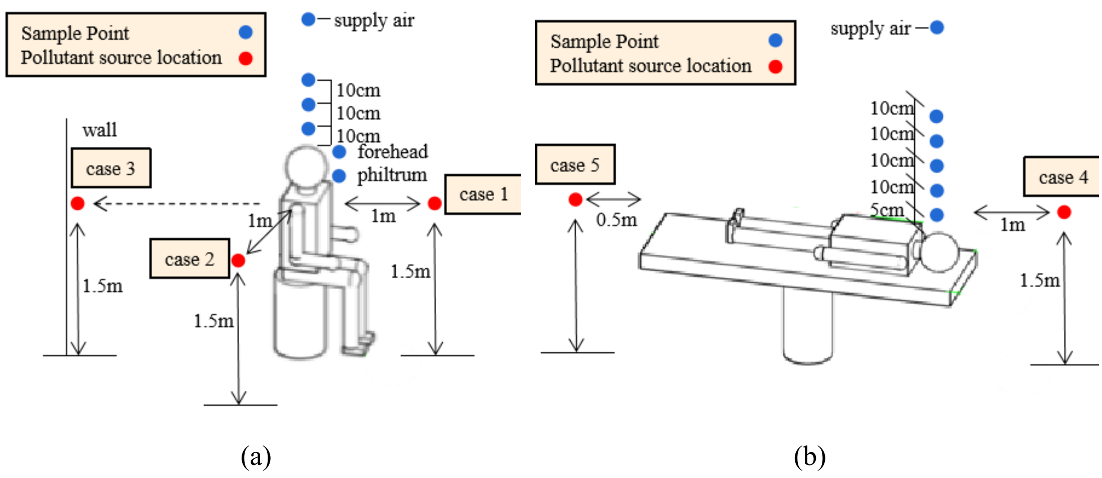


Figure 5 Placement of sampling and pollutant source

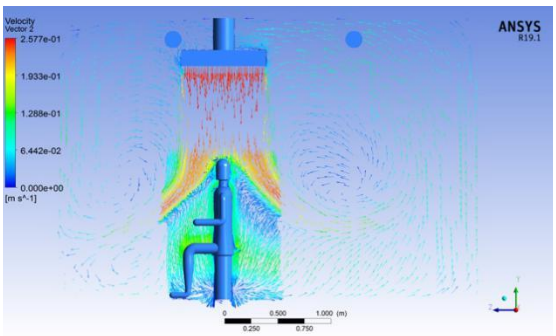
3. Results and discussion

3.1. Feasibility simulation

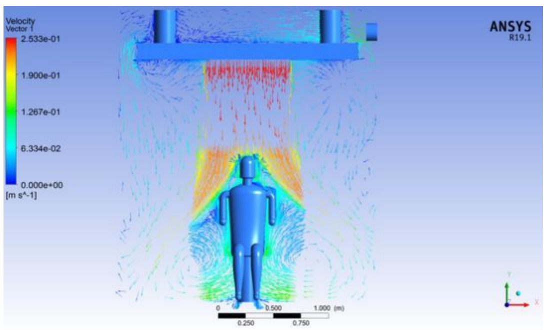
To see whether the modified airflow system was suitable or not, it was necessary to perform the simulation. If the simulation results showed that the supply can not reach the breathing zone, the experiment had no meaning.

3.1.1 Sitting posture simulation results

As shown in Fig.6(a) and (b), when the supply air velocity was 0.25m/s, the situation of the supply air got in touch with the human thermal plume. However, the thermal plume covered the breathing zone. The supply air spread from the head. Fig.6(c) and (d) showed the vector distribution 5cm and 10cm distance away from the manikin. At 5cm distance, the supply air could reach the height of mouth, and at 10cm distance, the supply air could reach the height of neck. It was not enough to improve the air quality in breathing zone.



(a)



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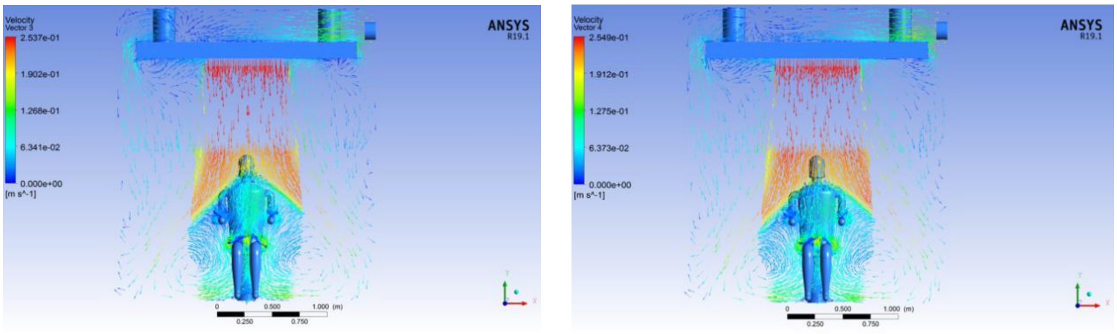
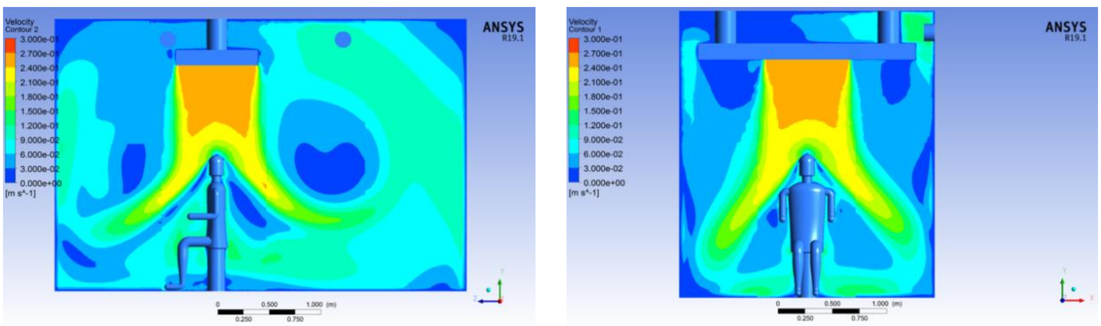


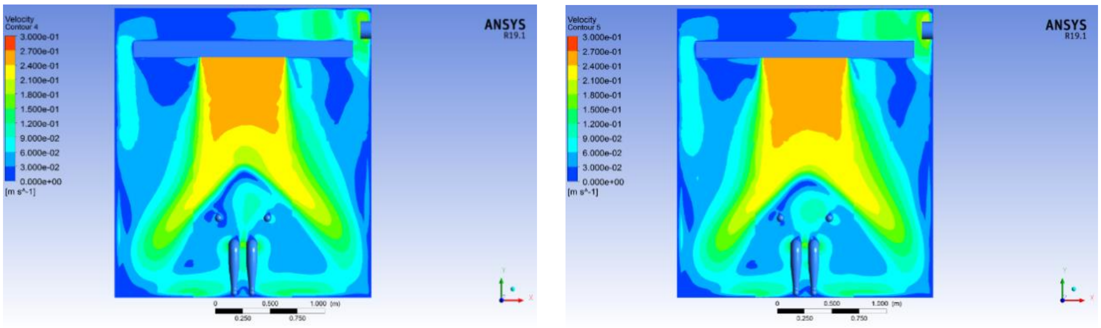
(c) (d)

Figure 6 Vector distribution(0.25m/s) (a)Side view;(b) Central of manikin;(c) 5cm away; (d)10cm away

In Fig.7, the magnitude of velocity could be seen very directly. In the side view, the supply air velocity dropped dramatically from a certain height above the head. Because of the thermal plume, the magnitude of velocity was very small close to the head. The velocity near the face region was very small, and the direction was upward. The distance of downward movement of supply air is limited, which could not achieve the desired effect on restricting the role of thermal plume, and the effect of improving the air quality in the breathing zone was limited.



