The investigation of the influence of thermal plume and breathing on sleeping microenvironment

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Abstract: Most of humans' lifetime was spent indoor, especially in bedroom. Thus, understanding the characteristics of the sleep microenvironment is a prerequisite for better control and improvement of our sleeping environment. This study investigated the temperature and velocity field above the heads of sleeping people with supine postures, and explored the interactions between the thermal plume and the breathing airflow, where both the thermal manikins and real human subjects were used in our experiment settings. Three different breathing modes were considered in this study, where the non-breathing mode was used to investigate the characteristics of the thermal plume, and the synergy of the mouth and nose breathing mode on the thermal plume was also investigated. The results showed that the thermal plume of a supine posture person was not strong compared to that of a standing or sitting person, and the breathing airflow could influence the development of the thermal plume. Over the head of a sleeping person, the velocity of the thermal plume could be increased by both of the breathing modes, but no significant difference in the velocity and temperature field was found for the two breathing modes. It was also found that pollutants near the bed surface could be brought to the breathing zone with low velocity airflow, but could be blocked by the nasal exhalation jet. The findings in this study could provide theoretical support and guidance to improve the air quality in the breathing zone.

Keywords: thermal plume; breathing thermal manikin; human experimentation; supine posture.

1. Introduction

The human skin temperature is normally maintained at 33~34°C under normal activity and at rest[1],[2], while the core body temperature is a little higher than that of the skin at around 37°C[3]. On the other hand, according to several indoor environment standards, the indoor air design temperature typically ranges from 20 to 26°C[4],[5], about 7~14°C lower than that of the human skin. Due to the temperature difference between the human skin and the conditioned indoor air, heat loss from the human body engenders the thermal plume and a convective boundary layer (CBL) near the human skin, which could have important implications on the airflow and the pollutants concentrations around people[6],[7]. For example, some scholars found that the thermal plume of people could affect the pollutant distribution around the human body, especially for that in the breathing zone (BZ). Thus, for indoor environments with little or no air ventilations, the thermal plume becomes a critical influencer for its airflow and temperature field[8],[9].

The sleep microenvironments are places that contain the bed frames and the bedding materials, mattresses, pillows, and the air above these items[10]. Notably, the BZ and the thermal plumes of the human are also part of the sleep microenvironment[11][12]. It is distinct from the other indoor environments in several aspects, and one of its most prominent feature is that the low ventilation rate here fosters the accumulation of pollutants. When compared to the other rest places, the BZ of the sleep microenvironment is closer to potential sources of pollutants such as the mattress and the pillow, which could result in serious health exposure[13],[14]. For example, the bedroom mattresses, cosmetics, clothes and furniture could release volatile organic compounds (VOCs)[15] and semi-volatile organic compounds (SVOCs) into the air[16],[17], and the mattresses, pillows and the bedding materials are also known as the gathering places for dust mites and allergenic particles[18].

In the undisturbed sleep microenvironment, the interaction between the thermal plume and the breathing airflow is a critical influencer for the airflow distribution and the velocity field in the bedroom[19]. Some scholars have found that the human breathing could have significant impact on the exposure of the sleeping person[20]. In addition, according to the results of a previous study, breathing through nose or mouth has different impact on the velocity and temperature distribution around people, especially in the BZ[21]. At low activity levels, most of the people exhale through the nose[22], and the two separate airflows from the nose could blow to the chest region, which differs from the mouth breathing completely[22],[23]. In an undisturbed indoor environment, the airflow trends to move upward due to the angle of the breathing airflow and the human thermal plume under the supine posture.

Scholars have found that the body posture has significant effect on the CBL and the thermal plume around the human body. That is, different body posture affect the growth of the CBL in different ways. For example, compared to the standing posture, the supine posture could result in weaker thermal plume in the head region[24],[25]. The reason is that, for supine posture, the heat loss of the lower body part has little effect on the thermal plume at the head region, and the heat loss in the head region of a supine person only accounts for about 30% of that for a standing person[26]. Thus, the thermal plume generated from the supine posture is slower and thinner[24] when compared to the person with standing or sitting posture.

As mentioned before, pollutants could release from the mattress surface, and the thermal plume generated by the sleeping person could transport these pollutants upward to the BZ[27]. For sleeping situation, the particles and other pollutants became airborne via applying one or more external forces, like air burst from the mattress when people lied on the bed, thermal plume around the human body, and the breathing airflow[26],[28],[29]. These airborne pollutants (e.g., the particles) would further transport into the BZ, which could cause exposure risk to the sleeping people. Some scholars found that the number of particles in the BZ was influenced by the body position of the sleeping person[26], strength of the thermal plume around human body [30],[31],[32], and the size of the particle[11], with the first and second factor highly related to the sleep microenvironment. Pet allergen can be detected in the indoor air and in soft furnishings inside households even without a pet[33],[34], the pet allergen problem is quite serious especially for family with babies. When people sleep with the supine posture, the allergen from the surface of bed would move into the BZ like particles[35].

Few research focused on the air velocity of the thermal plume generated by the human body with supine posture. However, most of people's relaxing time at home is in the supine posture, and the sleeping environment is hard to be disturbed in real situation. Therefore, research on the supine posture is especially of practical significance. A lot of scholars focused on the human exposure to the indoor air pollutants in the sleep microenvironments[27]. However, the interaction between the thermal plume and the breathing airflow is still not clear, and the develop mechanism of the airflow in the sleep microenvironment has not being paid enough attention in the past studies. Also, a previous research[27] claimed that the interactions between the buoyant plumes around the bed, the airflow in the BZ, the ventilation strategy, and the thermal plume needs further investigations. To achieve these goals (especially the improvement of the air quality in the BZ), studying the mechanism of the thermal plume and the interaction between the breathing and the thermal plume is one of the most fundamental research.

Previous studies failed to distinguish the influence on the thermal plume from different breathing modes. Specifically, most studies focused solely on the nose breathing mode because majority of the people breathe through the nose when sleeping[36], but such studies ignored the fact that some people snore through mouth when sleeping. For people with the supine posture, different breathing modes could have different effect on the thermal plume, and this effect could be significant when compared with the sitting or standing posture, however, the significance of this effect has not been quantified in the literatures yet, and the airflow characteristics near the bed also remains unclear. Moreover, few studies verified the validity of the thermal manikin experiment. Past studies used either the real human subjects or only used the thermal manikin[37], but real human measurements could be helpful for verifying the manikin data and ensure the accuracy and practical significance of the data. Finally, almost all the previous studies used "naked" manikins without wigs or covers. Thus, such measurement results may not present the real situation of the human thermal plume.

This research focused on the characteristics of thermal plume for people lying in a quiescent indoor environment with supine posture, and investigated the temperature and velocity field due to the interaction between the thermal plume and the breathing airflow. The main objective of this research work is to characterize the sleep microenvironment for people with the supine posture, aim at providing the theoretical basis for further research on the improvement of the BZ air quality in the sleep environment. In this work, two different breathing modes of human were studied, which were also being investigated using both the real human and thermal manikin experiments. Since pollutants can be lifted by the upward thermal plume, the investigation of the interaction between the thermal plume and the breathing mode could provide valuable data support for improving the breathing zone air quality and reduce the human pollutant exposure. The findings in this study could promote the understanding of the thermal plume in real human life. The results obtained from this study could be helpful for decision makings on optimized strategies for air distribution, ventilation system design, and indoor air quality (IAQ) improvement in the sleep microenvironment.

2. Experimental setup

In this research, the climate chamber at the Energy and Indoor Environment Laboratory at the Department of Energy and Process Engineering at Norwegian University of Science and Technology (NTNU), Trondheim, Norway was used as the simulated bedroom. Velocity, temperature and other environment parameters were tested and sampled in the BZ above the breathing thermal manikins and the human subjects.

2.1. Climate chamber

The size of the climate chamber was 3.95m×2.35m×2.65m (L×W×H) as shown in Fig. 1. In this climate chamber, a breathing thermal manikin, a bed, the ventilation system, two extracts were placed as this figure showed. The two extracts were placed about 0.3m below from the ceiling and about 1.0m away from the side walls. The head position of the bed was located right down the center of the laminar air flow panel. The ventilation system was not open during these experiments. The indoor temperature is at 23±0.5°C. There is a laminar air flow system in this chamber which is used to the next step of this study in order to improve the indoor air quality by using located laminar air flow system.

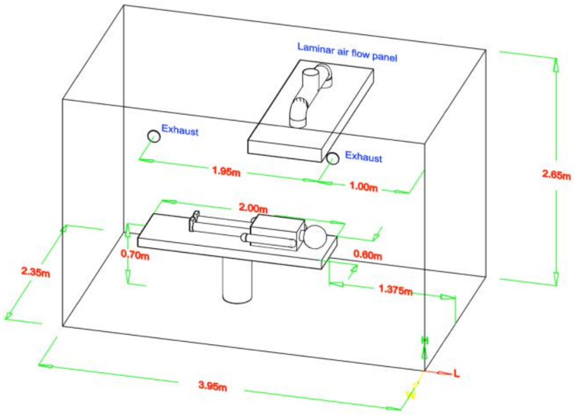


Fig. 1. Geometry of the chamber and the location of subject.

2.2. Breathing thermal manikin and real human subject

A breathing thermal manikin shaped as a 1.85m high average sized man was used to simulate the real male (Fig.2). The lying male manikin（type: Lo Lzm 09 Ada head (white)) is made by Morten Finckenhagen Butikkinnredninger AS. The manikin was developed and widely used in researches conducted in NTNU. Real human subjects kept the same posture and covered by a same blanket as the manikin during all the experiments.

