TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214 16/23 pp227-232
Volume 10, Number 2, April 2005

Prediction of Perceived Air Quality for Personalized Ventilation Systems[*]

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Abstract: The characteristics of the air jet from the outlet of a personalized ventilation system were related to the perceived air quality and ventilation rate. The perceived air quality was expressed as percentage of dissatisfied people for a system supplying isothermal fresh air. The relationship was verified using a thermal manikin with a breathing function in a climate chamber sitting by a desk equipped with a personalized ventilation system. A trace gas was introduced into the climate chamber and fully mixed. The personal exposure effectiveness (ε_p) is based on concentrations of trace gas in the chamber and in the manikin nose which is affected more by the distance between the movable outlet and the occupant's breathing zone than by the personalized air flowrate and does not change much for the personalized air flowrate higher than 10 L/s when the distance is fixed. Some predicted dissatisfied values for a personalized ventilation system compared with those acquired in human subject experiments have an absolute difference of less than 3%.

Key words: air quality; perceived air quality; personalized ventilation; personal exposure effectiveness

Introduction

Today many people spend more than 80% of their time in an artificial climate, i.e., offices, factories, public buildings, houses, transport vehicles, etc. Therefore, comfortable indoor environments must be created for the occupants.

Thermal comfort and air quality are the main factors affecting indoor environmental quality. Recent research has improved understanding of the impact of thermal environment on human comfort and performance. However, the impact of indoor air quality on human health, comfort, and performance has been less studied and understood.

According to American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) standards, room temperatures should range from 20℃ to 26℃ with relative humidities from 30% to 60%. To avoid drafts, mean air speeds should range from 0.2 m/s to 0.6 m/s, depending on the room temperature and turbulence intensity. These requirements are normally met using mixing and displacement ventilation. Mixing ventilation provides air into the space from a diffuser at a relatively high velocity, generally placed in or near the ceiling above the occupied zone. The aim is to mix the supplied air with the room air and to remove pollutants and heat through diffusers placed either near the ceiling or on the floor. Displacement ventilation works by providing cooled air at a temperature 2-3℃ below room temperature at a low velocity directly into the occupied zone at the floor. With displacement ventilation, the polluted room air is driven to the ceiling where it is removed through diffusers.

Studies have shown that poor indoor air quality may cause health problems for the occupants. Some people complain of symptoms associated with time spent in a certain building, which is usually referred to as sick

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Received: 2003-08-26

[*] Supported by the Danish Technical Research Council (STVF) and the National Natural Science Foundation of China (No. 50178037)

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building syndrome. The symptoms normally occur after a short time in the sick building and often increase during the stay in the building. Many of the symptoms disappear once the person leaves the building.

In a cross-sectional study of office workers (about 5000 people in 210 offices) in north Sweden[1], almost 40% of the men and 60% of the women reported at least one of the sick building symptoms per week. About 75% of these symptoms were associated with the indoor environment in the office, and 25% of those affected had been consulting a doctor regarding their symptoms.

Sick building symptoms have significant impact on occupant's productivity. Sick building symptoms such as headache and difficulty in concentrating obviously affect human performance directly. Wargocki et al.[2] reported significantly lower self-estimates of performance for those with more sick building symptoms in individual British office workers.

Fang et al.[3] found that air temperature and humidity (combined in the enthalpy) significantly impacted the perception of indoor air quality. Two studies were carried out with either face or whole body exposure. Both studies showed that decreased air temperature and humidity improved perceived air quality significantly.

However, neither the air temperature nor the humidity in a room can be reduced to very low levels. Or occupants will complain about their thermal comfort. One solution is to supply lower temperature and humidity air to the occupant's breathing zone while keeping the room temperature and humidity in the comfort zone.

Personalized ventilation systems supply low temperature and humidity fresh air to the occupant's breathing zone while minimizing mixing with the surrounding air. The system also allows each individual to control his own air flowrate, direction, and temperature. Thus, each occupant in the room can select his preferred thermal comfort and air quality.

Melikov et al.[4] proposed the personal exposure effectiveness (ε_{p}) to evaluate the performance of different air terminal devices in personalized ventilation systems. ε_{p} is defined as

$$\varepsilon_{\mathrm{p}} = \frac{C_{\mathrm{I,O}} - C_{\mathrm{I}}}{C_{\mathrm{I,O}} - C_{\mathrm{PV}}} \tag{1}$$

where $C_{\mathrm{I,O}}$ is the pollutant concentration in inhaled air without personalized ventilation, C_{I} is the pollutant concentration in the inhaled air, and C_{PV} is the pollutant concentration in the personalized air.