(a) (b)

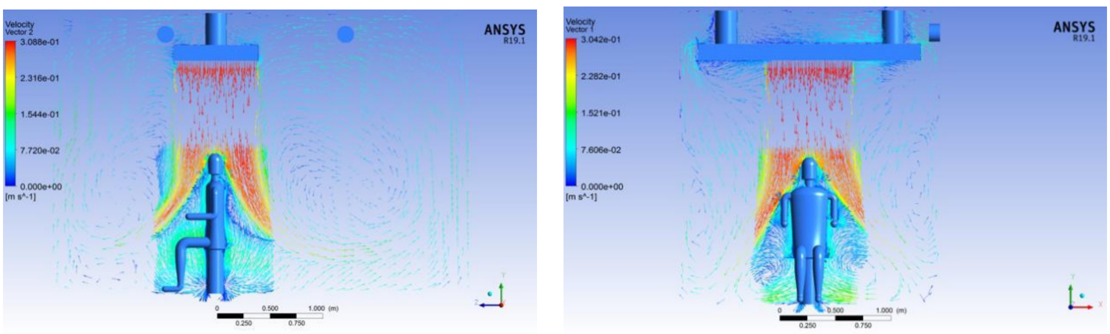


(c) (d)

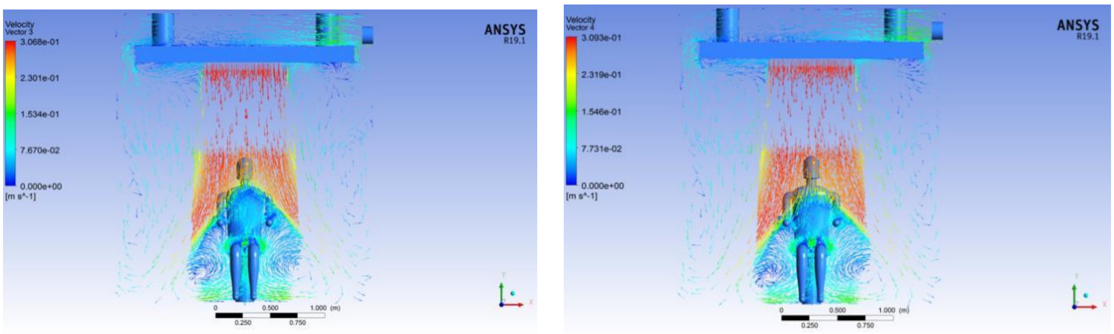
Figure 7 Velocity distribution(0.25m/s) (a)Side view;(b) Central of manikin;

(c) 5cm away;(d)10cm away

As Fig.8 showed, when the supply air velocity was 0.30m/s, the vector distribution had difference with the supply air velocity was 0.25m/s. First, the supply air could reach even further. Then, when the supply air touched the head, the angle of diffusion narrows compared to the lower supply air velocity. Most important, the supply air could reach the breathing zone, the impact of thermal plume was limited. The air optimization effect should be better.



(a) (b)

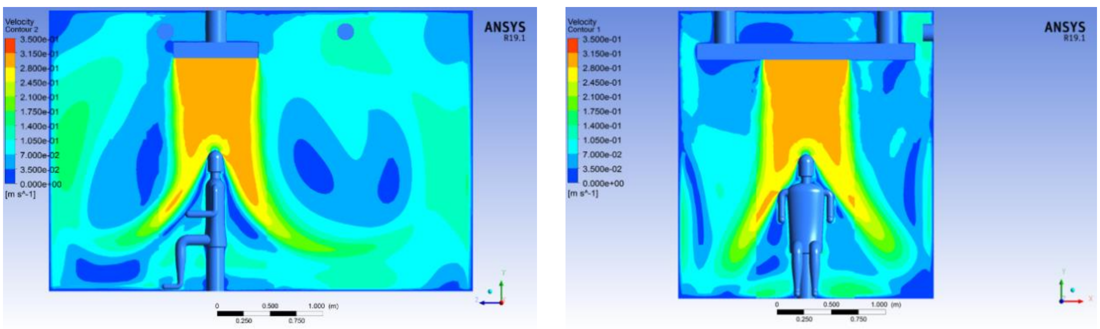


(c) (d)

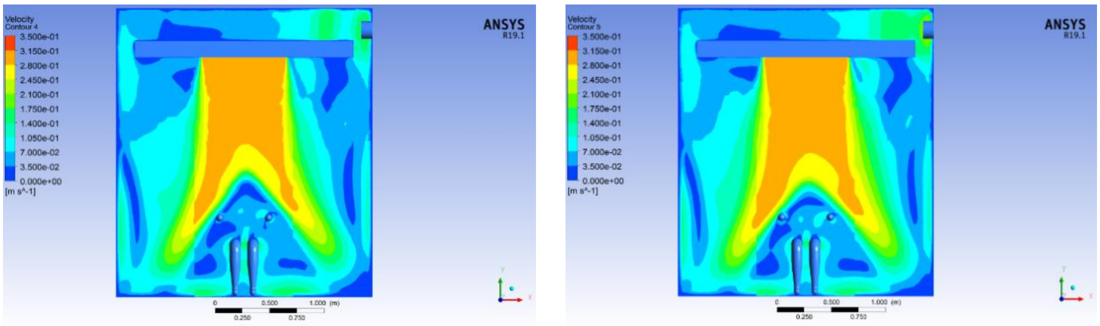
Figure 8 Vector distribution(0.30m/s) (a)Side view;(b) Central of manikin;(c) 5cm away;

(d)10cm away

In Fig.9, the magnitude of velocity near the face was bigger than the lower supply air situation. The supply air could reach the neck height. This supply air velocity could provide better air quality in breathing zone. The velocity around the manikin is near 0.2m/s, it has little influence on thermal comfort. The velocity will discuss in the next section.



(a) (b)

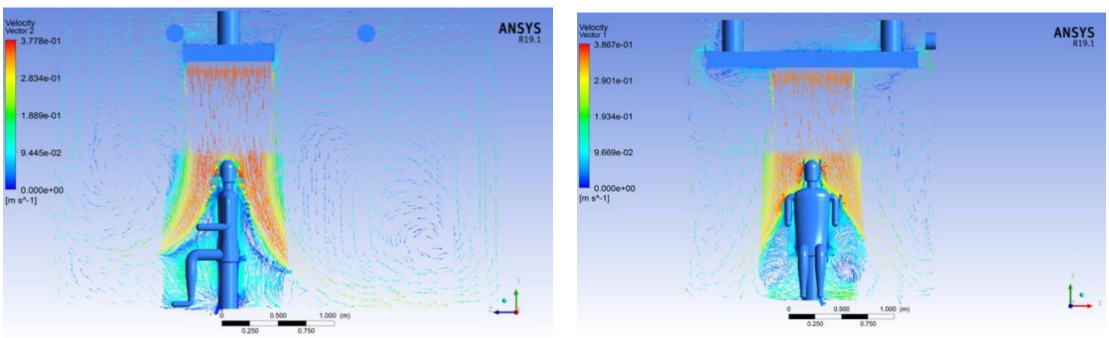


(c) (d)

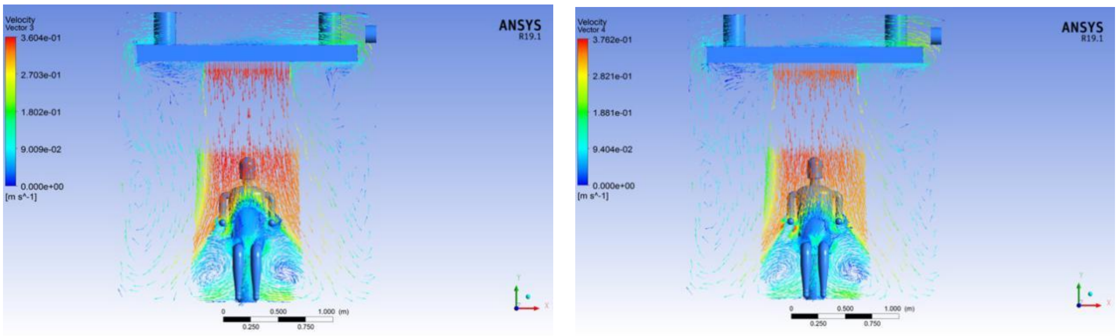
Figure 9 Velocity distribution(0.30m/s) (a)Side view;(b) Central of manikin;

(c) 5cm away;(d)10cm away

Fig.10 and Fig.11 showed the velocity distribution when the supply air velocity increased to 0.35m/s. In the side view (Fig.9(a)), it was very similar with the lower supply air velocity situations. The interaction between supply air and thermal plume was a little bigger than lower supply air velocity situation. The angle of diffusion narrows slightly. Meanwhile, the supply air could reach further distance in front the manikin. When the supply air was 0.35m/s, it might provide the best air quality in breathing zone. However, when the supply air was relatively high, it might disturb the pollutants near the floor. Also, the higher velocity might cause uncomfortable drafts feelings.