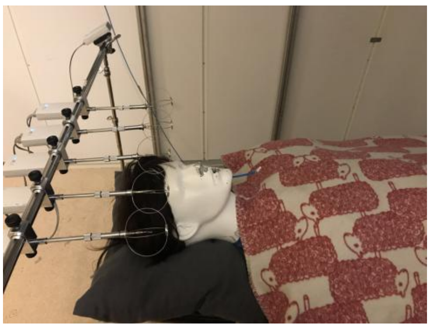


Fig. 2. The shape of breathing thermal manikin

The manikin was geometrically similar to a real human and can move arms and legs. The heating cables were placed inside the manikin, each part like legs, arms or torso had heating element so as to control the temperature of the different part of the body. The infra red picture (FLIR Systems, Inc. Mode: E75) was used to check the surface temperature. During the experiments, the surface of manikin's body was kept around 33-34°C, and heat loss of this supine manikin is 80W. There were four males participated in in the real human experiments, the height of the real males was 182.2 ±12.3 (mean±SD) cm, and the weight of the real males was 74.4±16.1 kg.

Table 1 Summary of the experiments with different parameters (Fig. 2).

Parameter	Conditions	Details/comments
Ambient	23±0.5°C	-
Manikin heat output	80W	33-34°C
Body posture	Lying	Supine
Clothing	Wig	Short hair wig
Bed	Single	0.7m×0.6m×2m (H×W×L)
Breathing	Mouth Nose	See Table 2

The average exhalation air velocity is 1.25m/s and 1.05m/s through mouth and nose separately, and the temperature is around 26°C. Due to the impact of breathing on the distribution of temperature and airflow in BZ, a artificial breathing device was placed in the manikin. The device made by two micro fans (AD0912DX-A76GL, ADDA Corp., Ltd), controllers (NI 9481 and NI 9203, National Instruments Corp.), and software (Lab VIEW, version 12.0f3, National Instruments Corp.). Fans were used to generate inhalation and exhalation airflow. The controllers were connected with the circuit and controlled the fan speed by controlling the current. The detail respiration parameters of the breathing thermal manikin was shown in Table 2. The breathing system in the manikin was shut down when we did 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

2.3. Measurement instrumentations

The equipment for measuring the velocity and temperature are shown in Table 3. The air velocity and temperature measurement system was “AirDistSys5000” (Sensor Electronic, Poland). The system contains a pressure sensor, five omnidirectional anemometer probes and a wireless transmitter. The pressure sensor is used to correct anemometer readings. The system connects to a computer so we can read the record in real time. Matlab (version: R2018b) were used to draw the figures.

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

2.4. Measurement scenarios

There are some previous studies can provide experience about measuring points selection and the placement of these points[9],[38],[39],[40],[41], [42],[43],[44],[45]. According to these studies, to investigated the characteristic of the thermal plume, in current study, both velocity and temperature sensors were placed at 5 different vertical locations, 3 lateral locations and 5 horizontal locations above the head (Fig.3). Every sampling points was tested 90 times within 3 minutes in one experiment. Because the sampling points were not continuous and there were intervals between them, the measuring data can not accurately represent the maximum and minimum value of the velocity and temperature in real situation. In this paper, all the mentioned maximum data were the relative value.

Different institutions has different definition of the dimension of BZ. Occupational Safety and Health Administration (OSHA)[46] defined the BZ as an area within a 25cm radius of the people’s nose and mouth, but U.S. Department of Energy[47] defined the BZ only had a radius of 15 to 23cm. In this study, by considering the development of the thermal plume, we defined the the BZ as an area within a 15cm radius of the people's Philtrum.

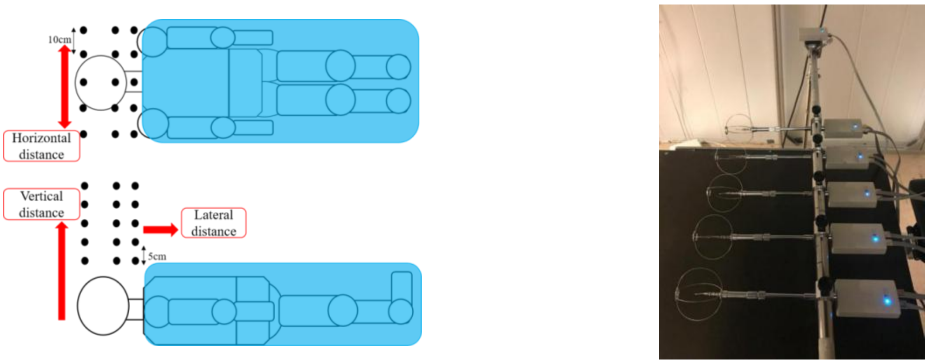


Fig. 3. The placement of sensors around the subject and the arrangement of the sensors.

The five different cases was showed in Table 4. Case 1 used the manikin with the breathing system turned off, this case was set to investigate the characteristic of the thermal plume. Case 2 and case 3 used the manikin with the breathing system on to investigate the interaction between breathing airflow and thermal plume. The real human subjects participated in case 4 and case5, these cases aimed to verify the manikin data. In general, the experimental setup made up by two different scenarios. These scenarios were subdivided into five different cases by different breathing modes.

Table 4 Detail of different cases for manikin and real human.

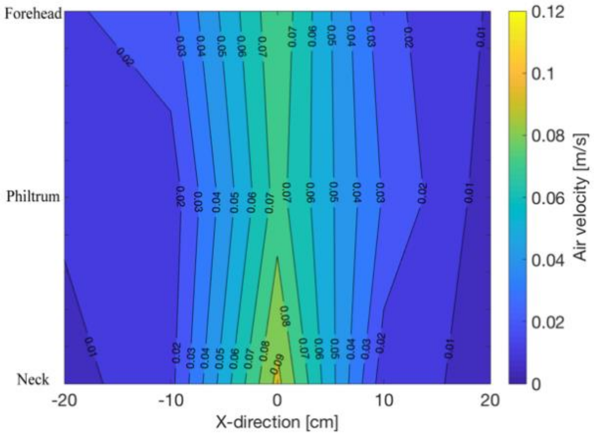
Scenario	Subject	Detail
Case 1		Without breathing
Case 2	Manikin	Mouth breathing
Case 3		Nose breathing
Case 4	Real human	Mouth breathing
Case 5		Nose breathing

3. Results and discussion

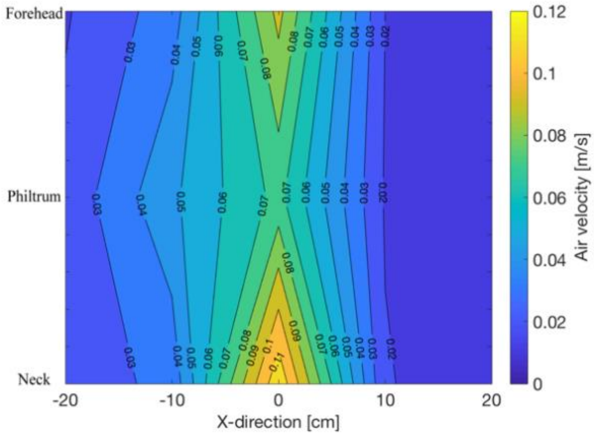
3.1. Velocity measurements

3.1.1. Measured velocity distribution of thermal plume without breathing mode

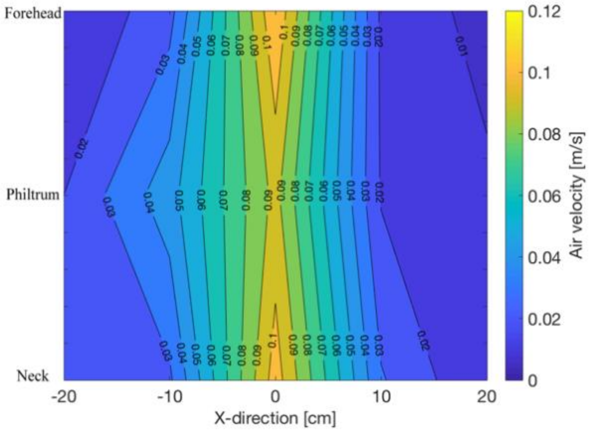
As Fig. 4 shows, at 5cm vertical distance above the head, the airflow velocity is the highest around the neck, however, in this distance, the magnitude of velocity are all relatively low. At 10cm vertical distance above the head, the airflow velocity in neck and forehead region grows fast, the velocity around philtrum remains low level. At 15cm vertical distance above the head, different from the 10cm distance, the airflow velocity in philtrum and forehead region grows fast, the velocity in neck region starts to decrease. At 20cm vertical distance above the head, the velocity in forehead and neck region decreases to a lower level, the velocity around philtrum becomes the highest. At 25cm vertical distance above the head, the velocity around philtrum keeps increasing and the area of the airflow widely spreads. This observation might be explained because the lower part of the manikin is covered with blanket, the thermal plume generated by head and the less heat loss from lower part of the body is relatively low compared to sitting or standing. The velocity value in philtrum increasing to the highest also accords with the development law of thermal plume. The development of velocity above the head is also similar to the previous study[45],[48].



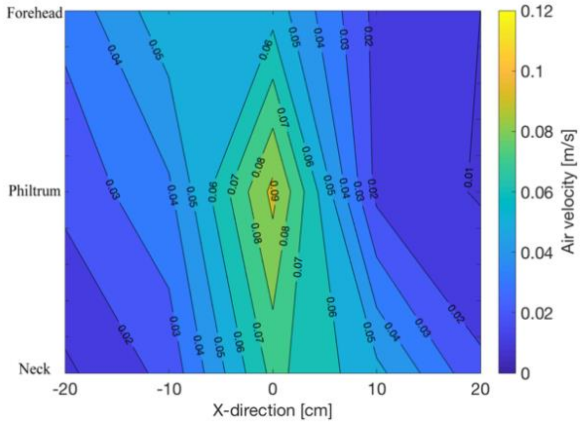
(a) 5cm vertical distance above the head.



