This is a postprint version of the article published as:
Zong, J., Liu, J., Ai, Z. & Kim, M.K. (2022). A review of human thermal plume and its influence on the inhalation exposure to particulate matter. Indoor and Built Environment. 2022, 31 (7), 1758-1774.
10.1177/1420326X221080358

A review of human thermal plume and its influence on the inhalation exposure to particulate matter

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Abstract

This paper reviews studies on the human thermal plume and its influence on the inhalation exposure to particulate matter in the breathing zone under different conditions. The human thermal plume transports particle pollutants from the floor to the breathing zone, increasing the inhaled particulate matter concentration. The concentration can be four times higher than that in the ambient environment. Studies have reported that the human thermal plume may prevent particulate matter from entering the breathing zone under specific conditions. Indoor airflow patterns significantly affect the dispersion of pollutants, especially in rooms equipped with displacement ventilation at low airflow velocities. It has been shown that the particle concentration is two times lower in the breathing zone of a rotating manikin than a static manikin. Understanding the characteristics and influencing factors of the human thermal plume is crucial to formulate measures to mitigate the inhalation exposure to particulate matter, achieve independent and personalized control of the human microenvironment, and create a healthy, intelligent and energy-saving indoor environment.

Keywords

human thermal plume, indoor particulate matter, human exposure, human microenvironment, advanced ventilation

Introduction

People's demand for indoor air quality and thermal comfort is increasing, however, improving these parameters is typically associated with increased building energy consumption. Reducing the energy consumption of buildings has therefore become an urgent need for society.[1,2] Traditional heating, ventilation and air conditioning (HVAC) systems of buildings are mostly designed to provide a uniform thermal environment for the whole space.[3-5] Conditioning the indoor environment of unoccupied spaces causes unnecessary energy use.[6] In addition, since people may have different preferences in indoor thermal environments, such as air temperature and air movement,[7] they are often not satisfied with the same thermal environment provided by traditional HVAC systems. An individually controlled human microenvironment providing local heating/cooling for the body to improve individual comfort and energy performance is expected.[8] The skin temperature, specifically, the temperature of the hands or fingertips, has been identified as an essential indicator of thermal comfort,[9,10] and has been used as a parameter to control the human microenvironment.[8]

Epidemiological studies have reported that a strong correlation between outdoor particulate matter levels and human health.[11] Elevated particulate matter levels can lead to respiratory diseases,[12] cardiovascular diseases,[13,14] pulmonary dysfunction,[15] and early mortality.[16,17] People spend more than 80-90% of their lives in indoor environments,[18,19] which is usually densely populated and sometimes poorly ventilated.[20,21] In some cases, particulate pollutants in the indoor environments are more likely to be inhaled than outdoor sources.[22] Therefore, considerable attention has been focused on the transport characteristics of indoor particles and the inhalation exposure in the human breathing zone. The evidence so far is that the total volume ventilation method does not prevent occupants from inhaling airborne particles.

Many studies have shown that the indoor airflow pattern could significantly affect the dispersion of pollutants, especially in spaces with displacement ventilation where the human thermal plume plays a leading role in the exposure to particulate matter. Melikov[23] revealed in detail the free convection flow generated by a human body (including the convective boundary layer around the body and the thermal plume above the body), and discussed its interaction with incoming air flows and the resulting heat and mass transfer. The control of the airflow around the human body is crucial to improving indoor thermal comfort and inhaled air quality. People are affected by respiratory pollutants of co-occupants through direct exposure and indirect exposure.[24,25] Direct exposure occurs when exhaled pollutants from the source person enter the breathing zone of the susceptible person before they mix with the indoor air. In contrast, indirect exposure occurs when pollutants enter the breathing zone of the susceptible person after they mix with the indoor air. Transmissions through droplets and droplet nuclei are effective transmission routes of Coronavirus Disease 2019 (COVID-19). Since the exposure occurs in the breathing zone, the airflow around the human body is crucial for determining the risk.[26] Sun et al.[27] reported that the human thermal plume brought small droplets and airborne particles from the lower area to the breathing zone and moved respiratory droplets from the source person to the upper indoor area, increasing the airborne transmission of COVID-19 in closed spaces.

Traditional HVAC systems condition the entire space, including occupied and unoccupied zones, leading to energy waste. However, individual differences between occupants require for a non-uniform indoor thermal environment. In addition, well-mixed indoor air does not guarantee high-quality inhaled air. Complete mixing of air in a room is seldom achieved.[28] Therefore, local, personalized and intelligent control of the human microenvironment, i.e., the thermal plume around a human body, is an important control target. An in-depth understanding of the characteristics and influencing factors of the human thermal plume is needed to research and develop human microenvironment control and technologies, including intelligent, personalized air supply devices, local air supply and exhaust methods, and other advanced ventilation and airflow technologies. In this regard, this study performs a systematic literature review on the human thermal plume and its influence on the inhalation exposure to particulate matters.

Overview of the method

We searched publications in several scientific databases, including ScienceDirect, SpringerLink, Taylor Francis Online, Wiley Online Library, SAGE Journal, Molecular Diversity Preservation International Journal, Google Academic Search Engine, and China National Knowledge Infrastructure. The following search keywords were used: "human thermal plume", "indoor particulate matter", "respiratory exposure", "personalized ventilation", "building energy consumption" and different combinations of these words. Based on the evaluation of the abstracts, 96 papers were initially shortlisted and 81 papers were eventually selected after reviewing the retrieved full texts. Since there are many publications on indoor pollutant exposure, this review focuses on the analysis of the influence of the thermal plume on the exposure of particulate matter in the breathing zone. The dispersion and propagation of pollutants such as droplets, virus particles, toxic gases and photochemical smog, are beyond the scope of this paper. We conducted a comprehensive review of the relevant literature, summarized the characteristics of the thermal plume and its influencing factors, and determined the influence of the thermal plume on particulate matter exposure under different conditions. The flowchart of this study is shown in Figure 1.

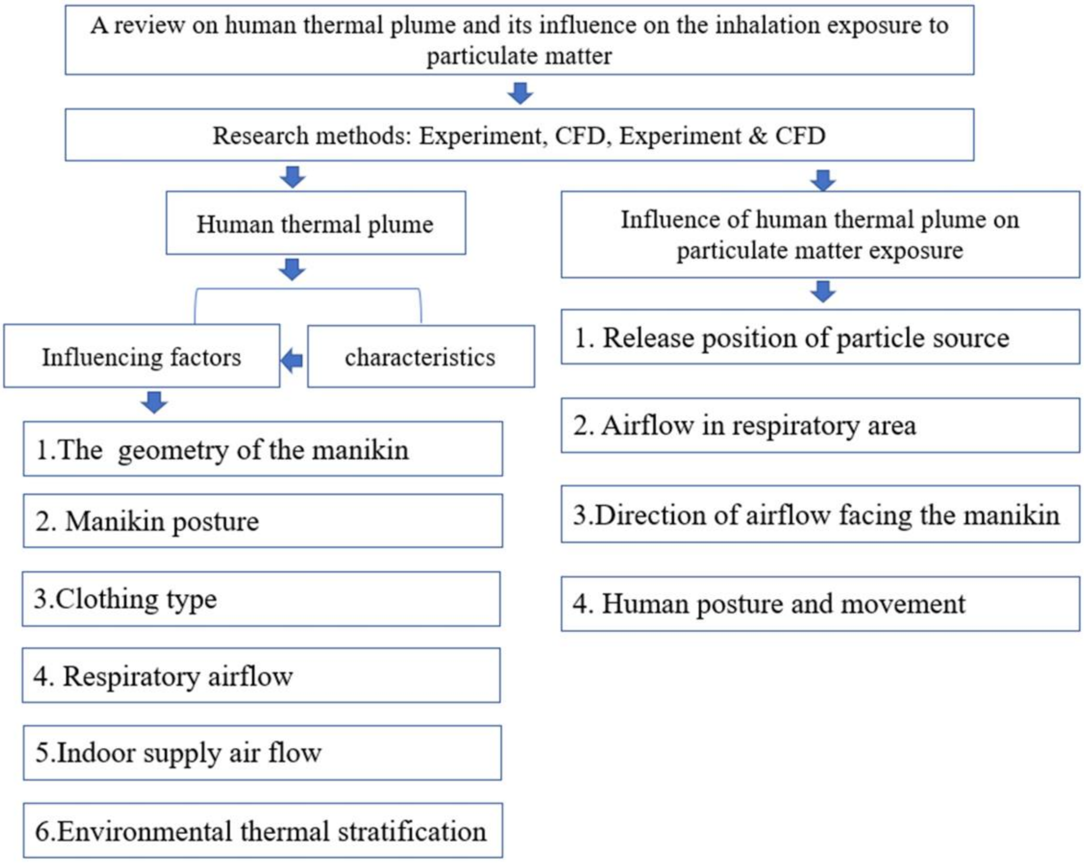


Figure 1. Flowchart of the research content.