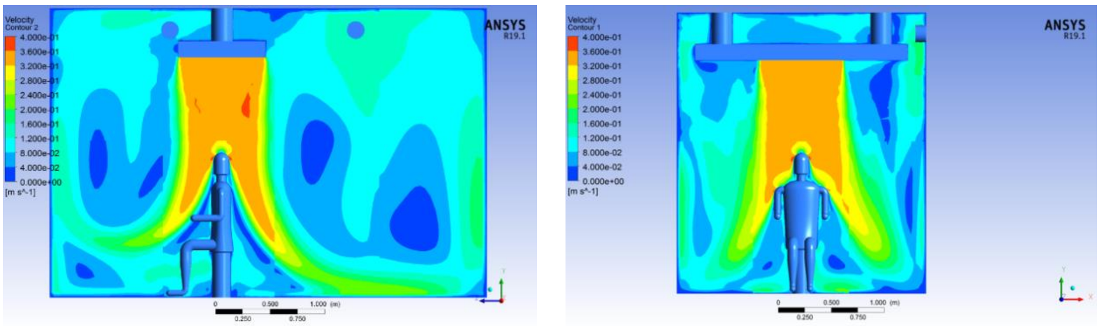
(a) (b)



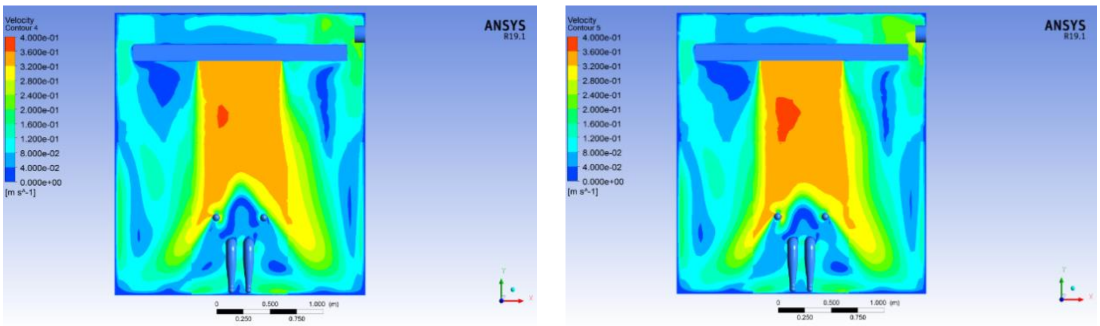
(c) (d)

Figure 10 Vector distribution(0.35m/s) (a)Side view;(b) Central of manikin;(c) 5cm away; (d)10cm away

In Fig.11, the pollutant near the floor was disturbed because of the high supply air velocity. This might have influence on the whole indoor environment. In addition, the influence of air velocity on the thermal comfort should have bad impact.



(a) (b)



(c) (d)

Figure 11 Velocity distribution(0.35m/s) (a)Side view;(b) Central of manikin;

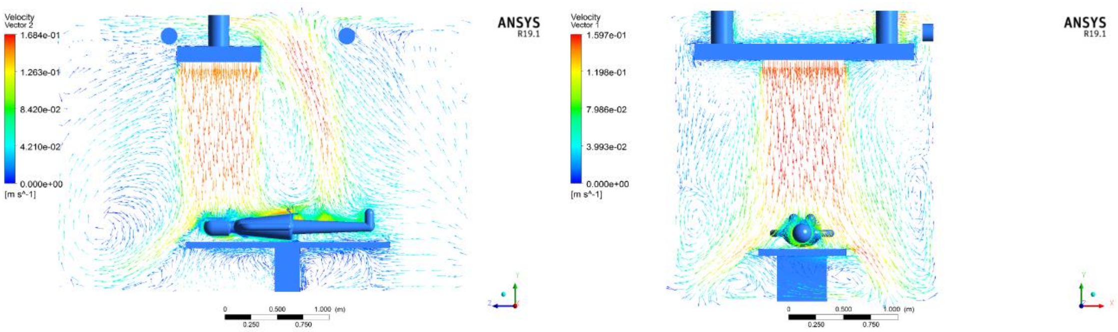
(c) 5cm away;(d)10cm away

3.1.2 Supine posture simulation results

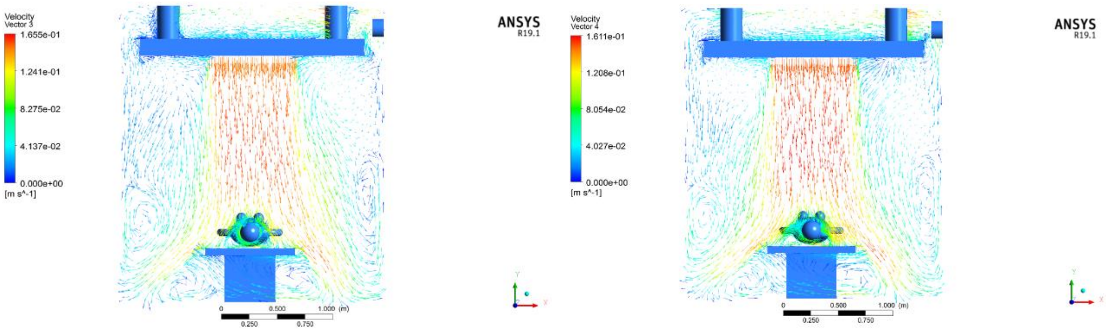
For the supine posture, breathing zone is the most important zone. In this section, the velocity distribution was focused.

As Fig.12 showed, when the supply air was 0.15m/s, the magnitude of velocity dropped rapidly near the surface of the head. And the vortex was generated near the face. The fresh air could not reach the face. Although, the 0.15m/s supply air could separate the breathing zone from other space, the low supply air could not provide as much as possible fresh air into the breathing zone.

Near the bed, the air could follow the thermal plume move to the breathing zone, which means that the pollutant near the bed might also move to the breathing zone, but it needs more detail research.



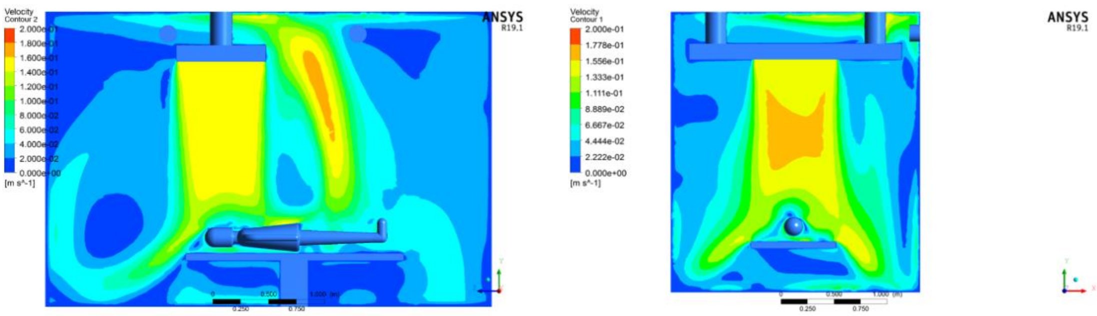
(a) (b)



(c) (d)

Figure 12 Vector distribution(0.15m/s) (a)Side view;(b)Philrum;(c)Forehead;(d)Neck

As Fig.13 showed, the velocity distribution presented that the velocity dropped dramatically near the head. The 0.15m/s supply air velocity was not enough to provide the high-quality air in breathing zone. The pollutant near head region would not move away according to this figure.