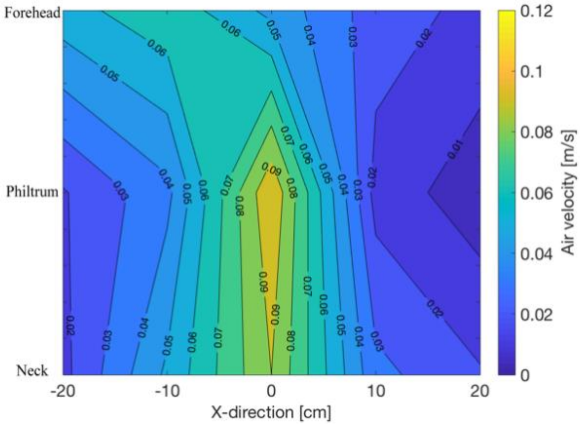
(b) 10cm vertical distance above the head.



(c) 15cm vertical distance above the head.



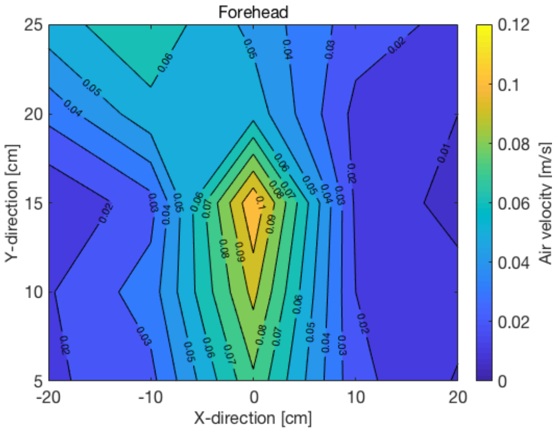
(d) 20cm vertical distance above the head.



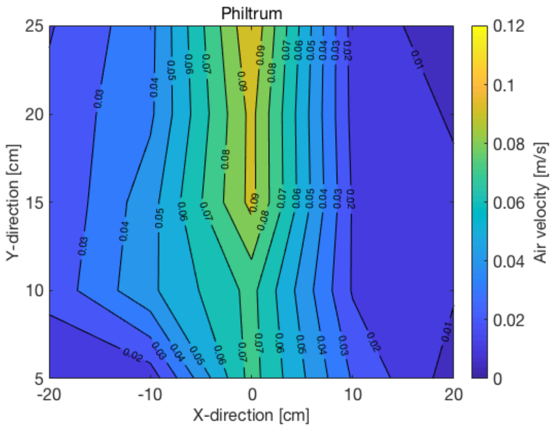
(e) 25cm vertical distance above the head.

Fig. 4. Velocity distribution above the head (non-breathing mode).

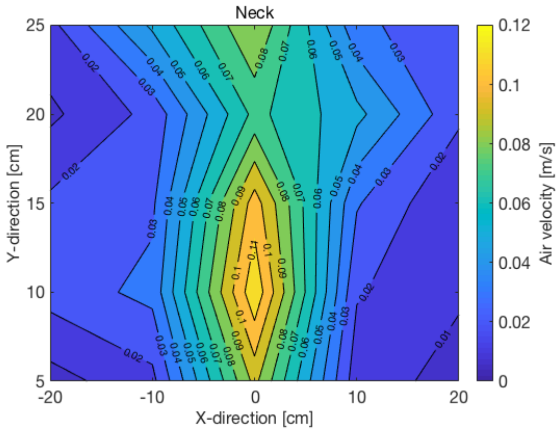
In Fig.5, there are velocity distribution at 3 different lateral position. At first sight, they are different from each other. As figure shows, we can straightly observe the change of the velocity of the thermal plume. At the forehead position, with the height increasing, the velocity keeps increasing til at 15cm vertical distance, then the velocity drops. At the philtrum position, the velocity keeps rising and the largest velocity appears above the 25 vertical distance. At the neck position, the development and distribution of velocity is similar with forehead position, but the velocity reaches the highest value with lower vertical distance, 10cm. In the case of non-breathing mode, the velocity above the head is lower as a whole, which is related to the smaller heat loss of the human body in the sleeping. In addition, except for the head, other parts of the manikin are covered with blanket, so the rest of the body has less impact on the head. Due to the curved shape of the human’s head, at a 5cm height above the head, the CBL should still exists at the central point.



(a) Forehead.



(b) Philtrum.



(c) Neck.

Fig. 5. Velocity distribution at different lateral position(non-breathing mode) (a) Forehead; (b) Philtrum; (c) Neck.

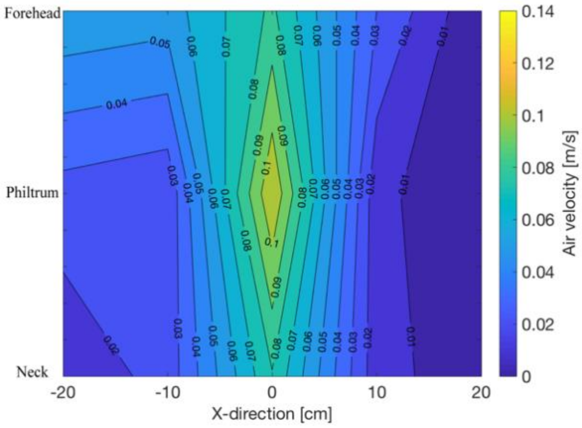
3.1.2. Measured velocity distribution of thermal plume with breathing mode

All the experimental conditions were the same as in section 3.1.1, except the breathing mode which is active in these cases. The influence of nose and mouth breathing modes are studied separately.

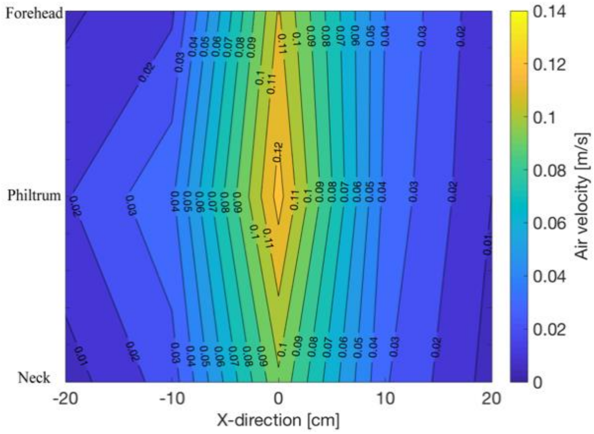
1) Mouth breathing mode

In Fig. 6, the distribution of the velocity is different from it in non-breathing mode. At 5cm vertical distance above the head, the airflow velocity is the highest around the philtrum, the same with non-breathing mode, in this distance, the magnitude of velocity are all relatively low. At 10cm vertical distance above the head, the airflow velocity is still the highest around the philtrum, however, the velocity increases in the whole plane. At 15cm vertical distance above the head, the airflow velocity in philtrum and neck region grows fast and the area of the airflow widely spreads, but the velocity in forehead starts decreasing. At 20cm vertical distance above the head, the velocity in every position starts to decrease, the highest value of velocity observed in philtrum region. At 25cm vertical distance above the head, the area of the airflow in philtrum region narrowed, the biggest velocity is in forehead region.

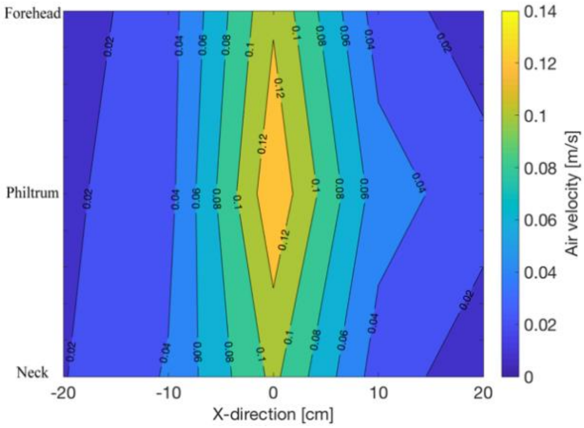
Compared with the velocity distribution in the non-breathing mode, mouth breathing has a great impact on the velocity above the head, and the velocity will diverge and increase with the philtrum region as the center point, and the airflow velocity is larger than that in the non-breathing mode, because the mouth breathing air flow increases the air flow velocity.



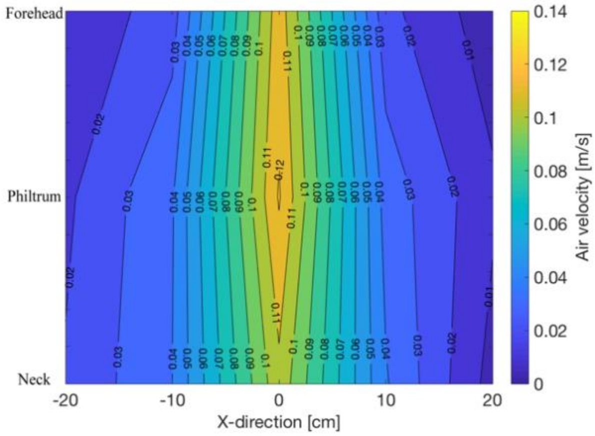
(a) 5cm vertical distance above the head.



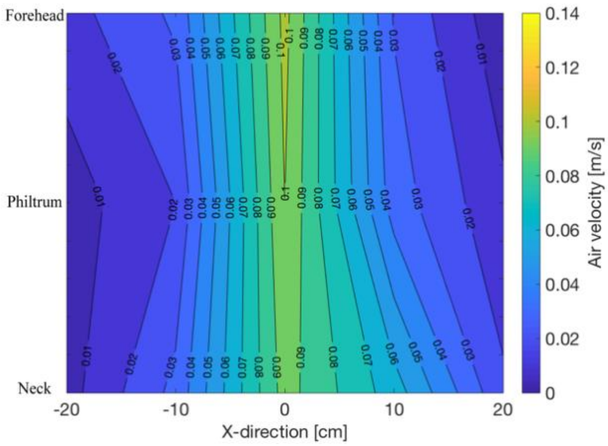
(b) 10cm vertical distance above the head.