Research methods

Experiments, computational fluid dynamics (CFD) simulations, and their combination are widely used by scholars to study the human microenvironment and inhaled exposure of particulate matters, as listed in Table 1. As shown, the thermal plume around a human body affected by the displacement ventilation has been receiving a broad interest.

Experimental methods

Particle image velocimetry (PIV) was used to measure the airflow velocity around the human body in a temperature-stratified room.[29] Temperature stratification would lead to a decrease in the thermal plume buoyancy and would significantly affect the thermal plume behaviour. Wang et al.[30] measured the human thermal plume in a 7-row cabin model using mini-PIV and determined its instability and chaotic behaviour using statistical and chaotic methods. A bimodal Gaussian mixture model was used to obtain the probability density distribution of the velocity time series of the human thermal plume, revealing the oscillation characteristics of the human thermal plume.

Smoke visualization uses static objects and flowing fluids to visualize airflows. Tao et al.[31] developed a new smoke display method to analyze the wake of a human moving through the smoke. The smoke was generated by the chemical reaction between acetic acid (CH_3COOH) and cyclohexylamine ($C_6H_{13}N$). Sheng et al.[32] used a Harvard sampling system combined with a polytetrafluoroethylene membrane, glass slide and an aerodynamic particle size spectrometer as a standard to study the influence of the human thermal plume on the active and passive exposure to indoor particulate matter. In addition, the phase Doppler anemometer was used to measure the particle concentration in the breathing zone of a sitting, breathing thermal manikin.[33] Liu et al.[34] conducted a water tank experiment using the similarity protocol to simulate human expiratory airflow and compared the particle trajectory in uniform and layered environments. The layered environment was created using the heating and cooling method to form a vertical temperature profile of the water.

Simulation method

A CFD simulation of a human body model can provide detailed information that cannot be obtained from experiments.[35] Salmanzadeh et al.[36] used the Euler method to simulate the airflow field in a compartment and the Lagrange method to calculate the trajectory of pollutant particles. They measured the plane and volume-averaged particle number concentration in the breathing zone and its vicinity. Xu et al.[37] simulated the concentration of five typical particle sizes for two pollution sources and found that particles with different particle sizes had different effects on indoor air quality when released from different locations.

Gao and Niu[35] observed that the data analysis of thermal manikins with simple geometry required less computational resources compared to an anthropomorphic manikin. In the simulations using complex geometric representations of the human body the computational domain was discretized by body-fitted co-ordinates or unstructured grids. The total number of cells can reach the quantitative magnitude of 1 million. A more anthropomorphic geometry can provide more accurate results.[38]Xu et al.[39] employed a scanned human upper respiratory tract to construct an embedded model consisting of the nasal cavity, oral cavity, oropharynx, larynx, trachea and bronchi, which was used to study the effects of the respiratory patterns of nasal and oral inhalation and different exposure conditions on the deposition of particles in the human respiratory tract. The human body model and fifth-generation respiratory tract model are shown in Figure 2. It is necessary in a simulation of the human thermal plume to consider the latent heat transfer and sensible heat transfer of the thermal manikin. At present, it is difficult or impossible to conduct a coupled simulation that considers both the heat and mass transfer between the human body and the ambient environment and the human body thermal regulations. Therefore, CFD has advantages for analyzing the effect of the human thermal plume on the exposure to particulate matter, although further advancements are required.

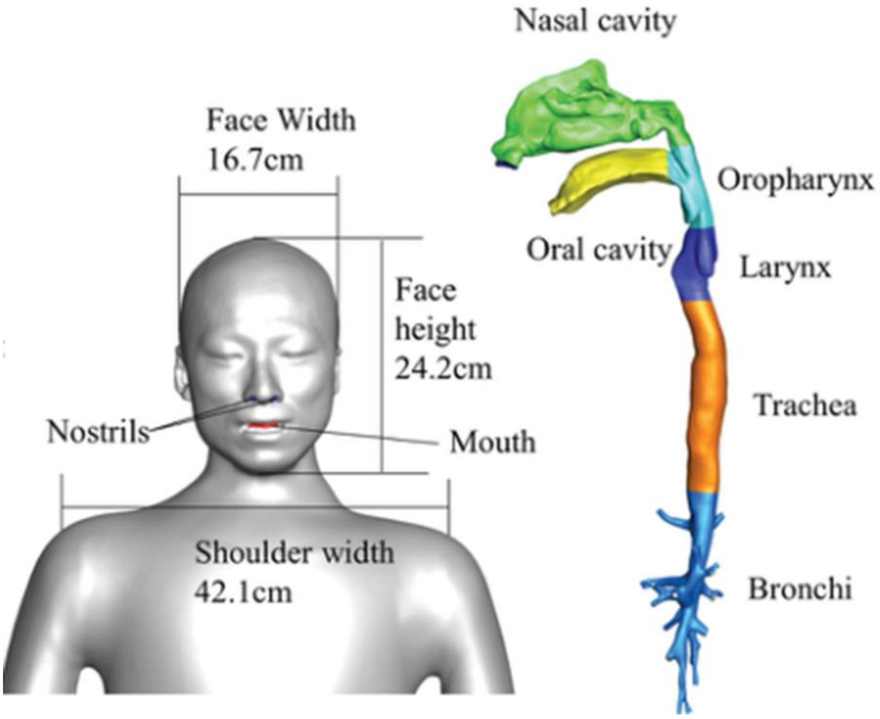


Figure 2. Human body and respiratory airway model.[39]

Table 1. Summary of research methods of the thermal plume and its influence on particulate matter exposure

Author (s)	Year	Research method	Manikin posture	Ventilation mode	Particle Diameter (μm)	Main findings
Ge et al.[40]	2013	CFD	Standing	Piston ventilation	1.0	The direction of the indoor airflow in relation to the human body is the key factor affecting particle inhalation.
Salmanzadeh et al.[36]	2012	CFD	Sitting	DV	1.0	The human thermal plume increases the concentration of suspended particulate matter in the breathing zone.
Rim and Novoselac[41]	2009	Exp.	Sitting	MV/DV	30, 770, 3200	In stratified flow, the upward thermal plume transports pollutants from the floor to the breathing area, increasing occupant exposure.
Spitzer et al.[33]	2010	Exp.	Sitting	DV	1~12	The rotation of a manikin reduces the velocity of the thermal plume and the concentration of larger particles, but the effect on smaller particles is unclear.
Sheng[32]	2018	Exp.	Sitting	DV	3.2	The thermal plume attracts particulate matter to the breathing zone of the human body but reduces the passive exposure of the skin surface.
Xu et al.[37]	2008	CFD	Sitting	DV	0.5, 1.0, 2.5, 5.0, 10	When pollutants are released 0.4 m above the ground, the particulate matter concentration is very low in the breathing zone. However, when pollutants are released at 0.8 m, the particulate matter concentration is relatively high.
Xu et al.[39]	2020	CFD	Standing	Piston ventilation	0.001~0.8, 1~80	Respiratory patterns affect the local deposition of particles, increase the proportion of nasal inhalation flow, and slightly enhance the total deposition in the upper respiratory airway model.
Licina et al.[42]	2014	Exp.	Standing, Sitting	DV		Increasing the ambient temperature widens the thermal plume of a sitting manikin but does not affect a standing manikin.
Wang et al.[30]	2018	Exp.	Sitting	DV		The probability density distribution of the time series of human thermal plume velocity was modelled using a bimodal Gaussian mixture model, confirming the oscillation characteristics of the human thermal plume.
Habchi et al.[43]	2015	Exp.	Standing	DV	5000	An increase in the exhalation airflow speed of the infected person increases the risk of cross-infection.