This index is equal to one when only personalized air is inhaled and is zero if no personalized air is inhaled. A carefully designed and properly maintained system should provide clean air with no pollutants, i.e., $C_{\mathrm{PV}} = 0$. Equation (1) can be simplified to

$$\varepsilon_{\mathrm{p}} = \frac{C_{\mathrm{I,O}} - C_{\mathrm{I}}}{C_{\mathrm{I,O}}} \tag{2}$$

Kaczmarczyk et al. [5] and Zeng et al.[6] showed that personalized ventilation systems significantly improved the perceived air quality of the occupants compared with a mixing ventilation system with the same amount of fresh air supply. Their experiments used a movable panel. Zeng et al.[6] reported that the personalized air temperature (T_{PV}) only affected the perceived air quality at the beginning of the experiments. After 30 min, T_{PV} had no effect on the perceived air quality. Similar results were obtained by Kaczmarczyk et al. [5]

Although these recent research results have revealed some important characteristics of personalized ventilation systems, there are still some important questions which need to be answered. Since a personalized ventilation system is more expensive than a mixing ventilation system, the extent of the perceived air quality should be predicted before a personalized ventilation system is considered to replace a mixing ventilation system.

1 Experiments

The objectives of the study were:

- To identify ε_{p} of a personalized ventilation system with isothermal fresh air at four flowrates (Q_{PV}): 5, 10, 15, and 20 L/s with the delivery point at 15, 30, and 45 cm;
- To develop a function to predict the perceived air quality as a percentage of dissatisfied people with an isothermal fresh air supply;
- To verify the predicted perceived air quality with those acquired in human subject experiments; and
- To identify the degree of improvement in terms of the occupant's satisfaction achieved by the personalized ventilation system in comparison with that of a mixing ventilation system.

The experiments were performed in a 5 m×6 m×2.5 m climate chamber with controlled air temperature and relative humidity inside the chamber. A breathing thermal manikin was put into the chamber to simulate a human being. This manikin was equipped with an artificial lung to simulate the human breathing function. A set of B&K gas analyzer (1302, 1303) was used for dosing trace gas (SF_6) to the air inside the chamber and measuring its concentration. A detailed description of the climate chamber and the breathing thermal manikin was given by Melikov et al.[4]

The manikin was seated in front of a desk where the personalized ventilation system was mounted. The air delivery system consisted of a movable arm and an air supply outlet. The movable arm was originally produced for local exhaust systems (Flexoduct Type JPB) with its design slightly changed to fulfil the size requirement. The arm had a metal frame made of joined parallel beams, which gave good flexibility. The metal frame was placed inside a flexible duct (Φ80 mm). The arm was 100 cm long and was mounted on the right back corner of the desk.

The air supply outlet was made of an aluminium sheet shaped as a pipe with a round opening (Φ80 mm) for the air inlet and a rectangular opening (240 mm×75 mm) for air outlet. A special aluminium restrictor was mounted inside to make the air distribution more uniform. The shape of the restrictor was determined experimentally.

The outlet was covered with a perforated plate with round Φ14 mm openings. A glass fibre net was placed behind the plate to further improve the uniformity of the velocity profile. The air supply outlet was mounted on the movable arm so that the distance between the outlet and the nose of the manikin and the air direction could be controlled.

The air handling unit used to provide the personalized air supply was separated from that which controlled the climate chamber so that the system could supply air which is different from the air inside the chamber. The temperature and air flowrate of the personalized air was controlled and measured.

The distance between the manikin's nose and the air outlet was set at 15, 30, and 45 cm. The angle between the personalized air velocity and the vertical was kept at 45°. The arrangement of the manikin and the outlet is shown in Fig. 1. Four personalized air flowrates (5, 10, 15, and 20 L/s) were tested at each distance. During each test, the temperatures of the air inside the chamber and the personalized air were kept at 23℃.

During the experiment, the B&K gas analyzer provided SF_6 to the air handling unit that supplied air to the chamber. At the same time, the analyzer sampled and measured the SF_6 concentration of the air inside the chamber, the personalized air, and the air inside the artificial lung of the manikin. These three SF6 concentrations were recorded until all of them became stable.