(c) 15cm vertical distance above the head.



(d) 20cm vertical distance above the head.

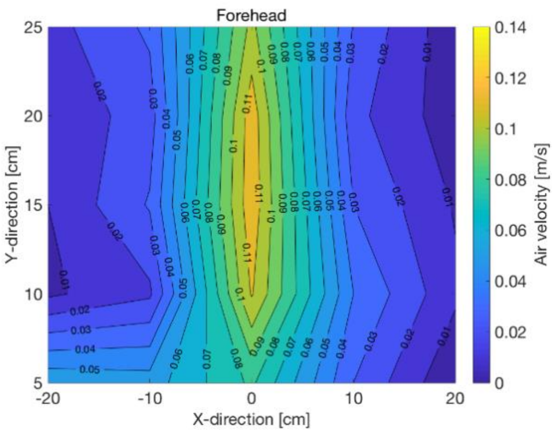


(e) 25cm vertical distance above the head.

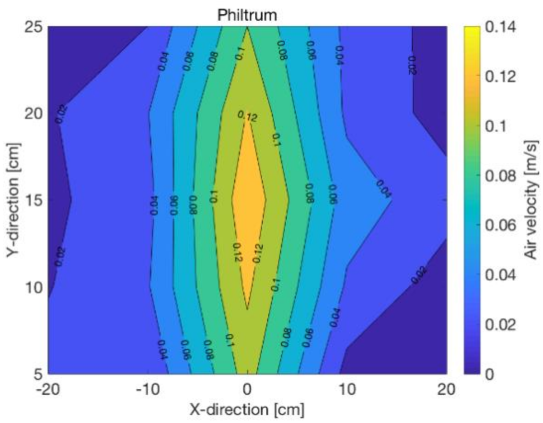
Fig. 6. Velocity distribution above the head (mouth breathing mode).

In Fig.7, at the forehead position, with the height increasing, the velocity keeps increasing til at 20cm vertical distance, then the velocity drops. At the philtrum position, the velocity keeps rising and reaches the highest value at 20cm vertical distance, then decreases. At the neck position, the development and distribution of velocity is similar with forehead position, but the velocity is lower.

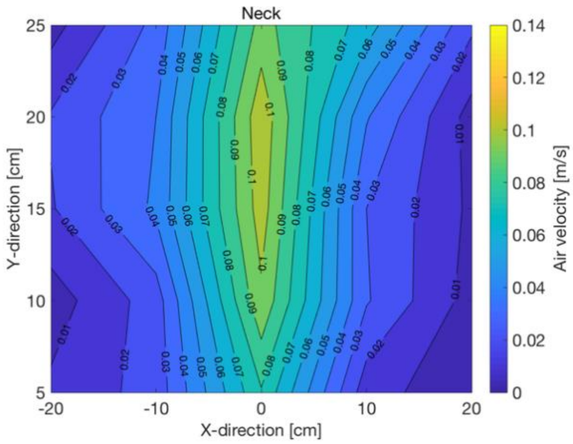
In the case of mouth breathing mode, the air velocity above the head is higher as a whole, and the high-speed area is concentrated in the philtrum region, which is also related to the human respiratory characteristics. Breathing will have a great impact on the air flow above the head, changing the distribution and velocity of the airflow.



(a) Forehead.



(b) Philtrum.



(c) Neck.

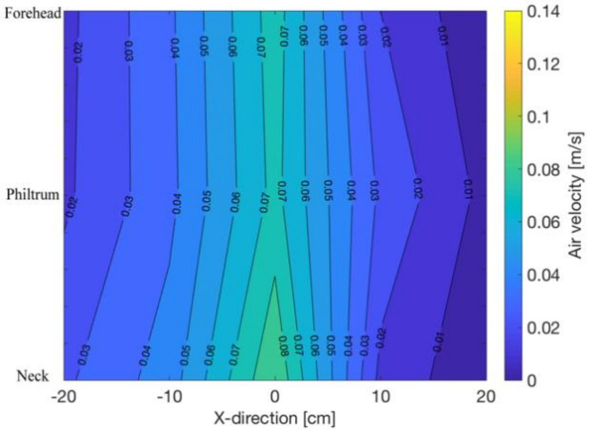
Fig. 7. Velocity distribution at different lateral position(mouth breathing mode) (a) Forehead; (b) Philtrum; (c) Neck.

2) Nose breathing mode

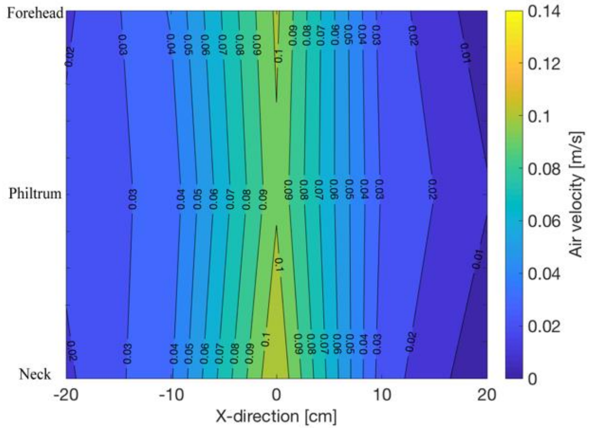
breathing mode, nose breathing has a greater impact on the velocity of thermal plume, and the area of the airflow will become narrower, and the velocity increases slowly. However, the velocity measured at the measuring point in the BZ is relatively larger. The effect of nose breathing airflow on the chin and neck area is more Compared with mouth breathing mode and non-breathing mode, nose breathing mode has the biggest difference, because the nose has two nostrils, and the nose exhalation will have a more inclined to the lower body of a blowing angle compared to mouth breathing.

As Fig.8 shows, at 5cm vertical distance above the head, the airflow velocity is the highest around the neck, the magnitude of velocity are all relatively low. At 10cm vertical distance above the head, the airflow velocity starts rising around neck and forehead, the velocity around philtrum increases slowly. At 15cm vertical distance above the head, the velocity increases in the whole plane, but the area of the airflow is almost the same. At 20cm vertical distance above the head, the highest value of velocity observed in philtrum region. At 25cm vertical distance above the head, the area of the airflow widely spreads, the biggest velocity is in philtrum region.

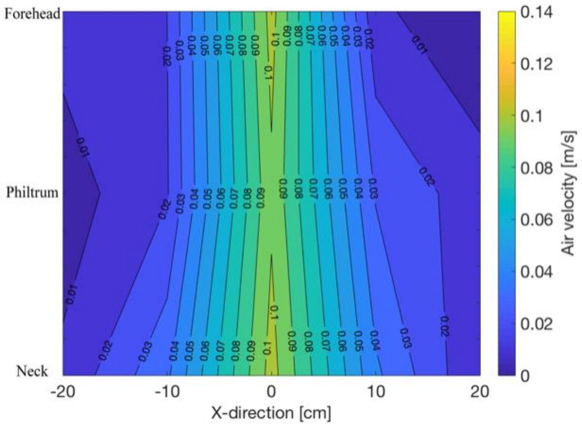
Compared with the velocity distribution of non-breathing mode and mouth obvious.



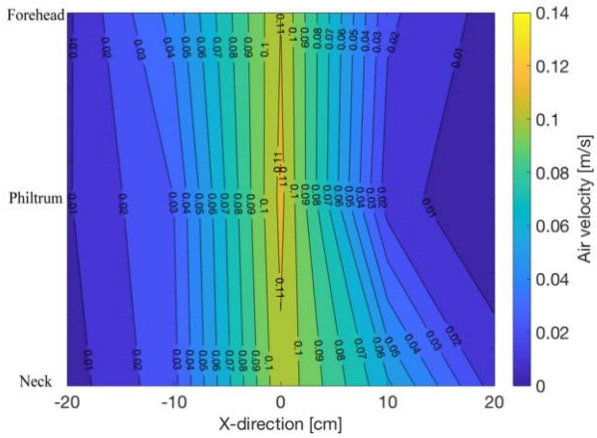
(a) 5cm vertical distance above the head.



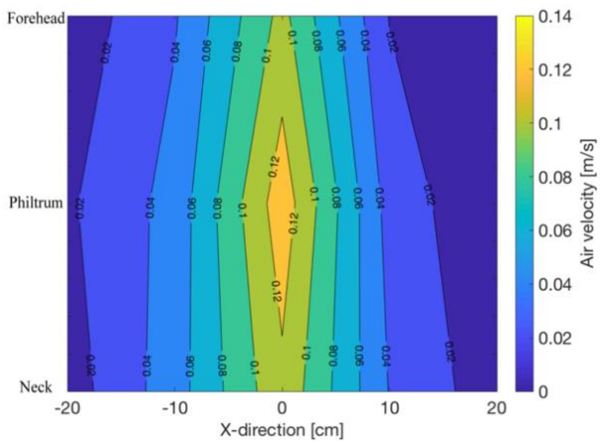
(b) 10cm vertical distance above the head.



(c) 15cm vertical distance above the head.



(d) 20cm vertical distance above the head.

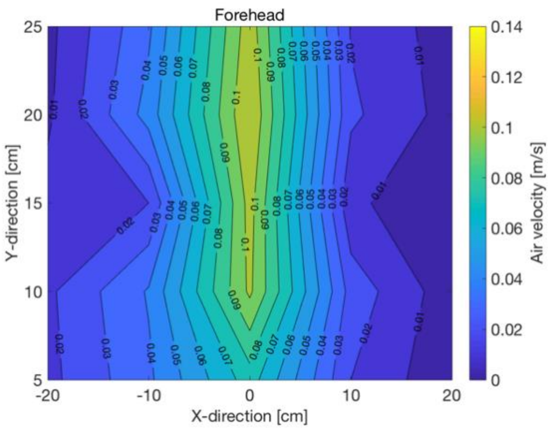


(e) 25cm vertical distance above the head.