Abbreviations: experiment (Exp.), computational fluid dynamics (CFD), displacement ventilation (DV), mixed ventilation (MV), natural ventilation (NV), downward ventilation (DnV)

Keshavarz et al.[44]	2017	CFD	Sitting	MV/DV	4.4	The human thermal plume is distorted by the airflow of the mixed ventilation system, whereas the displacement ventilation system has a negligible effect.
Tao et al.[45]	2017	CFD	Standing	NV	2.5	A dynamic grid is used to simulate the flow field of a walking person. When the wake momentum dissipates, the thermal plume effect becomes significant, affecting the disperson of particulate matter.
Zhong et al.[46]	2008	CFD	Standing	DV	0.5, 1.0, 2.5, 5.0, 10	The location of the aerosol source has a significant influence on the spatial distribution and removal rate of indoor particulate matter.
Naseri et al.[47]	2017	CFD	Standing	NV	0~80	The upward and downward human thermal plumes increase and decrease, respectively, the particle inhalation efficiency of nasal breathing.
Keshavarz et al.[48]	2014	CFD	Standing	DV	1~12	The rotation of a human body model significantly affects the thermal plume and particle transport around the human body.
Dong et al.[49]	2017	Exp.	Standing	NV		The shape of the simulators plays an important role in the characteristic of the thermal plume.
Voelker et al.[50]	2014	Exp.	Sitting	NV	5000	The larger the temperature difference between the surface temperature of the human model and the air temperature, the faster the airflow is in the human microenvironment.
Li et al.[51]	2014	CFD	Standing	MV	1~25	When the legs of the manikin are separated, air can flow through the gap, causing more particles to enter the breathing area from the lower level.
Jia et al.[52]	2013	CFD	Sitting	DV	5	Buoyancy-driven flow around the manikin disperses particles into different areas of the spaces.
Feng et al.[53]	2019	CFD	Standing, Sitting, Lying	NV	0.3~1	The thicker and faster the human thermal plume is, the more difficult it is for aerosols generated by nasal breathing to penetrate the plume.
Yang et al.[54]	2015	CFD	Standing, Sitting, Lying	DnV	0.5	The airflow velocity required to control the thermal plume and particle dispersion around the human body is at least 0.25 m/s when the manikin is standing or sitting and at least 0.2 m/s when the manikin is lying down.

Results

Thermal plume characteristics

At a normal activity level and moderate room air temperatures, the heat generated by the human body is approximately 100 W.[55] A temperature gradient exists between the human body and the surrounding environment, resulting in the formation of the human thermal plume.[49] A method, named as the Approximate Distributions Integration Method (ADI-method), is proposed by Zukowska et al.[56] to calculate the parameters of the asymmetrical thermal plume above a heat source. They found at a height of 0.7 m above the manikin head, the mean integral characteristics of the plume and their 95% certainty range (in parentheses) were volume flux 258 m^3/h (1.8%), momentum flux 0.0087 N (2.0%), buoyancy force density 0.0038 kg/s^2 (3.8%) and enthalpy flux 16 W (2.8%). Some studies found that the human thermal plume can produce vertical air velocity of 0.10~0.25 m/s in the breathing zone.[29] Rim and Novoselac[41] conducted experiments with a human body simulator in a full-scale environmental chamber to measure the air velocity of the thermal plume above the head. As shown in Figure 3, the average value of the velocities measured at eight positions above the head was used to represent the velocity of the upward thermal plume.

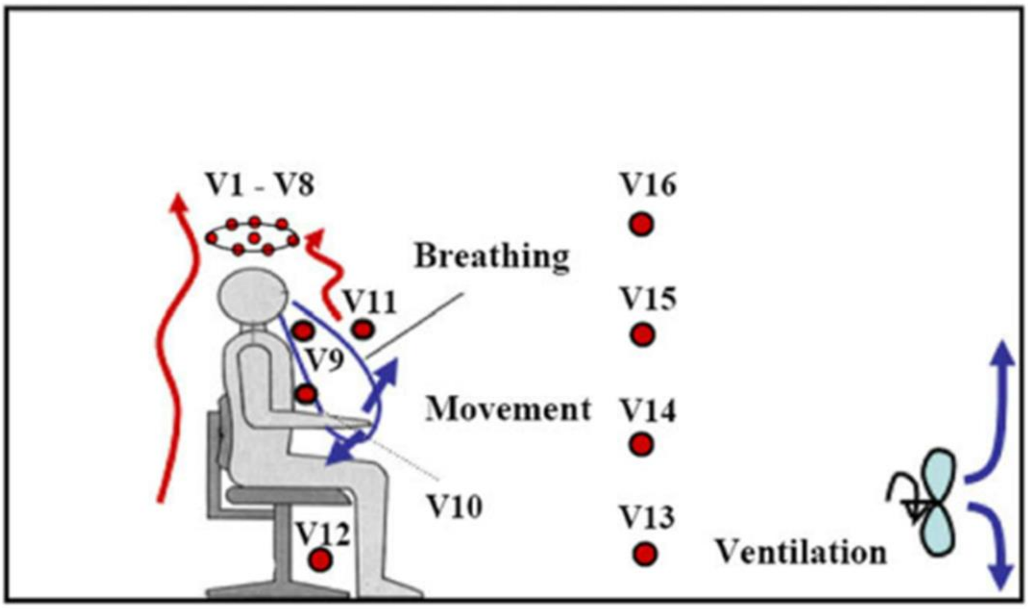


Figure 3. Locations of airflow velocity monitoring points.[41]

In addition, the study also reported that the maximum average velocity above the head was 0.20 m/s. Liu et al.[57] performed an unsteady numerical simulation and observed that the maximum average velocity generated by the thermal plume at 18 cm above the head was 0.23 m/s. Murakami et al.[58] obtained the same maximum velocity of 0.23 m/s by using a CFD simulation. The thermal plume velocity observed by Zukowska et al.[59] was 0.255 m/s. The above studies of the human thermal plume, indicate that the maximum velocity of the thermal plume occurs above the head. The specific values were different due to differences in the configuration of the manikins but were similar. Craven and Settles[29] qualitatively analyzed the development of the thermal plume around the human body. Initially, the boundary layer at the feet was laminar and gradually changed as the airflow moved up the legs. Then, the upper body was surrounded by turbulent flows, and the boundary layer separated at the shoulder and head to form a recirculation zone. The thermal plume around the human body typically exhibits low-frequency fluctuating flow with intermittence.[57] The thickness of the velocity boundary layer around the human body was about 8 cm around the feet and legs and increased to 15 cm around the neck.[58] Likewise, the thermal boundary layer on the manikin surface was about 5 cm thick at the feet and about 19 cm thick at the neck.[41]

Factors affecting the properties of thermal plumes

The geometry of the manikin

An occupant of a room is a heat source, and the buoyant airflow generated by the human body affects the indoor air distribution.[59] The analysis of a thermal plume with real people as the heat source causes many problems due to human movements and differences in physiological characteristics. Thus, it is crucial to choose a reasonable human simulator.

Zukowska et al.[60] compared the simulation results of a thermal plume around four human simulators with different geometric complexity but equal surface area. It was found that a simplified manikin and a human-like manikin produced almost the same thermal plume. Although a cylinder or a cuboid frame can correctly simulate enthalpy flux and buoyancy density, they produce a more concentrated thermal plume than a thermal manikin. Four types of human body simulators are shown in Figure 4.