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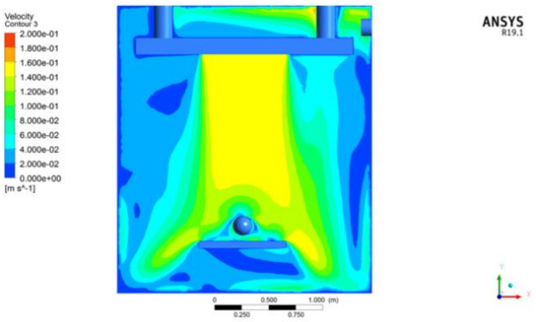
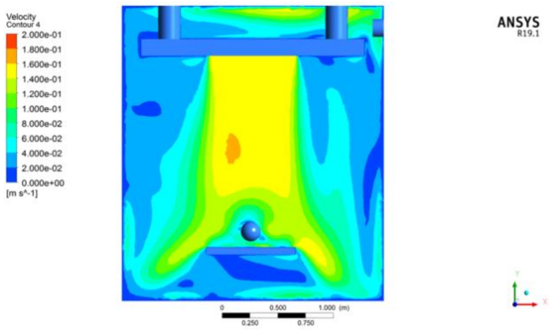


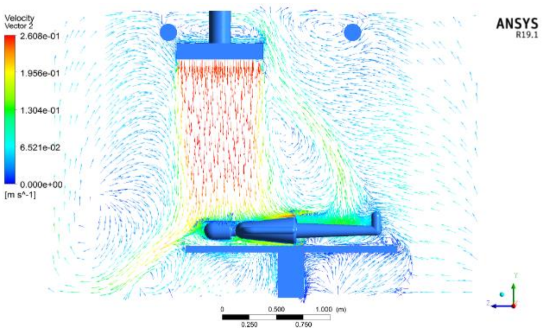
(c)



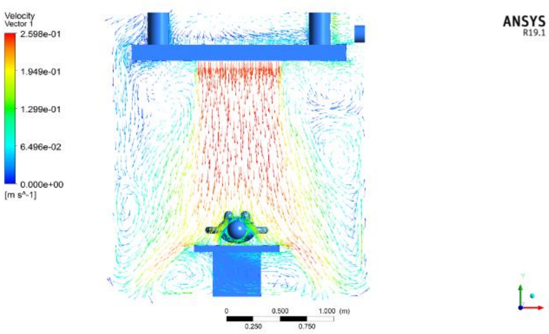
(d)

Figure 13 Velocity distribution(0.15m/s) (a)Side view;(b)Philrum;(c)Forehead;(d)Neck

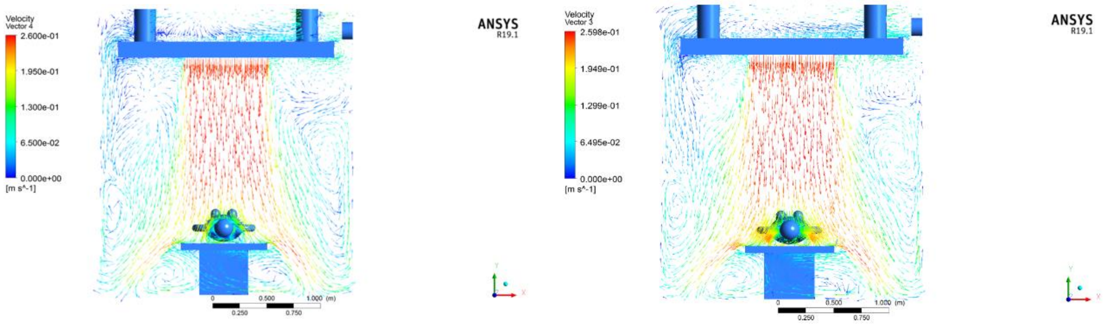
As Fig.14 showed, when the velocity increased to 0.25m/s, the fresh air could move directly near the face, also it could make the air near bed not move to the breathing zone. This velocity could change direction of the air around the head and let the breathing zone have high-quality air. The pollutant around the lower part of the manikin would not move into the breathing zone.



(a)



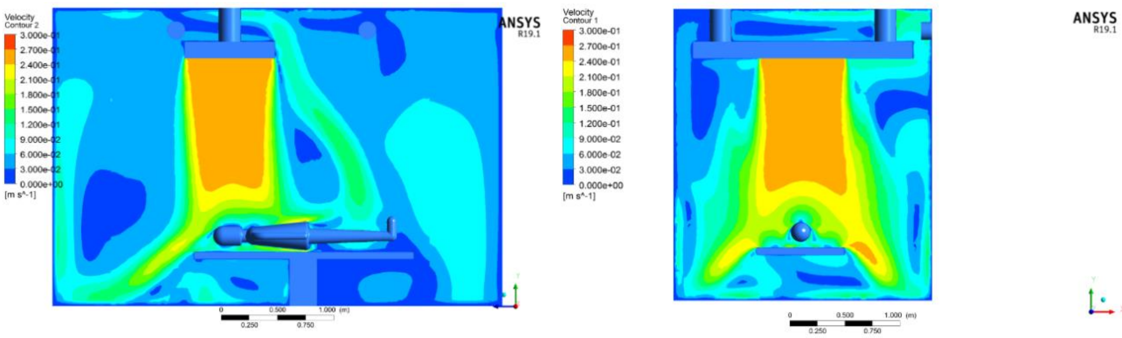
(b)



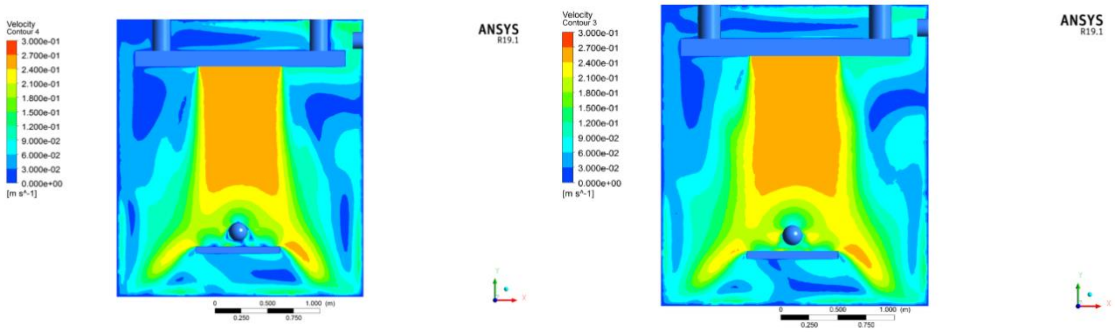
(c) (d)

Figure 14 Vector distribution(0.25m/s) (a)Side view;(b)Philrum;(c)Forehead;(d)Neck

The velocity distribution was very similar with the lower supply air velocity situation (Fig.15). This velocity has little impact on the air near the floor. The air above the manikin is downward and the velocity near head is around 0.15m/s, it has little impact on thermal comfort.



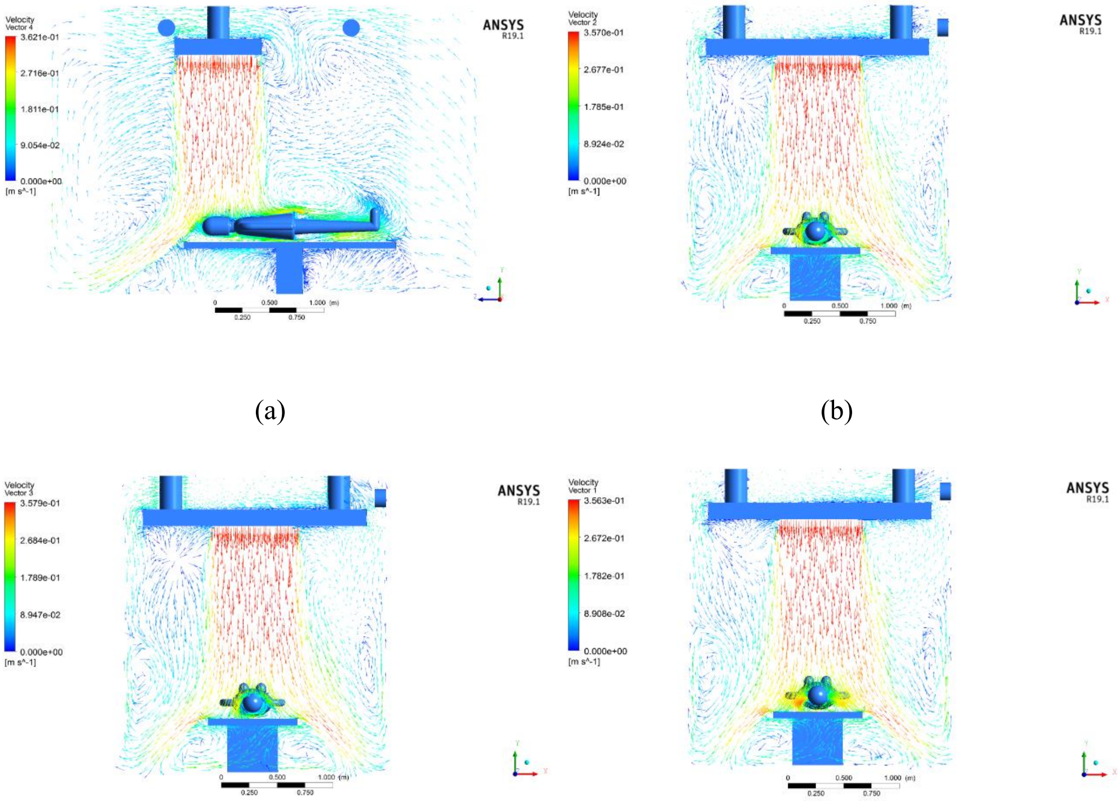
(a) (b)



(c) (d)

Figure 15 Velocity distribution(0.25m/s) (a)Side view;(b)Philrum;(c)Forehead;(d)Neck

When the supply air was 0.35m/s, the interaction with thermal was the same with 0.25m/s supply air (Fig.16). However, above the lower part of the body, the air had vortex, which means the pollutant could gather here and not move to the exhaust.