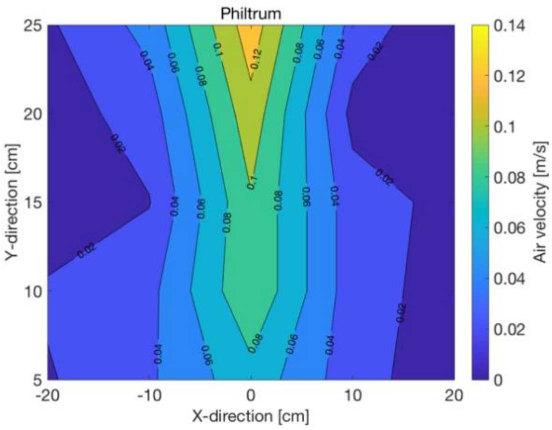
Fig. 8. Velocity distribution above the head (nose breathing mode).

In Fig. 9, we can directly observe the velocity distribution of different vertical planes, and there are differences in each position, and the velocity distribution is quite different from that in non-breathing mode and mouth breathing mode. Nose breathing increases the distance that produces the maximum velocity.

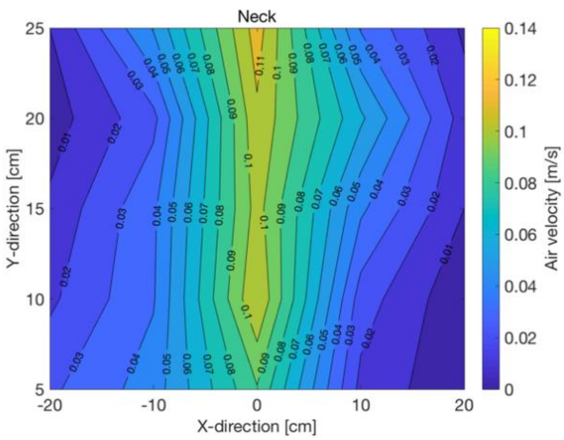
At the forehead position, with the height increasing, the velocity increases slowly. Due to the effect of nose breathing, the velocity in forehead region is low. At the philtrum position, the velocity keeps increasing, and the area of the airflow is wide. At the neck position, the development of velocity is similar with it in philtrum position, only the area of the airflow is little smaller. In the case of nose breathing mode, the airflow above the head will be greatly affected by breathing, which leads to the problem that the velocity of thermal plume develops more slowly, slows the velocity around forehead and increases the velocity in neck region.



(a) Forehead.



(b) Philtrum.



(c) Neck.

Fig. 9. Velocity distribution at different lateral position(nose breathing mode) (a) Forehead; (b) Philtrum; (c) Neck.

3.2. Temperature measurements

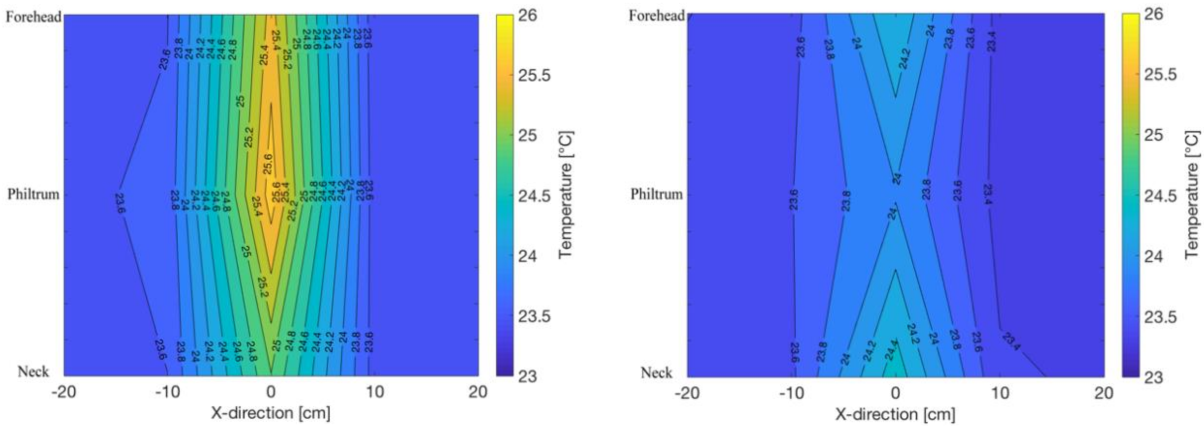
3.2.1. Supine manikin without breathing mode

Temperature distribution above the manikin’s face can be observed in Fig.10. The temperature drops as the height increases, and the central point always has the highest temperature in the same horizontal direction. The temperature above philtrum region is absolutely higher than other regions. With the height increasing, temperature above the philtrum region drops sharply and fast, temperature above forehead and neck regions drops relatively low. At the height 25cm, the temperature is similar to the indoor air temperature, and the difference of temperature distribution is no longer obvious.

In general, the thickness of the thermal boundary layer (TBL) was the distance between the surface to the point that the temperature drops to environment temperature. Some scholars had defined that the thickness was assumed that the outer edge of the TBL extends to a distance where the air temperature drops 90% from the manikin’s surface temperature to the indoor air temperature[20],[49]. The air temperature at the outer edge of the TBL was determined as follows:

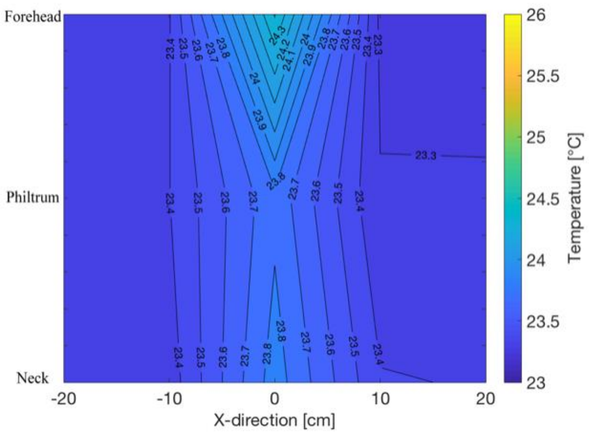
$$T_{TBL} = T_{surf} - 0.9 \times (T_{surf} - T_{amb})$$

Where the T_{TBL} is the temperature at the outer edge of the thermal boundary layer, the T_{surf} is the temperature at the surface of the manikin, and the T_{amb} is the indoor air temperature.

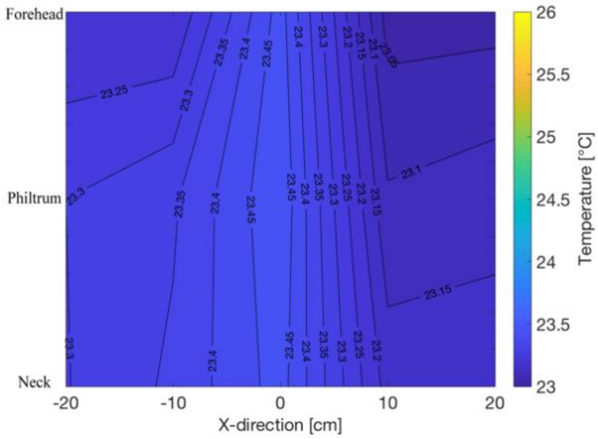


(a) 5cm vertical distance above the head.

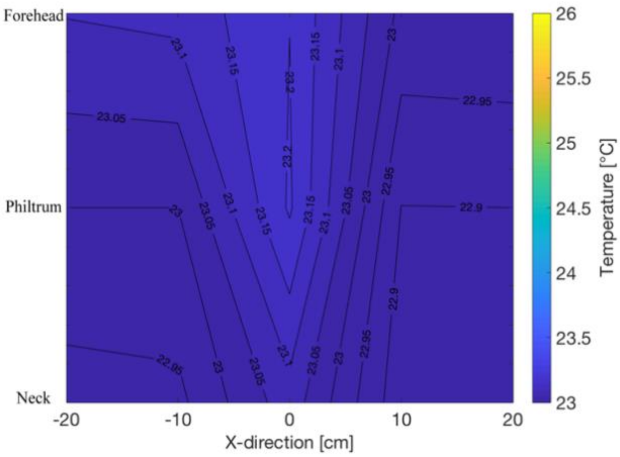
(b) 10cm vertical distance above the head.



(c) 15cm vertical distance above the head.



(d) 20cm vertical distance above the head.



(e) 25cm vertical distance above the head.

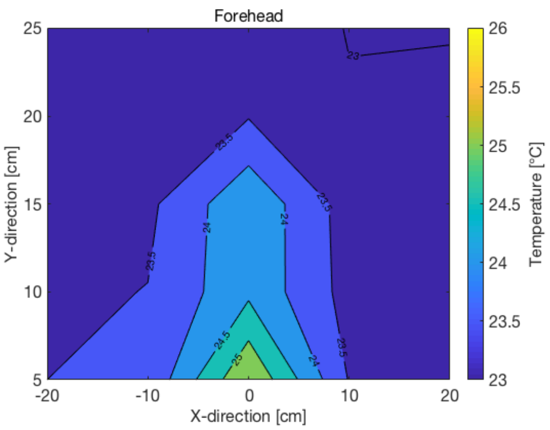
Fig. 10. Temperature distribution above the head (non-breathing mode).

According to this equation, the TBL above the head could be estimated.