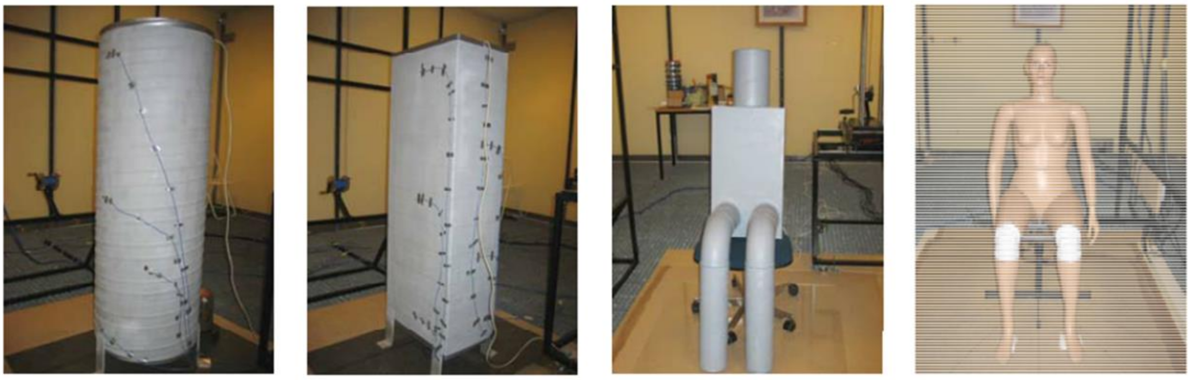


Figure 4. Human body simulator: cylinder, cuboid, simplified manikin and human-like manikin.[59]

Manikin posture

Different manikin postures have different effects on the intensity of the thermal plume.[53] The thermal plume is primarily produced by convective heat transfer. The largest convective heat transfer coefficient (representing the heat transfer rate) occurs for a sitting posture. The thermal plume generated by bending the thigh increases the size of the facial thermal plume in horizontal direction. When the room air temperature of an air-conditioned room is around 24–27°C in summer, the thickness of the thermal plume of a sitting person is about 1.28 times that of a standing person. Since there is no accumulation of the thermal plume in the lying position, the maximum velocity and the range of the thermal plume are much smaller than those of the standing and sitting position. Figure 5 shows the contours of the thermal plume velocity of three different human postures. At a room temperature of 24°C, the maximum velocity of the thermal plume occurs at 0.65 m above the head in the sitting position, 0.45 m above the head in the standing position, and 1.3 m to 1.5 m above the head in the lying position.

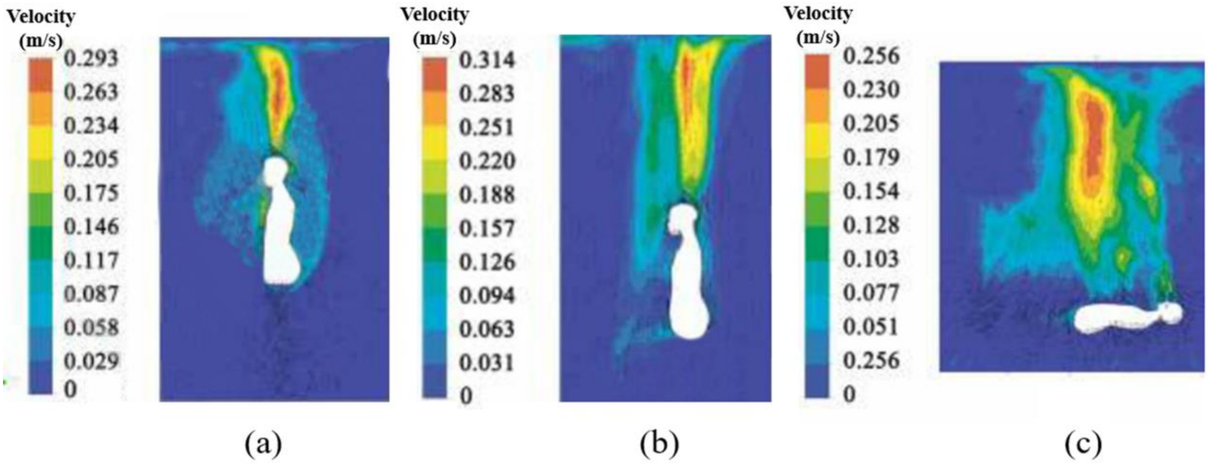
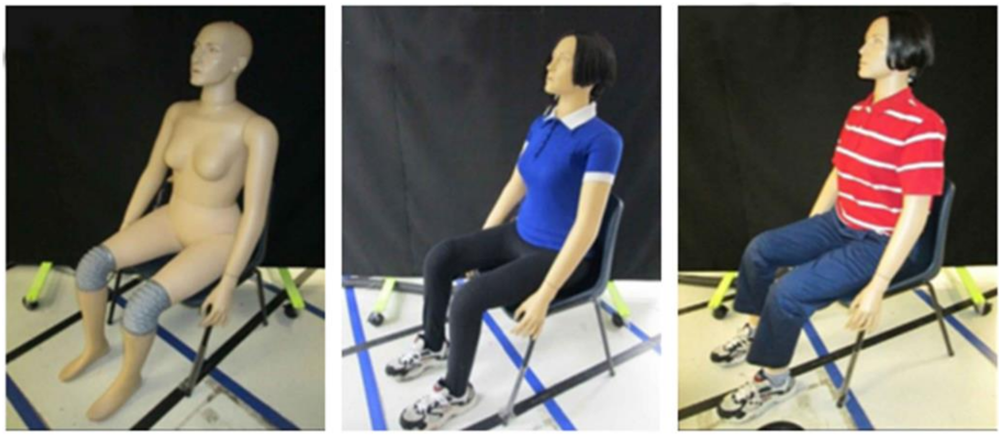


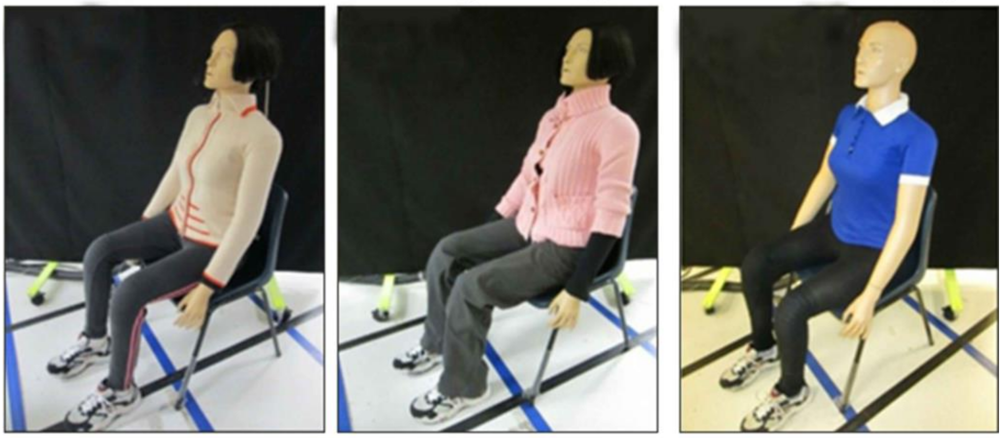
Figure 5. Contours of the thermal plume velocity for different human postures; (a) standing, (b) sitting, and (c) lying.[53]

Clothing type

Because people wear clothes indoors and generally have hair, it is necessary to investigate the thermal plume of manikins wearing wigs and clothes.[42] Figure 6 shows manikins with no clothing and different types of clothing (thin and thick), different designs (tight and loose) and wigs. A wig on the manikin head appears to be important because a bald head decreases plume volume flux by 15%.[61] Likewise, the peak velocity of the thermal plume increases from 0.17 m/s to 0.187 m/s due to the strong convection above the bald head and the upward airflow from below. In addition, the effect of clothing becomes more pronounced as the clothing insulation increases. Compared to the manikin with thin and tight clothing, the peak velocity in the breathing zone was 28% (0.148 m/s) and 40% (0.124 m/s) lower for manikins with thick and tight clothing and thick and loose clothing, respectively.