(a) (b)

(c) (d)

Figure 16 Vector distribution(0.35m/s) (a)Side view;(b)Philrum;(c)Forehead;(d)Neck

As fig.17 showed, the highest supply air velocity had impact on the air near the floor. The air was forced to move upwards, also the pollutant near the floor. For the whole environment, this velocity might not be the best choose. The velocity around head is around 0.2m/s, it has more impact on the thermal comfort compare to the lower supply air velocity.

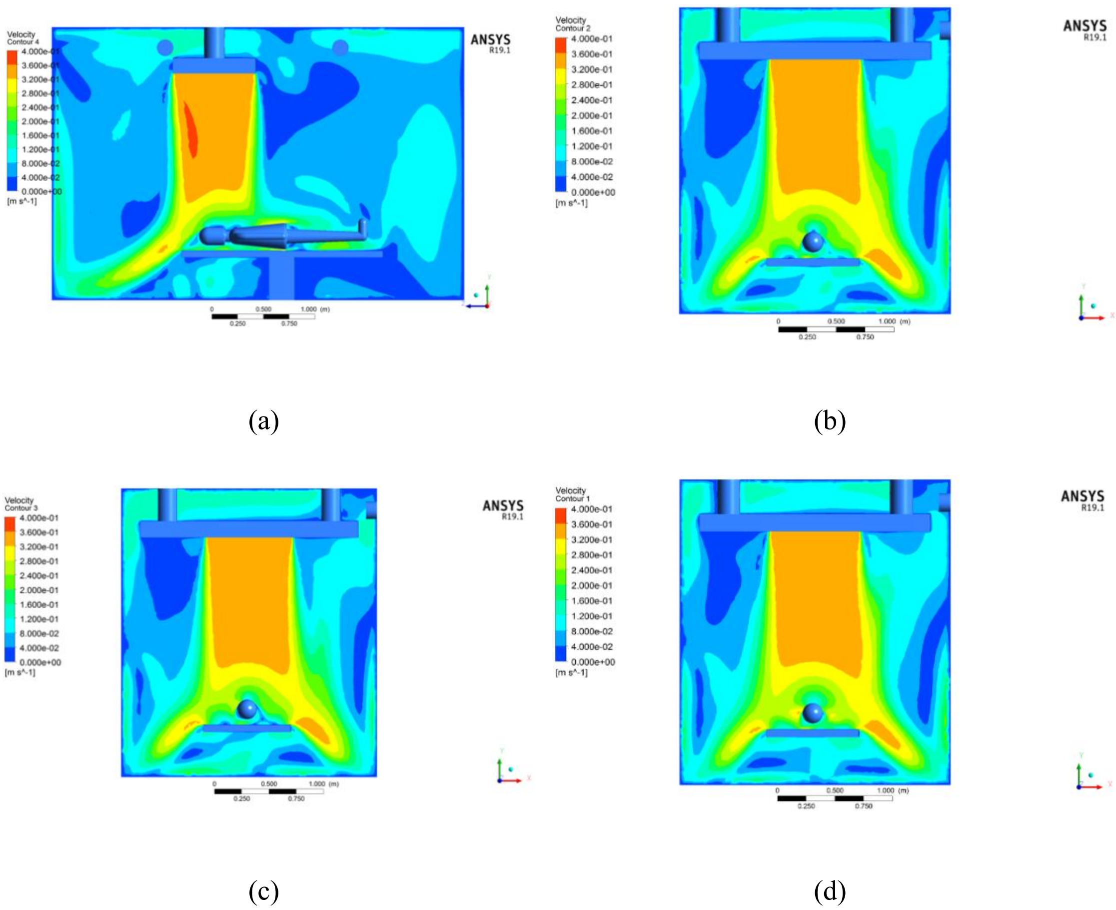
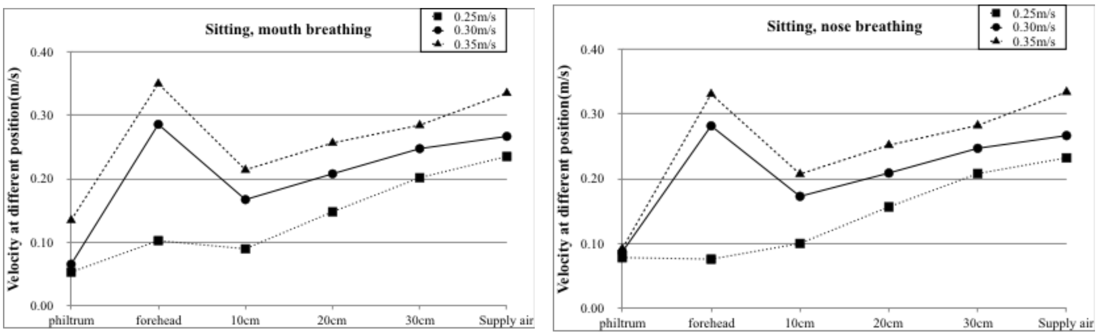


Figure 17 Velocity distribution(0.35m/s) (a)Side view;(b)Philrum;(c)Forehead;(d)Neck

3.2. Characteristic of the airflow above the manikin

3.2.1 Sitting position

To investigate the characteristic of the airflow above the sitting manikin, there were 6 sampling point located above the manikin. The sampling points placed at 5cm horizontal distance away from the philtrum and forehead, and 10cm, 20cm, 30cm above the head. The last point placed at supply air inlet.

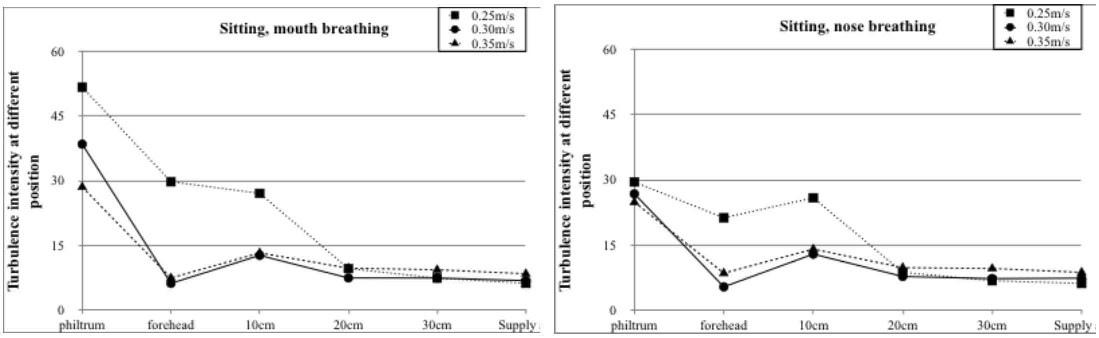


(a) (b)

Figure 18 Velocity at different position(a)Mouth breathing;(b)Nose breathing

As for sitting position experiment, the supply air had 3 different velocities, 0.25m/s, 0.30m/s and 0.35m/s respectively. The Fig.18 present the velocity above the manikin. The velocity distributions were very similar between mouth breathing case and nose breathing case, the change of the velocity value were almost the same.