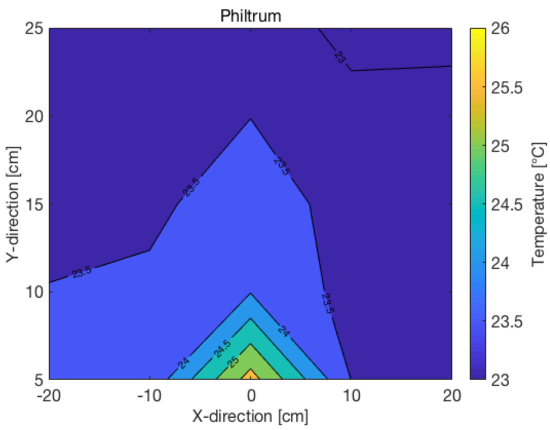
At the 5cm vertical distance above the head, the measured temperature is higher than the T_{TBL}, meanwhile, at 10cm vertical distance above the head, the temperature near the central point is also higher than the T_{TBL}, however, other rest measured temperature lower than the T_{TBL}. At the 15cm vertical distance above the head, the temperature near the central point is lower than the T_{TBL}. According to this situation, it means that the thickness of TBL above the head near the central point or central line is between 10cm and 15cm, the thickness of TBL above the head in the rest regions is between 5cm and 10cm.

In Fig.11, above the forehead, with the central point extends about 5cm to both sides, we can obtain that the measured temperature is higher than the T_{TBL}, which means above the forehead region, some part of this region has a thickness of TBL between 5cm and 15cm. According to the measured temperature above the philtrum region, the thickness of TBL is lower than 10cm. The thickness of TBL above the neck region is similar to it above the forehead region.

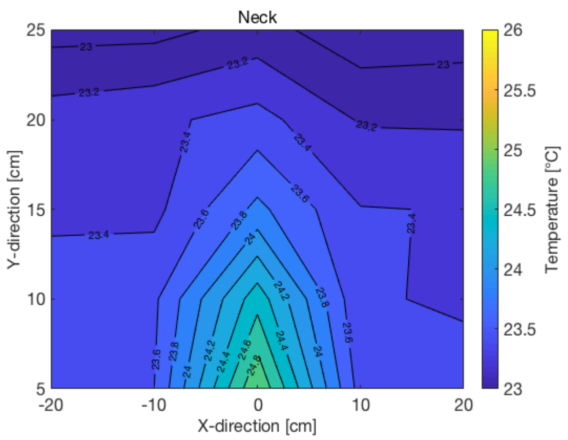
As Fig.11 shows, it is more direct to observe the vertical height temperature distribution above each region separately. The temperature above each region decreases with the increase of height, and the temperature of the center point is the highest. Affected by the face, the width of the measured temperature distribution is similar to width of the manikin’s face. The chin and neck are not only affected by the face, but also affected by the neck, trunk and shoulder, so the width of the temperature distribution is relatively wider.



(a) Forehead.



(b) Philtrum.



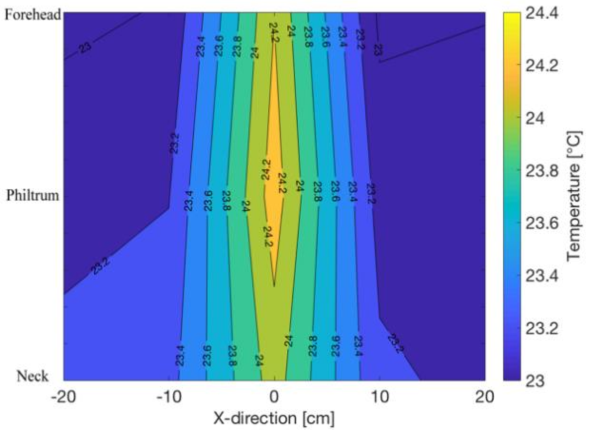
(c) Neck.

Fig. 11. Temperature distribution at different lateral position(non-breathing mode) (a) Forehead; (b) Philtrum; (c) Neck.

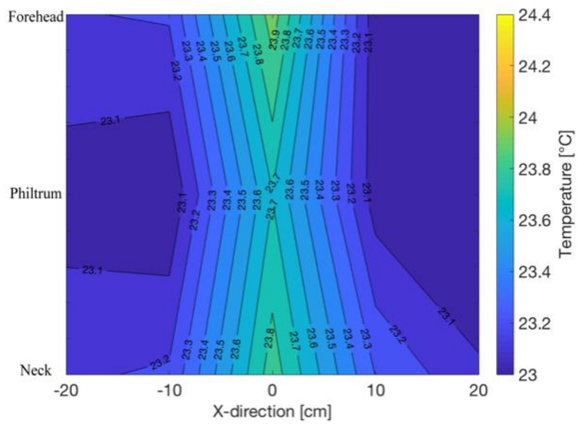
3.2.2. Supine manikin with breathing mode

1) Mouth breathing mode

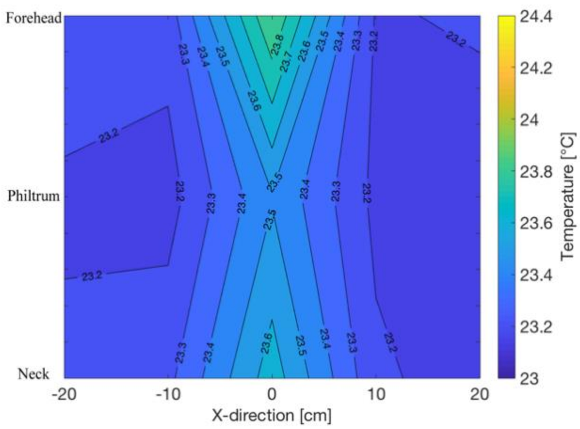
Under mouth breathing mode, the results can be observed in Fig.12 and Fig.13. Temperature distribution above the manikin's face with different vertical distance can be observed in Fig.12. Same with the non-breathing mode, the temperature above philtrum region is higher than other regions and the temperature drops as the height increases. The temperature above the philtrum region drops sharply and fast with the height increasing compared to neck region and forehead region. However, there are some differences compared to non-breathing mode. With mouth breathing, the temperature is lower and the temperature gradient is smaller. At the height 25cm above the head, the measured temperature is higher than that in non-breathing mode, but the temperature is relatively low in the region near the face.



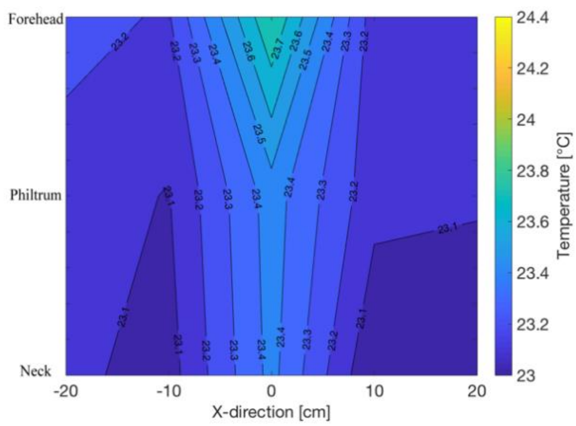
(a) 5cm vertical distance above the head.



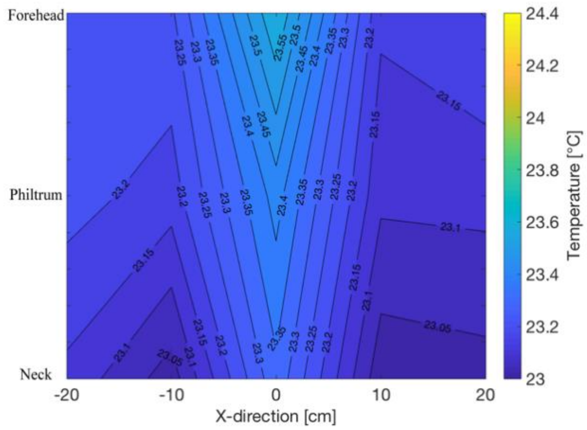
(b) 10cm vertical distance above the head.



(c) 15cm vertical distance above the head.



(d) 20cm vertical distance above the head.



(e) 25cm vertical distance above the head.

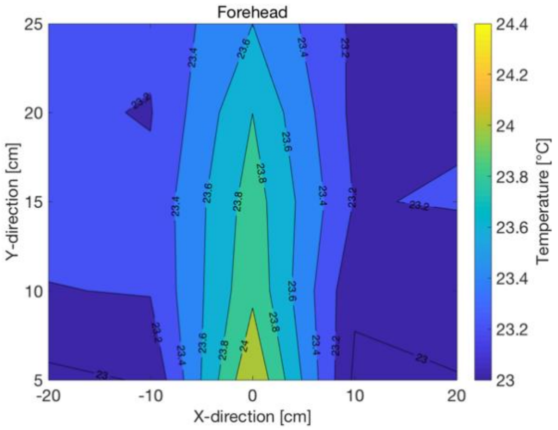
Fig. 12. Temperature distribution above the head (mouth breathing mode).

According to the equation showed in section 3.2.1, the TBL above the head with mouth breathing could be estimated.

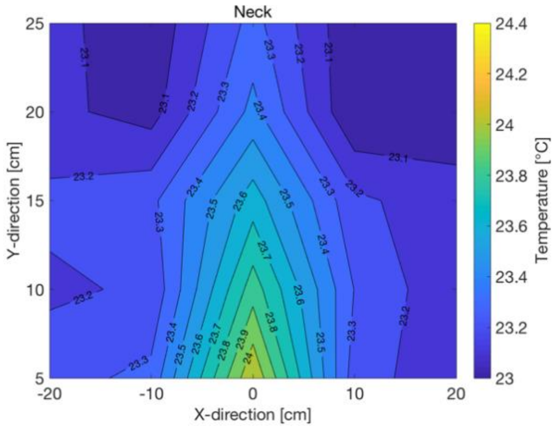
At the 5cm vertical distance above the head, the measured temperature near the central point and central line is higher than the T_{TBL}, and at the 10cm vertical distance above the head, the measured temperature near the central point and central line is lower than the T_{TBL}. It means the thickness of T_{TBL} above the head is between 5cm to 10cm.

In figures, we can observe that the temperature distribution above every region is similar, but the magnitude of the temperature has little difference. At the 5cm vertical distance above the forehead, the measured temperature near he central point and central line is higher than the T_{TBL}, which means some part of this region has a thickness of T_{TBL} between 5cm to 10cm.