Nude Thin-tight clothing Thin-loose clothing



Thick-tight clothing Thick-loose clothing No wig

Figure 6. Thermal manikin with different levels of clothing insulation/design.[42]

Respiratory airflow

In a study of the interaction between the human thermal plume and respiratory airflow, the airflow velocity in the breathing zone increased sharply when the breathing mechanism was activated. However, the change in the average velocity above the head was negligible.[41] The presence of respiratory airflow interfered with the rising human thermal plume in the breathing zone but had little effect on the thermal plume above the breathing zone.[62] However, the respiratory airflow was substantially influenced by the thermal plume. The thermal plume in front of the face pushes the respiratory airflow upwards, generating eddy currents. It was found that the respiratory flow lost kinetic energy quickly due to the influence of the thermal plume.[53]

Indoor supply air flow

The thermal plume above the human body is highly sensitive to indoor airflow. The airflow directed at the face weakens the thermal plume above the human body, whereas the airflow directed upwards enhances the free convection flow in front of the manikin.[23] Figure 7 shows the airflow field around a standing manikin at different downward airflow velocities.[54] At an airflow velocity of 0.05 m/s, the upward airflow induced by the thermal plume of the manikin strongly disturbs the downward airflow in the room. However, when the airflow velocity reaches 0.25 m/s, only the airflow near the thermal manikin is disturbed by the thermal plume. Yang et al.[54] conducted an experiment in a clean room with a ceiling air supply and found that, the downward airflow velocity for a standing manikin should be no less than 0.25 m/s and that of a lying manikin should be no less than 0.20 m/s to control the thermal plume. When the supply airflow velocity was less than or equal to 0.20 m/s and 0.15 m/s, the upward airflow velocity produced by the thermal plume of the manikin in the standing (sitting) and lying position was greater than that of the air supply.

Ma et al.[63] studied the interaction between ambient airflow and the human thermal plume to determine the dominant airflow in the human microenvironment. Figure 8 (a) and (b) show that the airflow in the human microenvironment is dominated by the thermal plume and the downward jet airflow, respectively. The latter case occurs when the airflow velocity of the downward ventilation system exceeds the upper threshold (v = 0.275 m/s), and the former case occurs when the airflow velocity is lower than the lower threshold (v = 0.075 m/s). When the air supply speed is between the upper and lower threshold, two steady-state flow solutions occur. The same boundary conditions and different initial conditions may induce different flow types, and there are multiple flow solutions.

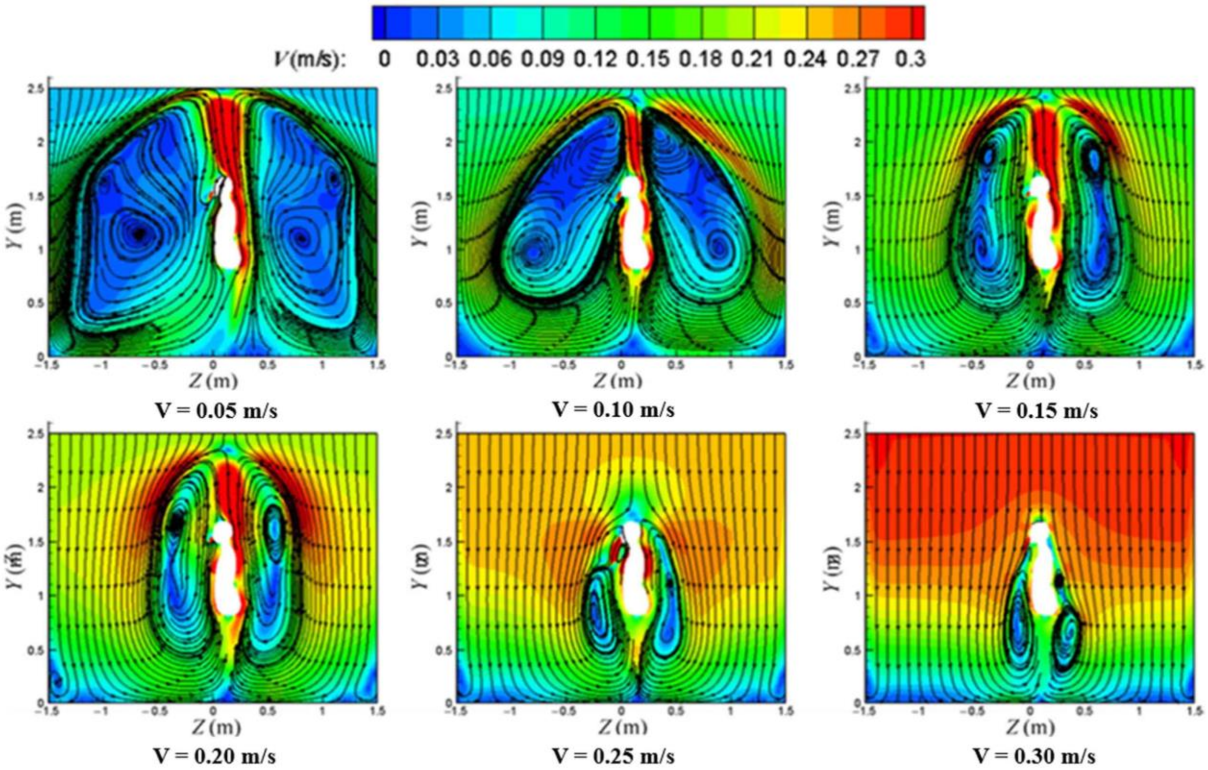


Figure 7. Airflow fields around a standing manikin at different indoor airflow velocities for one-direction downward ventilation.[54]

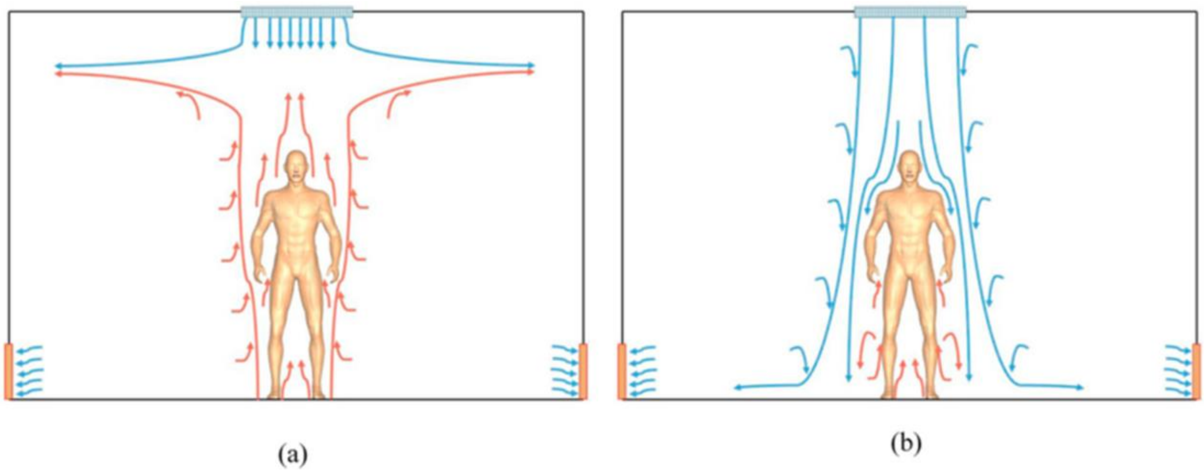


Figure 8. Airflow patterns dominated by different airflows. (a) Thermal plume is dominant, and (b) downward jet is dominant.[63]

Environmental thermal stratification

Because the indoor airflow is mostly unstable, and the air temperature is not uniform at different heights, the influence of environmental thermal stratification must be considered when simulating the human thermal plume in a standard room. Craven and Settles[29] compared the results of a thermally stratified environment and a thermally uniform environment. The plume buoyancy was found to decrease significantly and the plume volume flux decreased by 3 times due to stratification, substantially affecting the size and distribution of the plume's central linear velocity. Low to medium thermal stratification had a strong influence on the thermal plume. The higher the thermal stratification degree, the greater the impact on plume behaviour was.