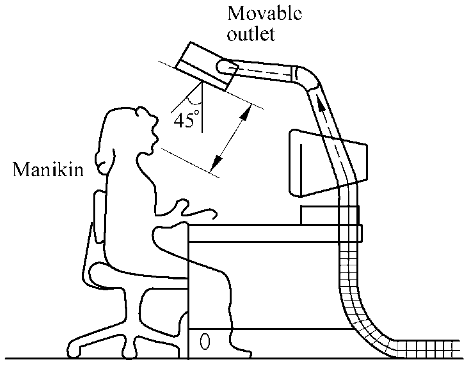

Fig. 1 Arrangement of ε_p measurement

SF_6 was introduced to simulate a pollutant. Without the personalized ventilation, the SF_6 concentration in the climate chamber was uniform and the SF_6 concentration in the inhaled air of the manikin was equal to that in the air supplied to and exhausted from the chamber. Therefore, in the present study, the definition of ε_p is modified as

$$\varepsilon_p = \frac{C_{S,SF_6} - C_{I,SF_6}}{C_{S,SF_6} - C_{PV,SF_6}} \tag{3}$$

where C_{S,SF_6} is the SF_6 concentration in the inhaled air without personalized ventilation, C_{I,SF_6} is the SF_6 concentration in the inhaled air with personalized ventilation, and C_{PV,SF_6} is the SF_6 concentration in the personalized air.

The test results are listed in Table 1.

Table 1 Personal exposure effectiveness (ε_p) for a personalized ventilation system supplying isothermal air at various air flowrates and distances (%)

Distance between manikin's nose and delivery outlet (cm)	Personalized air flowrate (L/s)			
	5	10	15	20
15	55.0	59.4	60.3	62.6
30	38.9	40.5	38.0	41.9
45	23.1	26.9	28.8	30.8

2 Discussion and Analysis

The results in Table 1 show that when the distance between the manikin's nose and the delivery outlet was fixed, the change of ε_p was less than 8% when the personalized air flowrate was increased from 5 L/s to 20 L/s. The change of ε_p was less than 4% when the personalized air flowrate increased from 10 L/s to 20 L/s. These results agree well with those of Melikov et al. [4] who used a movable outlet to show that increasing the personalized air flowrate above 10 L/s did not significantly increase ε_p.

Compared with the effect of the personalized air flowrate, the distance between the manikin's nose and the delivery outlet had more significant impact on ε_p. With each distance increase of 15 cm, ε_p decreased by more than 10%. This result can be explained by the jet flow from the nozzle. If the pollutant concentrations in the room air and in the personalized air are constant, the mean pollutant concentration (C_x) at a distance x from the outlet is determined by only the induction ratio Q_x/Q_0 at that distance. For a given outlet and a turbulent air jet, the induction ratio Q_x/Q_0 is determined by the distance from the outlet[7]. Therefore, for turbulent air jets, ε_p is only a function of the distance from the outlet which agrees with the trends in the ε_p measurements. For low air flowrate with the movable outlet, the air jet was not fully developed turbulent flow, so ε_p was not only affected by the distance from the outlet but also by the flow condition. When the air flowrate with the movable outlet was high, the air jet was fully developed turbulent flow, so ε_p was only a function of the distance from the outlet. Therefore, measured ε_p did not change when the air flowrate with the movable outlet was higher than an initial value and the distance was fixed.

With isothermal personalized air, only the pollutant concentration in the occupant's breathing zone will affect the perceived air quality. Since the personalized ventilation system provides fresh air without pollutants in the human subject experiments, Eq. (2) was simplified to

$$\frac{C_{\mathrm{I}}}{C_{\mathrm{I,O}}} = 1 - \varepsilon_{\mathrm{p}} \tag{4}$$

The analysis further assumed that the fresh air provided by the mixing ventilation system was fully mixed with the room air and the pollutant concentration inside the room was uniform at steady-state. Therefore, if only the mixing ventilation system was used in the room and the pollutant concentration in the inhaled air was C_{I}, the required fresh air flowrate Q_{MIX} (L/s) would be

$$Q_{\mathrm{MIX}} = \frac{E}{C_{\mathrm{I}}} \tag{5}$$

where E is the pollutant emission's rate in the room (g/s).