With the sampling point height decrease, the velocity magnitude went down from inlet to 10cm vertical distance from head. However, at the 5cm horizontal distance from forehead, the magnitude of velocity changes drastically. When the supply air velocity is 0.25m/s, because of the magnitude of the supply air velocity was small, the velocity direction might have changed above the head which means that the velocity with small magnitude at philtrum and forehead height might had opposite direction with supply air velocity, this phenomenon needs further study. When the supply air velocity was 0.30m/s or 0.35m/s, the velocity at forehead height increased dramatically which means the supply had downward trend after contacting with head and the airflow could flow through the zone in front of face.



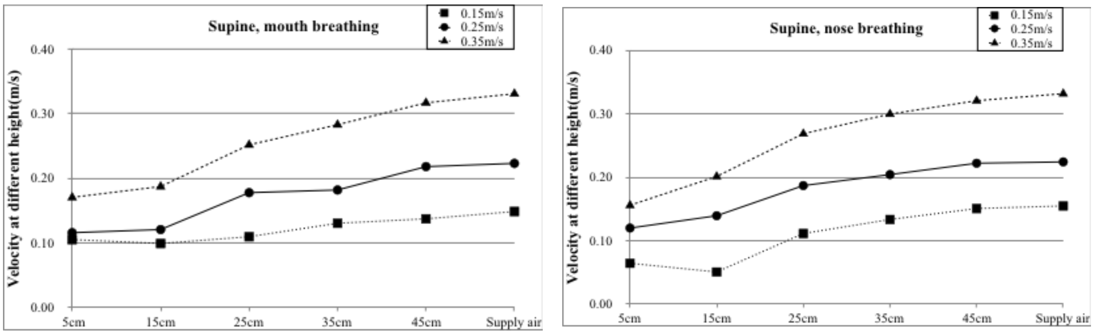
(a) (b)

Figure 19 Turbulence intensity at different position(a)Mouth breathing;(b)Nose breathing

In Fig.19, when the supply air velocity was 0.25m/s, the airflow had big turbulence at 10cm vertical distance above the head. Because the human thermal plume had the impact on the supply air, the supply air with this magnitude can not deliver the clean air to the breathing zone. When the supply air velocity was 0.30m/s or 0.35m/s, the turbulence intensity increased slightly because of the shape of the head blocked the movement of supply air. At the height of philtrum, the turbulence intensity increased dramatically, because of the interaction of breathing air and supply air.

3.2.2 Supine position

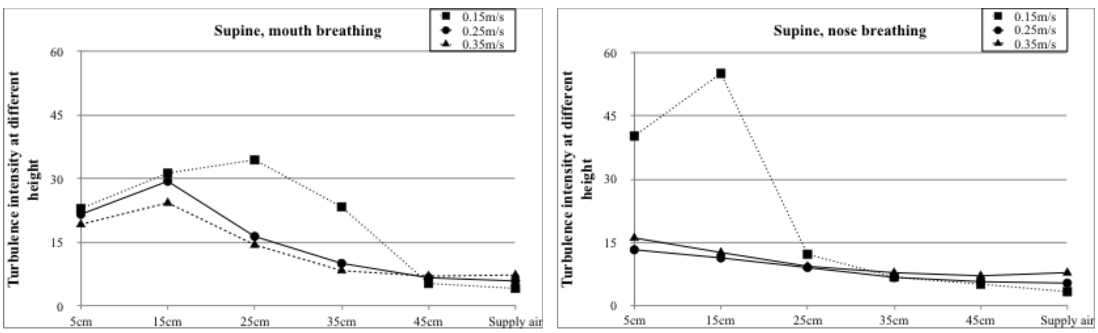
To investigate the characteristic of the airflow above the supine manikin, there were also 6 sampling point located above the manikin's head. The sampling points placed above the philtrum, the distance were 5cm, 15cm, 25cm, 35cm and 45cm. The last point placed at supply air inlet.



(a) (b)

Figure 20 Velocity at different position(a)Mouth breathing;(b)Nose breathing

As for supine position experiment, the supply air had 3 different velocities, 0.15m/s, 0.25m/s and 0.35m/s respectively. The velocity distributions were very similar with different breathing mode and different supply air velocity. However, when the magnitude of supply air was 0.15m/s, from 15cm vertical distance to 5cm vertical distance, the velocity increased slightly. This phenomenon present that the human thermal plume has interaction with supply air at this height, the direction of velocity at 5cm vertical distance from head is upward.



(a) (b)

Figure 21 Turbulence intensity at different position(a)Mouth breathing;(b)Nose breathing

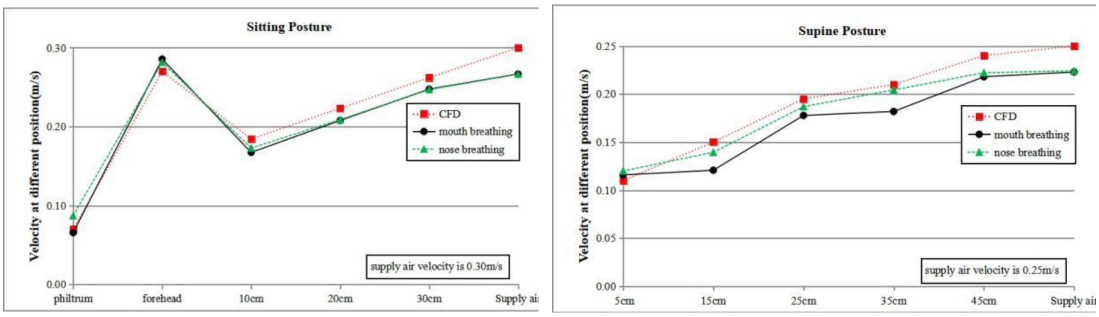
In these two figures, the impact of different breathing mode on turbulence intensity was different. Considering the direction of the breathing jet in different breathing mode, the direction of mouth breathing airflow is more vertical. When the supply air velocity is low(0.15m/s), the impact of mouth breathing mode was smaller than nose breathing mode. At the 35cm vertical distance above the head, the mouth breathing air had made disturbance to the supply air, when the magnitude of velocity is 0.15m/s, this disturbance was the most prominent. Mouth breathing would distract the supply air.

As for nose breathing case, when the supply air velocity was 0.15m/s, because of the nose breathing jets, at the 15cm vertical distance from face, the turbulence intensity increased dramatically. However, when the supply air velocity was 0.25m/s or 0.35m/s, the turbulence intensity increased slightly.

3.2.3 Comparison between the simulation and experiment

For both sitting and supine posture, the velocity above the head from the CFD results were a little higher than the experimental data. In Fig.22, It was easy to observed that the supply air velocity did not reach the setting point in experimental study, that might cause the simulation results larger than the experiment data.

For sitting posture, the trend of these three lines were the same, but the simulation results were a little lower than experiment data in philtrum and forehead region. That might because the impact of breathing air jet was stronger in these region. Except for the supply air point, the difference between the CFD results and experiment data was less than 10%. For supine posture, the three line also had the same trend. The CFD results were more close to the nose breathing experimental data. The impact of breathing mode was much more significant in supine posture.



(a) (b)

Figure 22 Velocity comparison between simulation and experiment

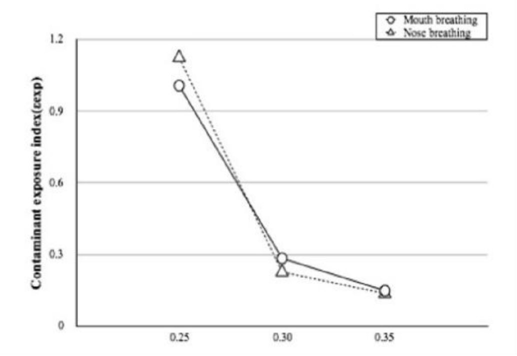
(a)Sitting posture;(b)Supine posture

3.3. air quality for the investigated cases

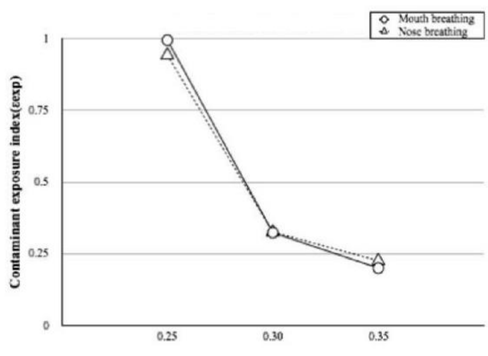
The average contaminant exposure indices (ε_{exp}) and the intake fraction (*IF*) were summarized for each group according to the location of the pollutant source.