Effect of thermal plume on the exposure to particulate matter

Numerous studies were conducted on human exposure to particulate pollutants, indicating that the human thermal plume could affect human exposure to particulate matter. At low velocities of the indoor air supply, the human thermal plume represents the dominant airflow in the human microenvironment. The active exposure to particulate matter of a sitting human body was increased by 200%, the passive exposure was decreased by 60%, and the overall exposure was increased by 69% compared with no thermal plume. These results show that the human thermal plume has a significant impact on the passive and active exposure to particulate pollutants.[32] Previous studies have shown that exposure to particulate matter is affected by the release source of the particles, the airflow in the breathing zone, the direction of the human body toward the indoor airflow, as well as the posture and movement of the human body.

Release source of particles

A study of the influence of the human thermal plume on the inhalability of fine particles/ultrafine particles in static layered indoor air showed that when the particle source was 0.15 m from the floor and close to the human body, the inhaled particle concentration by the human model was four times higher than that of the background concentration.[41] The reason is that the human thermal plume transports pollutants from the floor to the breathing zone, increasing the inhalation exposure. Xu et al.[37] used CFD to simulate the particle release of walking and sitting people indoors. When the particles were released near the ground ($Y = 0.4$ m), the particle concentration in the breathing zone was relatively low. In contrast, the concentration of small particles near the human body was relatively high when the particle source was at 0.8 m, i.e., in the horizontal reflux area.

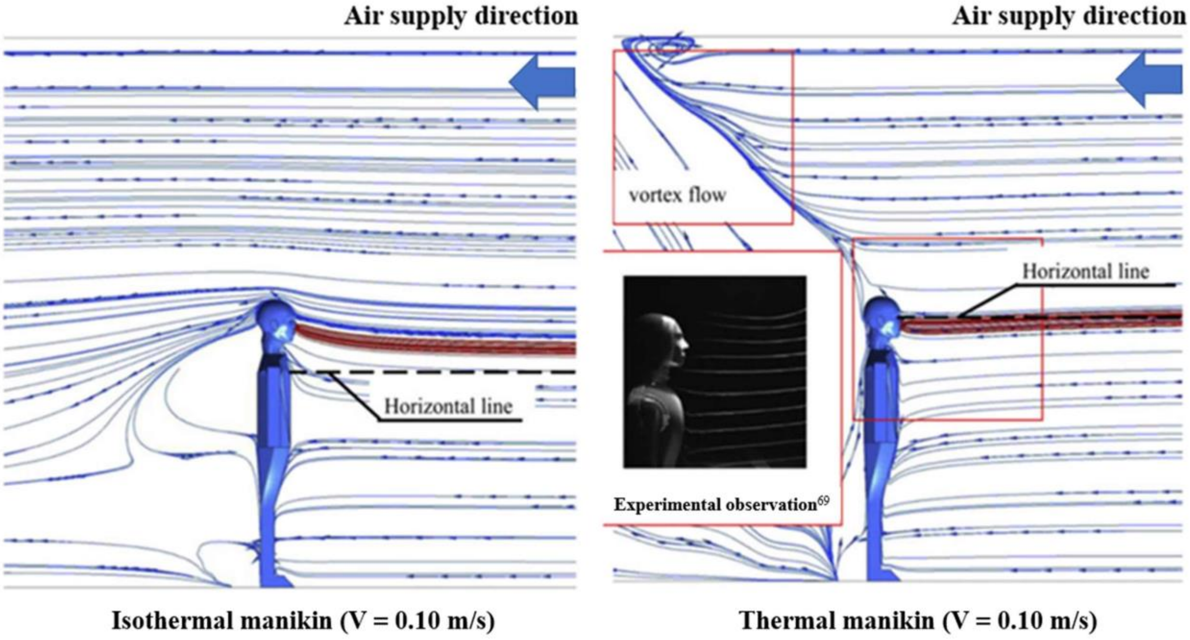
Rim and Novoselac[41] studied the trajectory of particles released at 0.25 m above the head and found that the thermal plume prevented pollutants from entering the breathing area, causing the inhaled particle concentration to be lower than particle concentration elsewhere in the environment. Therefore, the thermal plume may increase or decrease the exposure to particles, depending on the release location of the particles.

Airflow in breathing area

The human thermal plume interacts with respiratory airflow and indoor ventilation airflow.[64] The interaction with the indoor airflow, especially in the breathing zone, is crucial for evaluating the exposure to indoor air pollution.[65,66] The influence of indoor airflow interaction on indoor pollutant dispersion may be mutual assistance, mutual confrontation or mutual transfer of pollutants.[67] The thermal plume was found as the dominant airflow in the breathing zone at low indoor airflow velocities.[63] The human thermal plume could affect the flow field formed by the inhaled airflow near the chin of the occupant, and the airflow in the breathing zone of the lower jaw could prevent the inhalation of pollutants coming from other directions, which may reduce the risk of exposure.[68]

The human body faces the direction of airflow

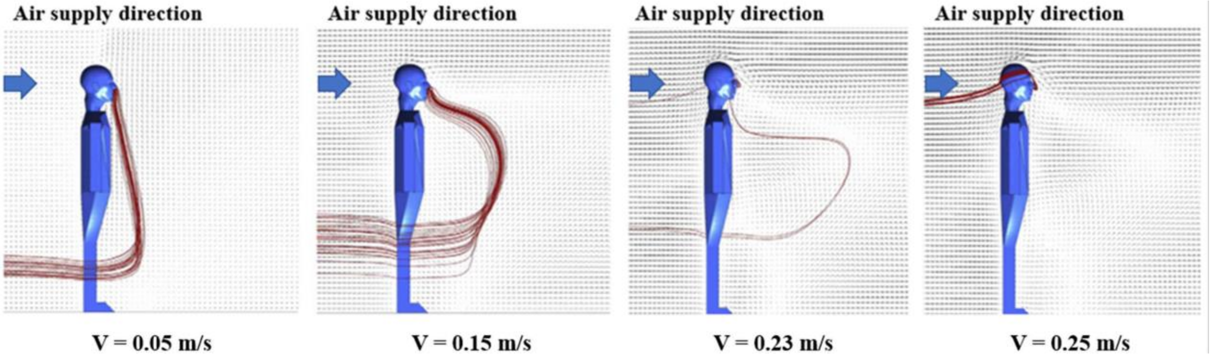
In most indoor environments, the direction of the human body relative to the airflow is crucial to determine the exposure level of humans to particles when the airflow velocity is lower than 0.2 m/s. Figure 9 shows the airflow field and particle trajectory near the isothermal manikins and the thermal manikins in the windward condition.[40] The human body temperature was assumed to equal to the ambient temperature in isothermal manikins. The figure shows that although the airflow field on the downstream side of the manikin is substantially different, the trajectory of the inhaled particles is the same under isothermal and non-isothermal conditions. Therefore, the influence of the thermal plume on the exposure to particulate matter can be neglected when the manikin is facing the airflow. On the other hand, when the manikin is facing away from the airflow, the thermal plume caused by the body heat has an important role in transporting particles from the lower level to the breathing area. Figure 10 shows the particle trajectories around a thermal manikin under upwind conditions. As the airflow velocity increases, the influence of the body heat on particle inhalation decreases.[40] According to a survey conducted by Rim and Novoselac,[41] human body heat is a crucial factor that could affect the inhalation concentration of particles, since the average wind speed in most indoor environments is lower than 0.2 m/s.