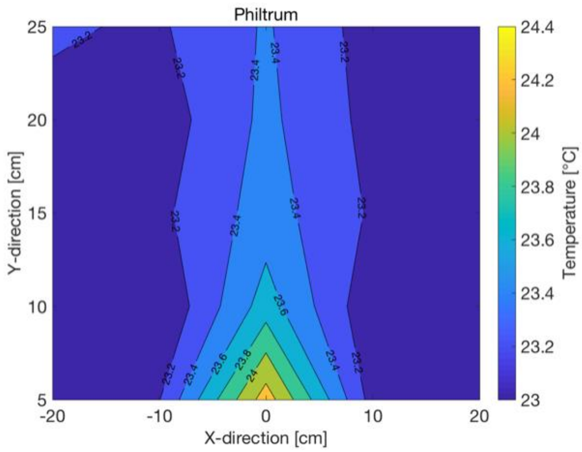
As Fig.13 shows, the temperature above each region decreases with the increase of height, and the temperature of the center point is the highest. Due to the influence of mouth breathing, the width of the temperature distribution is relatively narrow, and the temperature is close to the indoor temperature on both sides 10 cm away from the central line. The development of temperature generated by manikin can reach higher distance, which is affected by the vertical airflow of mouth breathing.



(a) Forehead.



(b) Philtrum.

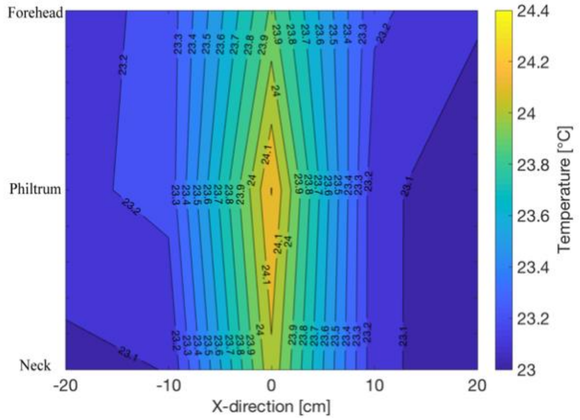


(c) Neck.

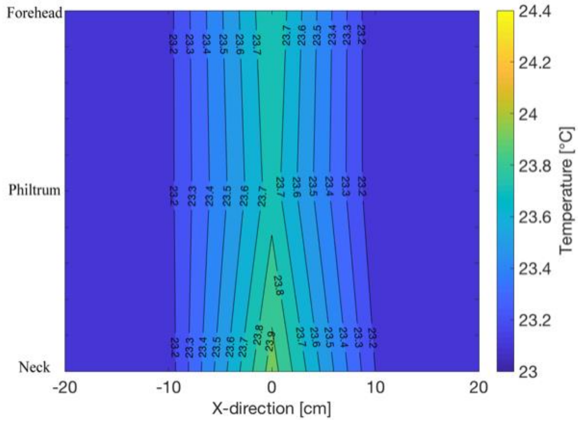
Fig. 13. Temperature distribution at different lateral position(mouth breathing mode) (a) Forehead; (b) Philtrum; (c) Neck.

2) Breathing through nose mode

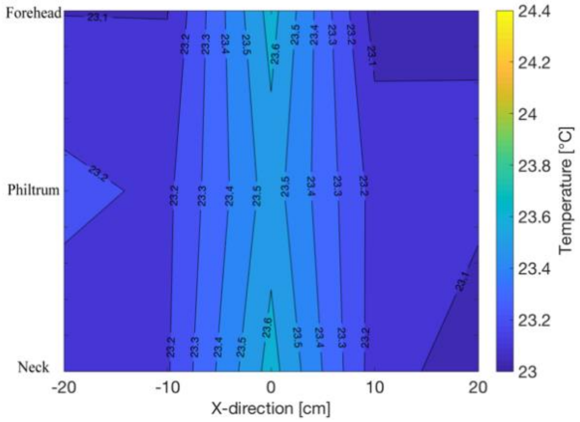
We can observe the temperature distribution above each region in Fig.14 and Fig.15. Same with the non-breathing mode and mouth breathing mode, the temperature distribution characteristic has no change. However, there are still some differences compared to non-breathing mode and mouth breathing mode. With nose breathing, the temperature is much more lower than it in non-breathing mode. At the height 25cm above the head, the measured temperature is almost consistent with the indoor air temperature. The temperature distribution at the same height is very similar to that in the mouth breathing mode.



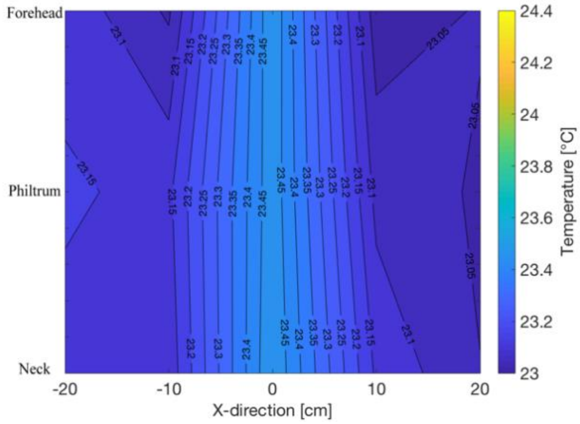
(a) 5cm vertical distance above the head.



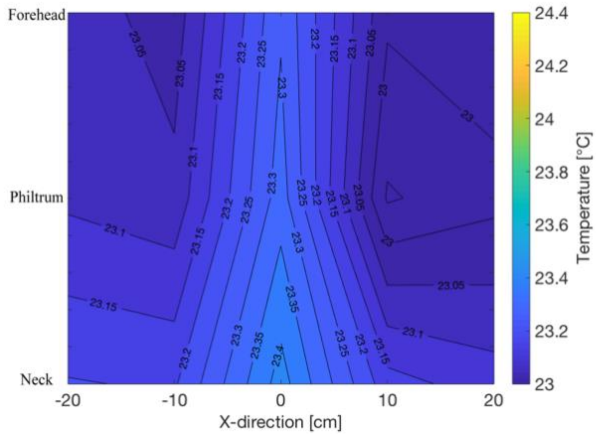
(b) 10cm vertical distance above the head.



(c) 15cm vertical distance above the head.



(d) 20cm vertical distance above the head.



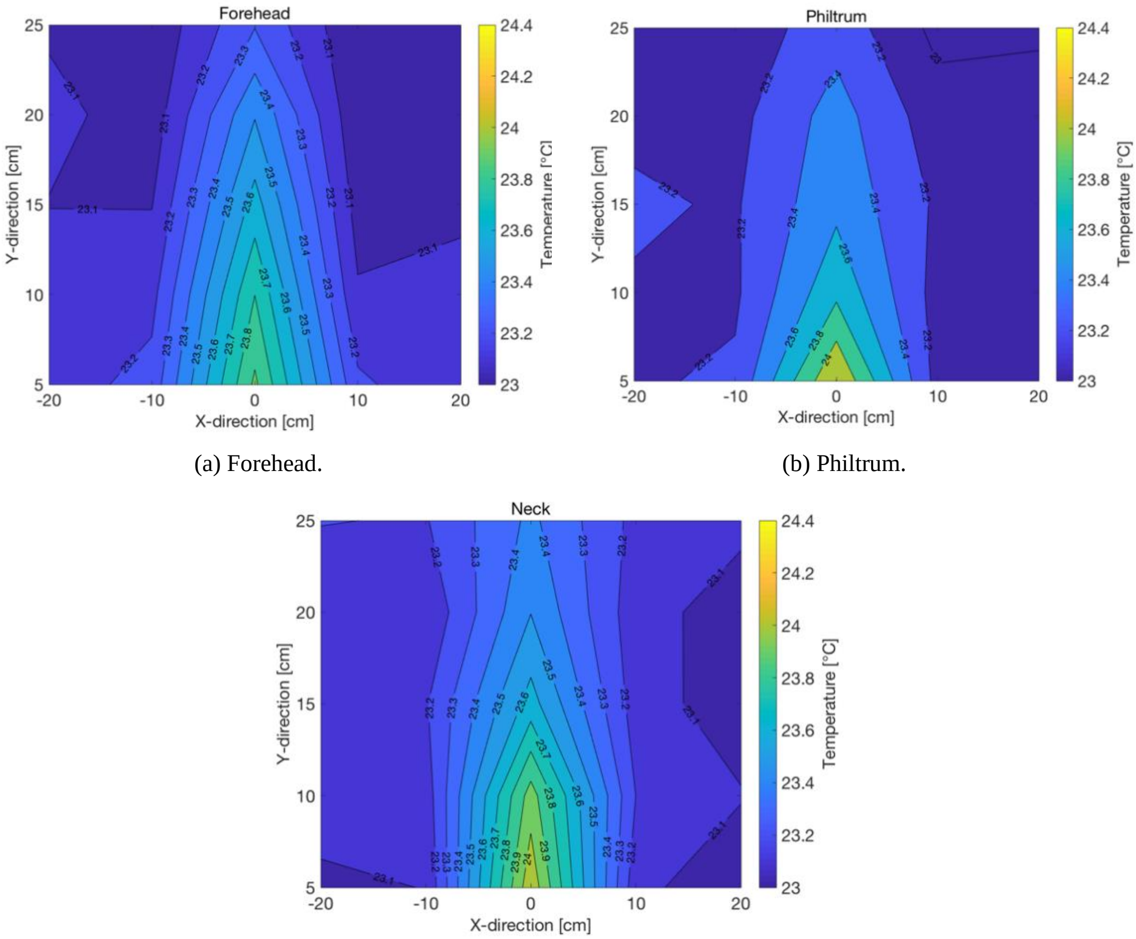
(e) 25cm vertical distance above the head.