3.3.1 Sitting position

With the increasing of the supply air velocity, the ε_{exp} value decreased significantly no matter where the pollutant source was placed. The flow mode of the inhalation and the exhalation of the manikin showed little influence on the ε_{exp} values. When the supply air velocity was at 0.25m/s, the supply air could not deliver the required fresh air to the BZ, and the pollutant concentration level in the BZ was almost the same with that at the exhaust, which means that a low supply air velocity is not helpful for improving the air quality in the breathing zone, as it for the mixing ventilation.



(a)



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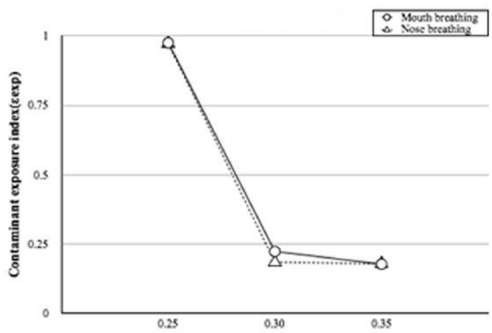


(c)

Figure 23 Contaminant exposure index(sitting) (a)case 1;(b)case 2;(c)case 3

As for the source placed in front of the manikin and near the manikin, when the supply air velocity was 0.30m/s, the ε_{exp} was significantly decreased, if increase the supply air velocity to 0.35m/s, the ε_{exp} could decrease lower than 0.25. Because these two source near manikin, increasing the supply air velocity had more efficiency to improve the air quality. When the pollutant source near the door, because of the distance from manikin to pollutant source was far, increasing the supply air velocity from 0.30m/s to 0.35m/s had less efficiency to improve the air quality.

The *IF* values show the same decreasing tendency with the increase of supply velocity as for ε_{exp} values. Similarly, the mode of the inhalation and exhalation flow of the manikin shows no influence on the *IF* values either.

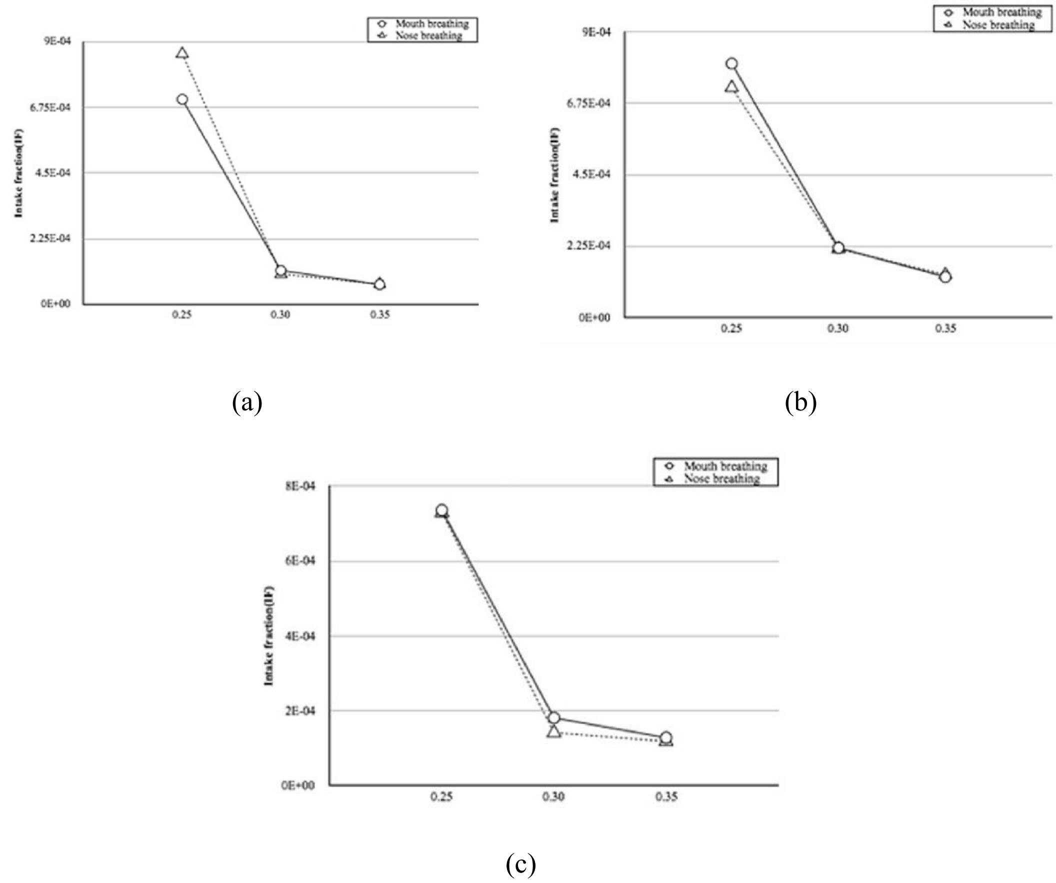
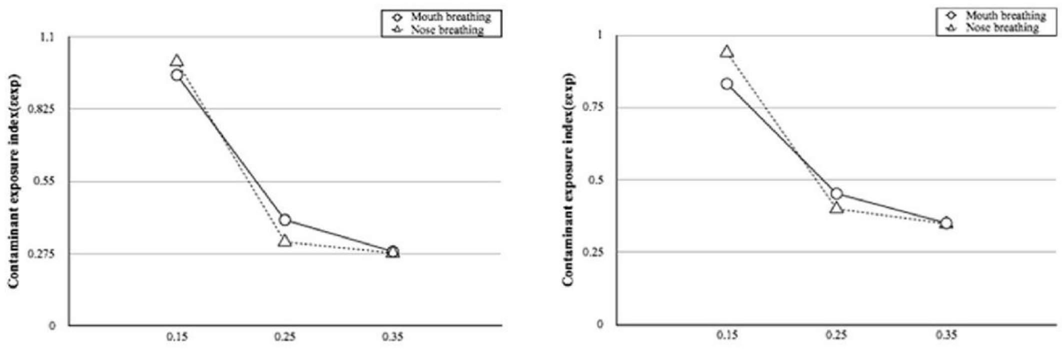


Figure 24 Intake fraction(sitting) (a)case 1;(b)case 2;(c)case 3

3.3.2 Supine position

The same with sitting position cases, the *IF* values show the same decreasing tendency with the increase of supply velocity as for ε_{exp} values. According to the results obtained, contaminant exposure index ε_{exp} shows an decreasing tendency with the increase of supply velocity for all four cases investigated. With the increase of the supply air velocity, no matter where the pollutant source placed, the ε_{exp} value was significantly decreased. The mode of the inhalation and exhalation flow of the manikin shows no influence on the ε_{exp} values. When the supply air velocity was 0.15m/s, the supply air can only deliver a little fresh air to the breathing zone, the pollutant concentration in breathing zone was slightly lower than pollutant concentration in exhaust which means the low supply air only has little effect on improve the air quality in breathing zone.

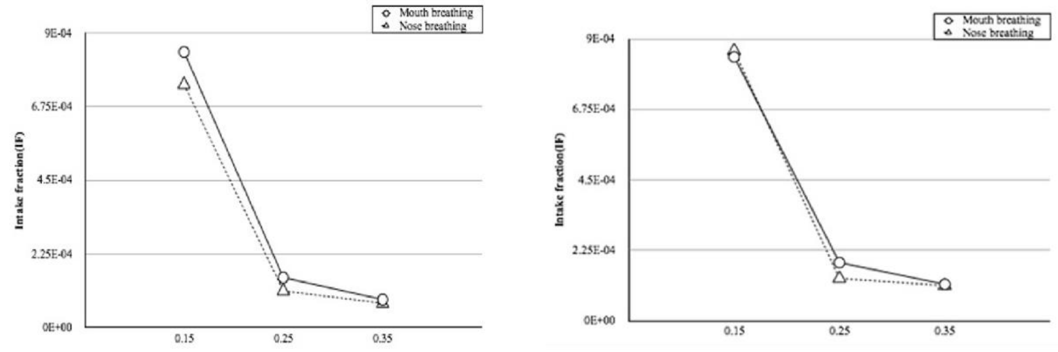


(a) (b)

Figure 25 Contaminant exposure index(lying) (a)case 4;(b)case 5

As for the supine position, when the supply air velocity increased to 0.25m/s, the ε_{exp} decreased quickly. If the supply air velocity increased to 0.30m/s from 0.25m/s, the ε_{exp} decreased slightly. It was the same with sitting position cases, however the supply air velocity had difference.