Isothermal manikin (V = 0.10 m/s)

Thermal manikin (V = 0.10 m/s)

Figure 9. Particle trajectory and streamline in the windward case.[40,69]



V = 0.05 m/s

V = 0.15 m/s

V = 0.23 m/s

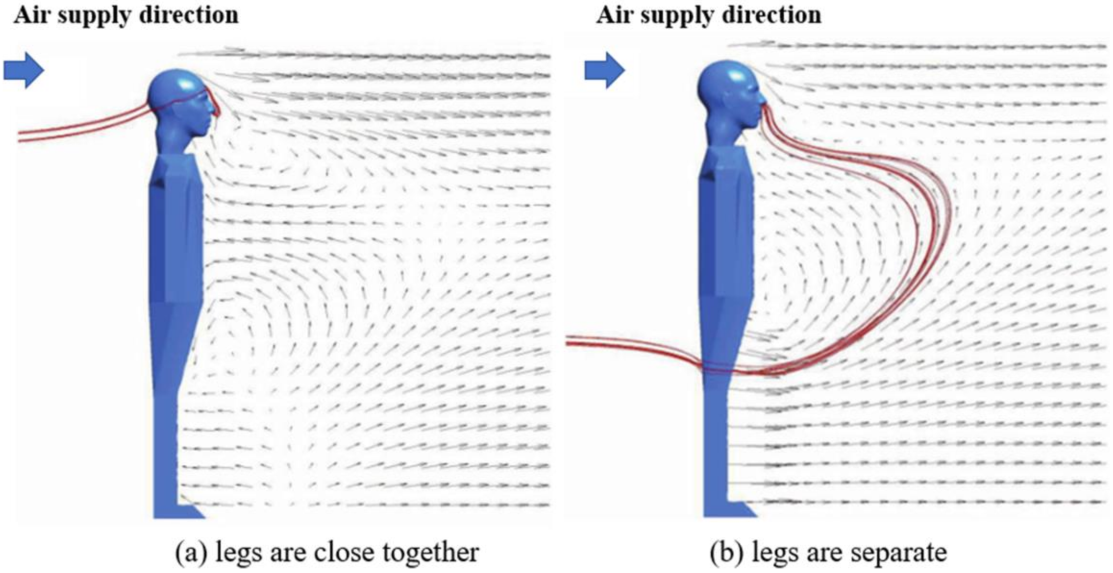
V = 0.25 m/s

Figure 10. Particle trajectory under upwind conditions.[40]

Human posture and movement

Different human postures have different effects on the intensity of the thermal plume.[53] Some studies found that the human posture affects the exposure to particulate matter in the breathing zone. Feng et al.[53] found that particles tended to gather near the chest of sitting and standing manikins, with a high particle concentration in the breathing zone. The distribution of particulate matter in the vicinity of a lying person was typically uniform, and there was no particularly high concentration area.

Anthony and Flynn[70] defined the area where inhaled particles are released as the 'critical area'. Li et al.[51] extended previous research and found that the leg posture was an important factor affecting the inhalation characteristics of particles when the manikin faced away from the airflow. Figure 11 shows the airflow field and particle trajectory for different leg postures. When the legs are separated, air can flow through the gap, causing more particles to enter the breathing area from a lower level. The centre height of the critical area does not change significantly with an increase in the wind speed. However, when the legs are close together, the height of the centre increases significantly with an increase in the wind speed. Although the thermal effect of the body heat is gradually suppressed as wind speed or particle size increases, the sensitivity of different leg postures to the environment is different, especially when the particle size is small or the wind speed is low. The rotation of the human body promotes the mixing of indoor air when a displacement ventilation system is used. The particle concentration in the breathing zone was reduced by about 2 times compared with a static manikin.[44] Spitzer et al.[33] determined the decrease in the particulate matter concentration in the breathing zone of a stationary and rotating human body. The rotation resulted in a 22% decrease in the concentration of small-sized particles (0~1μm), and 60% increase in the concentration of large-sized particles. When the manikin was rotated, the velocity of the thermal plume was decreased, and the number and concentration of large-sized particles was decreased, whereas the influence on small-sized particles was negligible.



(a) legs are close together (b) legs are separate

Figure 11. Comparison of airflow field and particle trajectory for different leg postures. [51]

Evaluation indices

The air quality of the human microenvironment is strongly correlated with human health, and the thermal plume could affect the concentration of particulate matter in the breathing zone. Different evaluation indices have been proposed to measure the exposure to particulate matter in the breathing zone. The authors[71] did not consider the peak exposure and assumed that the release of particulate matter was a slow process. The average or cumulative exposure index was used to measure the impact of particulate matter on human health.

(1) Personal exposure effectiveness

Melikov et al.[72] analyzed the change in pollutant concentration in the human microenvironment with and without a personalized ventilation system and proposed a new index, the personal exposure effectiveness ε_p, which is the percentage of personalized air in the inhaled air, as defined in Eq. (1). When $\varepsilon_p = 0$, the personalized air is completely mixed with the ambient air, and $\varepsilon_p = 1$ indicates that the inhaled air contains only personalized air.

$$\varepsilon_p = \frac{C_e - C_i}{C_e - C_s} \quad (1)$$

where C_e is the concentration in the inhaled air without personalized ventilation, C_i is the pollutant concentration in the inhaled air, C_s is the pollutant concentration in the personalized air.

(2) Pollutant exposure reduction index

Gao and Niu[73] investigated the microenvironment around the human body with and without a personalized ventilation system using a sitting thermal manikin with a realistic human geometry. They introduced a new evaluation index, the pollutant exposure reduction index η_{PER}, which is the percentage of pollutant concentration reduction in indoor air, as defined in Eq. (2). In their numerical simulation, the pollutant exposure reduction (*PER*) in the air was 74%, and the exhalation strongly affected the PER when the personalized airflow speed was low.

$$\eta_{PER} = \frac{C_{a,P} - C_{L,P}}{C_{a,P}} = 1 - \frac{C_{L,P}}{C_{a,P}} \qquad (2)$$

where $C_{a,P}$ is the pollutant concentrations in ambient air, and $C_{L,P}$ is the pollutant concentrations in the inhaled air.

(3) Inhalation efficiency

Assaad et al.[74] found that if infectious particles entered the breathing zone or the human microenvironment from all directions, infection could occur by inhaling infectious particles. Based on previous studies,[75,76] the authors proposed the inhalation efficiency (*IF*), as defined in Eq. (3). It represents the percentage of infectious particles generated by the pollution sources and inhaled by healthy people in the same room.

$$IF = \frac{C_{a,i}}{C_{a,g}} \qquad (3)$$

where $C_{a,i}$ is the particle concentration in the breathing zone of a healthy person and $C_{a,g}$ is the particle generation concentration.

(4) Deposition fraction

When particles are deposited on surfaces near the human body (computer, desk, floor near the work area, head, chest, chair and abdomen), infection may occur through secondary pollutants that are resuspended from these surfaces. The deposition fraction (*DF*) was proposed to evaluate secondary pollutants, as defined in Eq. (4). It represents the ratio of the particle concentration deposited on the surfaces to the initial concentration at the pollutant sources.

$$DF = \frac{C_{a,d}}{C_{a,g}} \qquad (4)$$

where $C_{a,d}$ is the particle concentration deposited on the nearby surface, and $C_{a,g}$ is the particle generation concentration.

Discussion

This paper reviewed studies on the human thermal plume and its influence on the inhalation exposure to particulate matters in the breathing zone. An in-depth understanding of the characteristics and influencing factors of the human thermal plume is needed to research and develop human microenvironment control and technologies, including intelligent, personalized air supply devices, local air supply and exhaust methods, and other advanced ventilation and airflow technologies.