Fig. 14. Temperature distribution above the head (nose breathing mode).

Same with the mouth breathing mode, according to the equation showed in section 3.2.1, the TBL above the head with nose breathing could be estimated.

At the 5cm vertical distance above the head, the measured temperature in the central point and central line in forehead region is lower than the T_{TBL}, it means the the thickness of T_{TBL} above the forehead is lower than 5cm. However, the measured temperature in the central point and central line in the philtrum region and the neck region with 5cm vertical distance is higher than the T_{TBL}, and lower than the T_{TBL} when the distance reaches 10cm, which means the the thickness of T_{TBL} above the philtrum region and the neck region is between 5cm to 10cm. The distribution of temperature is similar to it in mouth breathing mode.

Under the influence of nose breathing, the temperature is lower than the previous two modes, and also the temperature is close to the indoor temperature 10 cm on both sides 10 cm away from the central line. The relatively high temperature region is also affected by the nose breathing airflow, and becomes narrower.



(a) Forehead.

(b) Philtrum.

(c) Neck.

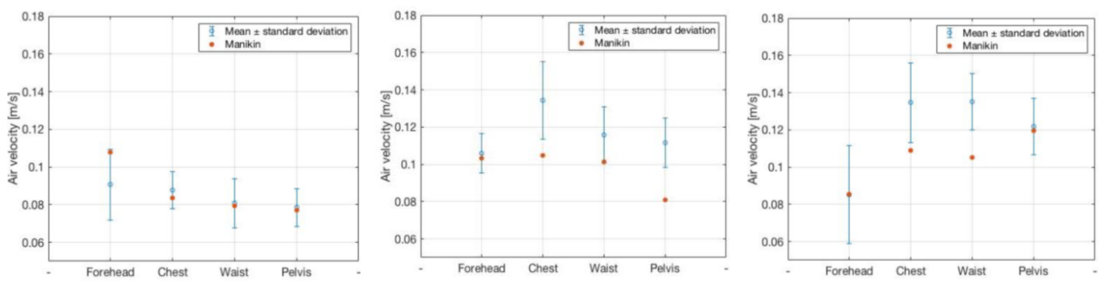
Fig. 15. Temperature distribution at different lateral position(nose breathing mode) (a) Forehead; (b) Philtrum; (c) Neck.

3.3. Measurement results with human subjects

In the contrast experiment, both the manikin and the real human subjects coverd with the same blanket during the experiment. In the real human subjects experiment, all experimental conditions and parameters were consistent with the manikin experiment, and the parameters of the subjects are consistent with the human model as far as possible. 3 measuring points with different vertical heights were selected to verify the data collected in the manikin experiment, which were 5cm, 15cm and 25cm respectively. 8 different male subjects participated in the supine posture experiment, and they adopted the same posture as the supine posture manikin. The characteristics of the subjects were shown in Section 2.2. The experimental results of the subjects only use the data of the central measurement point to compare with the experimental data of the human model.

The measured data were analyzed by the statistical method (SPSS, Version 25, IBM Corp.) with a significance level of p=0.05. The velocity distribution at each height was represented by high-low diagram.

In Fig. 16, the velocity generated by the thermal plume in the real human subjects experiment is consistent with the experimental results obtained by using manikin. The average velocity of each measuring point in the manikin experiment is similar to that in the real human subjects experiment. However, with the increase of height, the velocity above the chest region and waist region does not match perfectly. The airflow velocity measured by the manikin is lower than that measured by the real person, which indicates that there may be temperature inhomogeneity in the trunk of the manikin. The velocity in the head region of the manikin is highly consistent with the velocity measured by the real human experiment, which shows that the manikin can meet the needs when studying the breathing zone.

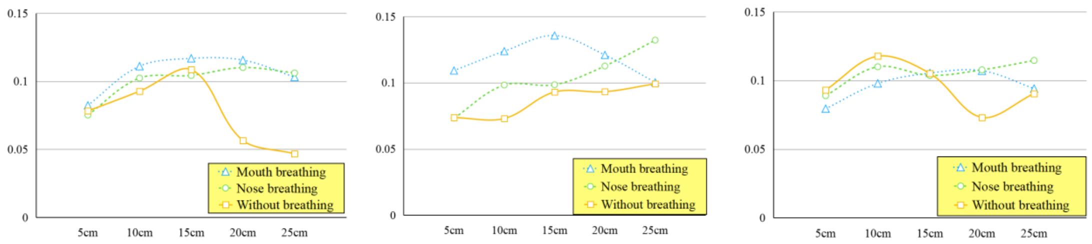


(a)5 cm (b)15 cm (c)25 cm

Fig. 16. Measured centerline velocities 25 cm above surface

3.4. Comparison of different cases

In Fig.17, it shows the difference between the results of 3 experiments. Obviously, the velocity distribution above each part is different. In these figures, the green line represents the mouth breathing mode, the orange line represents the nose breathing mode, the blue line represents the non-breathing mode, respectively. The results of this study can provide a fundamental knowledge of airflow distribution in front of and above the human body.



(a)above the forehead (b)above the philtrum (c)above the neck

Fig. 17. Central point velocity at different height above the head with different breathing mode.

Above the forehead, due to the influence of breathing, the air velocity still reaches more than 0.1m/s at the position more than 15cm away from the head. However, in the non-breathing mode, the air velocity drops rapidly after the distance exceeds 15cm from the head and reaches a low value. In addition, the airflow velocity in breathing mode began to decrease slowly after 20 cm.

Above the philtrum, the air velocity is affected most obviously by breathing. Mouth breathing will make the airflow velocity above the head relatively large, and when the height reaches 15 cm, the velocity will also drop rapidly. However, nose breathing will keep the airflow in an upward trend, which may decrease slowly after 25cm. In the non-breathing mode, the velocity above the philtrum region is always in a slow rising state, but the velocity is very small.

Above the neck, due to the influence of nose breathing, the air velocity is relatively large not far from the neck, and decreases first and then increases with the increase of height; while the velocity above the neck in the mouth breathing mode is almost the same as that above the forehead (Fig.18(a)), but the flow rate is smaller;

while the velocity in the non-breathing mode, which is close to the neck, is affected by the neck. After a certain distance, due to the geometric structure of the neck, the velocity decreased, and then the combined action of the trunk and face increased again, but the velocity was always at a low level.

By comparing the difference between the 3 mode, above the forehead region, the nose breathing mode and mouth breathing mode provide the similar airflow, in order to consider the breathing impact on the pollutants which might move with the airflow, the forehead region can be ignored. Above the philtrum region, the nose breathing could provide higher speed of the upward airflow after a long distance. However, at first, mouth breathing mode has the highest velocity value. Due to the high velocity appears in a short distance from the surface of bed, mouth breathing might have bigger impact on pollutant transmit. Above the neck, the velocity values in 3 mode are all low, however, according to the common sense, mouth breathing has more vertical airflow than nose breathing. Airflow or air jets generated by nose could temporarily change the upward trend of airflow generated by lower part of the manikin, it may generate airflow vortex, the change of air flow velocity may cause a situation that the pollutants drawn from lower part or the surface of bed would be blocked and make a good effect on the human health. For mouth breathing mode, the airflow generated by mouth has a upward trend. According to the analysis, using nose breathing might create a more clean microenvironment compared with mouth breathing.

4. Conclusion

In this study, characteristics of the human thermal plume in supine posture were studied through both manikin and human experimentations. With supine posture, both the mouth and the nose breathing have little influence on the BZ air quality, because the upward thermal plume of human body has almost the same direction as that of the hot breathing air. On the other hand, exhalation could promote the development of the thermal plume, but the promotion could be limited as affected by the respiratory angle. Moreover, if the airflow around the human head is not controlled by ventilation measures, pollutants could enter the BZ smoothly with uncontrolled airflows, which cannot be controlled effectively by the two different breathing modes of human.

For better improvement of the air quality in the BZ of the sleeping microenvironments, characterizing the temperature and velocity distribution around the human head (due to human's heat loss) is one of the most fundamental research that remain poorly understood. Thus, the development of the temperature and velocity field above human head with different breathing modes was investigated in this research through thermal manikin experiments. And for verification purpose, data from human experimentations was also gathered. Several main conclusions can be drawn from this study, which are summarized as follows:

- At room temperature 23°C, the highest values of velocity in these 3 breathing mode is not very big, to control the thermal plume, it may not need big ventilation.
- It was also found that the mouth breathing mode could play a positive role in the development of the thermal plume for people with supine posture, which increases the maximum velocity of thermal plume above the philtrum region; the nose breathing not only reduces the airflow velocity above the forehead, but also affects the airflow above the neck. In general, the influence of the mouth breathing on the development of the thermal plume above the head is greater than that of the nose breathing, and the influence of breathing mode on the airflow above the philtrum region is more obvious. However, because people generally breath through the nose under light work or at rest, the impact of the nose breathing on the environment around the human body is more important.
- In no ventilation or little ventilation environment, human thermal plume and breathing is an important factor leading to indoor airflow. How to better control room air flow and even how to control the indoor environment especially the BZ is an important measure to improve human comfort.
- The breathing has big effect on the TBL, however, the TBL of forehead gets little impact. To characterized the TBL, it would provide a basis of temperature selection for personal ventilation system design.

- Results of this study could provide data, theoretical support, and guidance for future projects such as developing modified localized ventilation system for air quality improvement in the BZ. The results of the present study could be also helpful for developing new ventilation strategies aiming at reducing human exposure to indoor pollutants and improving the BZ air quality.

Declarations

Funding

We thank Energy and Indoor Environment Laboratory at the Department of Energy and Process Engineering at Norwegian University of Science and Technology.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgments

We thank Energy and Indoor Environment Laboratory at the Department of Energy and Process Engineering at Norwegian University of Science and Technology for providing technical support, and all the volunteers for real human experiments.

Availability of data and material

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

Code availability

Not applicable.

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