The *IF* values show the same decreasing tendency with the increase of supply velocity as for ε_{exp} values. Similarly, the mode of the inhalation and exhalation flow of the manikin shows no influence on the *IF* values either.



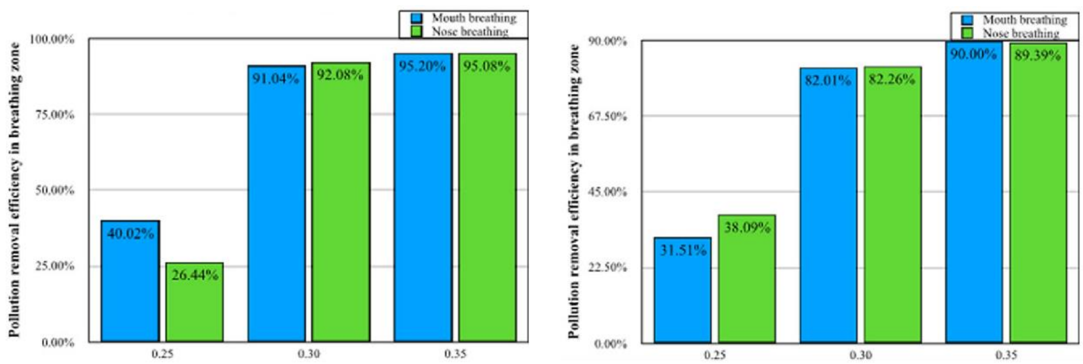
(a) (b)

Figure 26 Intake fraction(lying) (a)case 4;(b)case 5

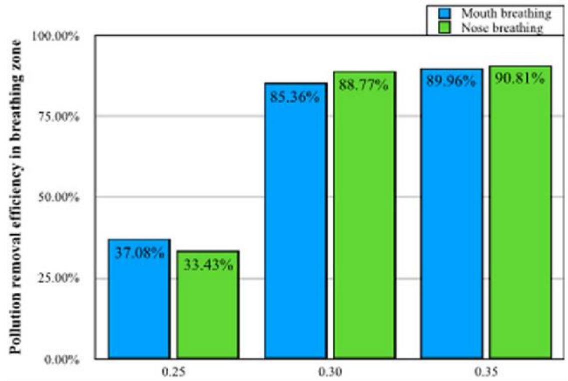
3.4. Pollutant removal efficiency

3.4.1 Sitting position

For the sitting position cases, when the supply air velocity increased to 0.30m/s, the E_{ff} reached over 82%, and even over 90% when the source was 1m in front of manikin. Although the ε_{exp} and *IF* were almost the same as that of the mixing ventilation system, the E_{ff} reached over 26% when the supply air velocity was at 0.25m/s. At 0.25m/s, the breathing mode and the position of the pollutant source were found to have much more significant influence on the E_{ff} compared to the other two experimented supply air velocities.



(a) (b)



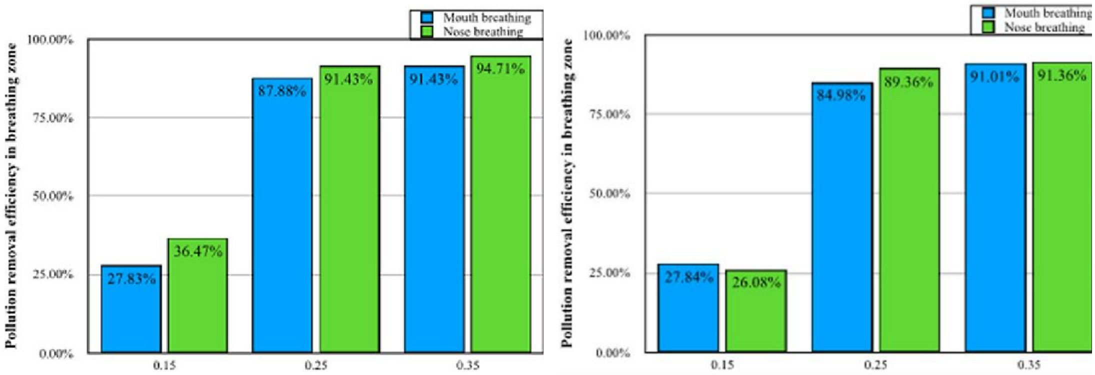
(c)

Figure 27 Pollutant removal efficiency (sitting) (a)case 1;(b)case 2;(c)case 3

When the supply air velocity increased from 0.30m/s to 0.35m/s, the E_{ff} increased slightly. When the supply air velocity increased from 0.25m/s to 0.30m/s, the E_{ff} increased dramatically. Compared to the 0.25m/s and 0.35m/s, the supply air velocity set at 0.30m/s was the most suitable one.

3.4.2 Supine position

For the case of supine position, when the supply velocity air increased to 0.25m/s, the E_{ff} reached over 84%, and even over 90%. Although the ε_e and *IF* were almost the same as that of the mixing ventilation system, the E_{ff} was over 26% when the supply air velocity was 0.15m/s. At 0.15m/s, the breathing mode and the position of the pollutant source were found to have much more significant influence on the E_{ff} when compared to the other two supply air velocities. With an increased supply air velocity, the influence mitigated.



(a) (b)

Figure 28 Pollutant removal efficiency(lying) (a)case 4;(b)case 5

When the supply air velocity increased from 0.25m/s to 0.35m/s, the E_{ff} slightly increased. However, the E_{ff} dramatically increased as the supply air velocity increased from 0.15m/s to 0.25m/s. Compared to when the supply air was 0.15m/s and 0.35m/s, 0.25m/s was found to be a better setting for pollutant removal.

3.5. Practical limitations

Although this study is unique in its design and could offer scientific evidence to support the potential realization of a new ventilation concept in bedroom, living room or ward of a hospital, it does suffer from some limitations. First, this study focused on the airborne contaminant and did not consider dynamic supply air temperature. Second, transient conditions that could influence the contaminant movement (e.g., door openings, and human movement) were also not taken into account.

4. Conclusion

This study presented detailed experimental and simulation results on the pollutant removal efficiency of a localized laminar airflow system considering the impact between respiratory activities and thermal plume. Localized laminar airflow system manifested a special form of mixing ventilation through the use of supply panel with small slot for direct breathing zone air delivery, to dilute the contaminated air in the sub-zones.

The contaminant exposure index (ε_{exp}) and intake fraction (*IF*) results indicated the effectiveness of the proposed ventilation strategy. We found that the contaminant exposure of the manikin was highly dependent on the supply air velocity, especially when the supply air at the relatively low velocity levels. With an increased supply air velocity, the impact of the breathing mode on the exposure index (ε_{exp}), intake fraction (*IF*), and pollutant removal efficiency alleviated.

Positions of the pollutant sources showed little effect on the exposure risk and the intake fraction (*IF*) of the manikin, so did it on the E_{ff}. The results also showed that the exposure risk is significantly lower if choosing a suitable supply air velocity.

Localized laminar airflow system was proven to be an effective way of maintaining air cleanness in the BZ. According to ASHRAE 55, ISO 7730 and the Chinese standard "Indoor air quality standard (GB/T 18883-2002)", with the modified system on, the temperature around human body is in the comfort range. For sitting posture, the velocity is over 0.25m/s, which is a little higher than the comfort range, but for supine posture, the velocity is in the comfort range. It means that, with the suitable supply air velocity, the localized laminar airflow system would not influence the thermal environment around human. This kind of system could be used in bedroom, living room or any other kind of room which people only has low labour intensity activities or they were in resting state.

5. Declarations

5.1. Ethics approval and consent to participate

Not applicable.

5.2. Consent for publication

Not applicable

5.3. Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

5.4. Competing interests

The authors declare that they have no competing interests.

5.5. Funding

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5.6. Authors' contributions

Zhu Cheng and Amar Aganovic did the experiment and analyzed the data. Zhu Cheng was the major contributor in writing the manuscript. Guangyu Cao provided technical support and theoretic instruction. Zhongming Bu helped to complete the simulation.

5.7. Acknowledgements

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