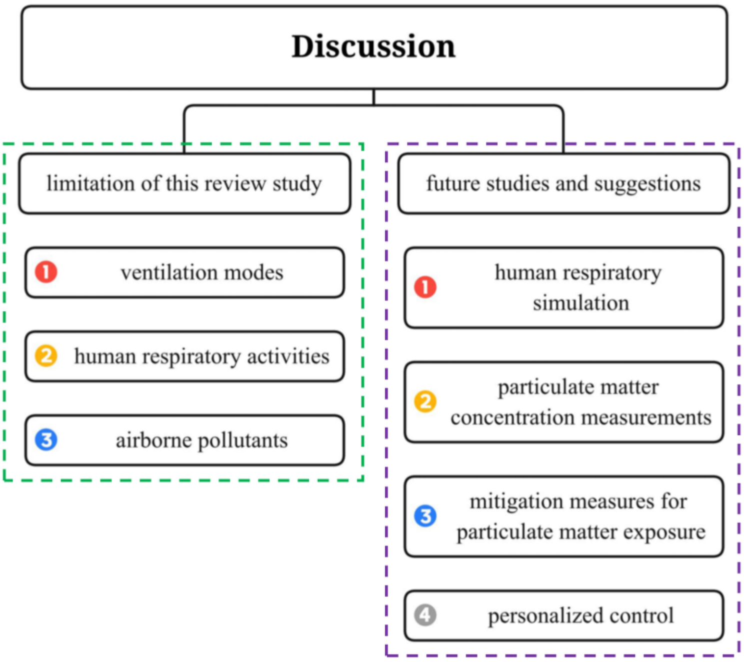


Figure 12. Schematic diagram of the limitations of this review and suggestions for future studies.

The ventilation mode is a crucial factor affecting indoor air distribution. However, this paper focused primarily on a review of the influence of the human thermal plume in rooms with displacement ventilation, and less on other total volume ventilation methods, including mixed ventilation, under floor air distribution, and downward ventilation. In addition, we reviewed studies analyzing the thermal plume of the human body during breathing, whereas other activities were not considered, e.g., breathing, sneezing, coughing and talking. Studies investigating the inhalation exposure to particulate pollutants were reviewed, but we did not consider other airborne pollutants, such as gas pollutants. To summarize the disadvantage and suggestions of this literature review, Figure 12 presents a schematic diagram of the discussion, showing the limitations and suggestions for future studies. Some important issues related to the suggestions and end-use application are discussed in detail as follows.

Human respiration simulation

Most studies on the human thermal plume used experiments or CFD simulations to analyze the influence of the geometry of the human model, clothing type and body posture on the thermal plume intensity. The human thermal plume interacts with the respiratory airflow and indoor ventilation airflow. Researchers analyzed the changes in the dominant airflow of the human microenvironment in the presence of multiple airflows by considering environmental factors. The results show that the thermal plume dominates the dispersion of particles in the human microenvironment only when indoor airflow has a low velocity or is static. When the indoor airflow velocity exceeds a threshold, the thermal plume is no longer the dominant airflow in the human microenvironment. Many researchers simplified breathing as a stable inhalation process to avoid the complexity of the transient characteristics of inhalation and exhalation.[41] However, the exhaled airflows may penetrate the thermal plume and affect the inhaled air quality.[35] The peak velocity and the breathing cycle of exhalations differ considerably between different persons;[77] thus, it is necessary to simulate respiration realistically, especially exhalation.[78]

Particulate matter concentration measurements

Existing evidence shows that the thermal plume affects the level of exposure to particulate matter due to inhalation. Many experts and scholars studied the release source of particles, the direction of the human body in relation to the airflow, indoor airflow interaction and human posture. Most studies found that the thermal plume could transport pollutants from the lower part of the body to the breathing zone, increasing the exposure to particulate matter. In contrast, some studies indicated that the thermal plume might improve the quality of the human microenvironment and prevent particulate matter from entering the breathing zone. This discrepancy in the results inspired us to investigate and clarify the influence of the thermal plume on the exposure to particulate matter and to explore the use of local ventilation measures to dilute the particulate matter concentration to improve air quality in the breathing zone.

Most studies do not provide a specific range of the particulate matter concentration in the human breathing zone, and most studies measured the concentration at a single point. Therefore, it is difficult to draw a general conclusion about the particulate matter concentration in the human breathing zone under indoor conditions. Future research should focus on determining the range of the particulate matter concentration and consider the volume average or area average concentration as indicators rather than the concentration at a single point. Rooms with stratified airflow have a more uneven distribution of particles near the human body than rooms with highly mixed airflow. The human thermal plume carries particulate matter to the breathing zone, increasing inhalation exposure. Therefore, it is inappropriate to assume that the air and pollutants in the thermal plume are entirely mixed when estimating the exposure.[79-81]

Mitigation measures for particulate matter exposure

People are affected by respiratory pollutants of co-occupants through direct exposure and indirect exposure. Building materials, air fresheners, heating, cooking and smoking produce particulate matter, which can be removed by air cleaning systems with high-efficiency filters. The indoor particulate matter concentration can be reduced by changing the filters regularly and maintaining the air conditioning and ventilation system. Particulate matter is concentrated near the chest of sitting and standing manikins, with the highest concentration in the breathing zone. Thus, it is more efficient and energy-saving to remove particles through local exhaust measures. Personalized air supply methods can increase the airflow control in the breathing zone and improve the human microenvironment in densely populated places, such as cinemas, buses, factories and workshops. Particles are evenly distributed near a human body in the lying position, with no area of high concentration. In this case, mixed ventilation can reduce the overall particulate matter concentration in the room and achieve energy savings.

Personalized control

People's demand for building services and comfort is increasing, leading to increased building energy consumption, which will continue into the future. People have different preferences for the indoor thermal environment, such as air temperature and air movement; thus, they are often not satisfied with the same thermal environment provided by the traditional HVAC systems. In addition, residents spend most of their time indoors, and indoor particulate pollution can cause cardiopulmonary diseases. A paradigm shift in indoor environmental control is needed for health reasons, personal comfort preferences and energy savings. One possible solution is to develop advanced indoor environmental control strategies that use the traditional total volume HVAC systems to condition the background environment and personalized control systems to adjust the human microenvironment.

Conclusions

This paper conducted a literature review on the human thermal plume, focusing on the influence of the local airflow interaction, the exposure of particulate matter in the breathing zone under different conditions, and the evaluation indices for assessing the exposure level of inhaled particulate matter. The information summarized in this study is expected to be useful for the development of new HVAC systems with a better balance of the occupants' health, personal comfort preferences and energy savings. The major points of this review are listed as follows:

(1) The velocity range of the human thermal plume is 0.10~0.255 m/s, with the maximum value above the head. Due to the influence of human geometry and environmental conditions, the values reported in the literature are different but are within a similar range.
(2) The human thermal plume interacts with the respiratory airflow and indoor ventilation airflow. The airflow caused by breathing sitting person does not significantly affect the thermal plume, whereas the thermal plume strongly interferes with the breathing airflow.
(3) The thermal plume only affects the exposure to particulate matter when the indoor airflow velocity is relatively low. As the indoor airflow velocity increases, the influence of the thermal plume on the airflow pattern in the human microenvironment decreases.
(4) Depending on the release source of the released particles, the thermal plume may increase or decrease the exposure to particles. In most indoor environments where the airflow velocity is lower than 0.2 m/s, the direction of the human body relative to the airflow is the key factor determining the level of exposure to particulate matter.
(5) In sitting and standing manikins, particles tend to gather near the chest, and the particulate matter concentration is the highest in the breathing zone. The distribution of particulate matter in the vicinity of a lying person is typically uniform.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit author contribution statement

Jie Zong: investigation, data analysis, methodology, writing — original draft preparation; Jiying Liu: supervision, methodology, writing — review and editing; Zhengtao Ai: supervision, methodology, project administration, writing — review and editing; Moon Keun Kim: writing — review and editing.

Acknowledgements

This work was funded by the National Natural Science Foundation of China (No. 51908203) and the Support Plan for Outstanding Youth Innovation Team in Colleges and Universities of Shandong Province (2019KJG005) and Natural Science Foundation of Shandong Province (ZR2020ME211, ZR2021ME199). This work was also supported by the Plan of Introduction and Cultivation for Young Innovative Talents in Colleges and Universities of Shandong Province.

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