When the fresh air is provided by a personalized ventilation system and C_{I} is to be maintained only in the occupant's breathing zone, then the required fresh air flowrate Q_{PVS} (L/s) would be expressed as

$$Q_{\mathrm{PVS}} = \frac{E}{C_{\mathrm{I,O}}} \tag{6}$$

By combining Eqs. (4), (5), and (6), to keep the same pollutant concentration in occupant's breathing zone as would be required in the entire room with a mixing ventilation system, the ratio of the fresh air flowrates for the personalized ventilation system and the mixing ventilation system would be

$$\frac{Q_{\mathrm{PVS}}}{Q_{\mathrm{MIX}}} = \frac{C_{\mathrm{I}}}{C_{\mathrm{I,O}}} = 1 - \varepsilon_{\mathrm{P}} \tag{7}$$

Assuming that only the pollutant in the occupant's breathing zone will affect the perceived air quality when the personalized ventilation system provides isothermal fresh air, Eq. (7) shows that the fresh air flowrate from the mixing ventilation system will be $\frac{1}{1-\varepsilon_{\mathrm{P}}}$ times that of the personalized ventilation system for the same perceived air quality. This conclusion can be expressed as

$$P_{\mathrm{PVS}(Q)} = P_{\mathrm{MVS}\left(\frac{Q}{1-\varepsilon_{\mathrm{P}}}\right)} \tag{8}$$

where $P_{\mathrm{PVS}(Q)}$ is the percentage of dissatisfied people when the fresh air is supplied by a personalized ventilation system at the flowrate Q; $P_{\mathrm{MVS}\left(\frac{Q}{1-\varepsilon_{\mathrm{P}}}\right)}$ is the percentage of dissatisfied people when the fresh air is supplied by a mixing ventilation system at the flowrate $\frac{Q}{1-\varepsilon_{\mathrm{P}}}$.

It is well-known[7] that dissatisfaction caused by a standard person (one Olf) at different ventilation rates of a mixing ventilation system is:

for $q \geq$ 0.32 L/s per Olf, $P_{\mathrm{MVS}} = 100\%$;

for $q <$ 0.32 L/s per Olf,

$$P_{\mathrm{MVS}} = 395\exp(-1.83q^{0.25})\ \% \qquad (9)$$

where q is the ventilation-emission rate, L/s per Olf. Equation (9) can be revised as

$$\ln(100P_{\mathrm{MVS}}) - 5.98 = -1.83q^{0.25} \qquad (10)$$

The relationship between the dissatisfaction regarding the perceived air quality for the same amount of fresh air supplied by a mixing ventilation system and a personalized ventilation system in the same room can be found by combining Eqs. (8) and (10):

$$\frac{\ln(100P_{\mathrm{PVS}(Q)})-5.98}{\ln(100P_{\mathrm{MVS}(Q)})-5.98}=\frac{\ln\left(100P_{\mathrm{MVS}\left(\frac{Q}{1-\varepsilon_{\mathrm{p}}}\right)}\right)-5.98}{\ln(100P_{\mathrm{MVS}(Q)})-5.98}=\frac{-1.83\left(\frac{Q}{(1-\varepsilon_{\mathrm{P}})c}\right)^{0.25}}{-1.83\left(\frac{Q}{c}\right)^{0.25}} \qquad (11)$$

where c is the pollutant concentration expressed in Olf. Equation (11) can be simplified to

$$P_{\mathrm{PVS}(Q)} = \exp[(1-\varepsilon_{\mathrm{P}})^{-0.25} \bullet (\ln(100P_{\mathrm{MVS}(Q)}) - 5.98) + 5.98] \qquad (12)$$

The dissatisfaction due to a personalized ventilation system supplying isothermal fresh air can be calculated from Eq. (12). If $\varepsilon_{\mathrm{p}}=0$, $P_{\mathrm{PVS}(Q)} = P_{\mathrm{MVS}(Q)}$ which means that if no personalized air is inhaled, the dissatisfaction for the personalized ventilation will be the same as for a mixing ventilation system. Also, if $\varepsilon_{\mathrm{p}}=1$, $P_{\mathrm{PVS}(Q)}=0$, which means if all the inhaled air is personalized air, the dissatisfaction due to the personalized ventilation system will be zero.

This equation was verified by the results of human subject experiments by Kaczmarczyk et al.[8] and Zeng et al.[6] Kaczmarczyk[5] gave the percentage of dissatisfied people with the air quality at workstations after about 30 min exposure to different ventilation systems in the same room. During the experiments, the room air temperature was fixed at 23°C and the fresh air flowrate was fixed at 15 L/s. The result showed that 21.8% was dissatisfied with a mixing ventilation system. With a personalized ventilation system, 14.4% was dissatisfied. The average distance from the outlet to occupant's breathing zone was 30-40 cm and the personalized air flowrate ranged from 3 L/s to 15 L/s[8]. As shown in Table 1, ε_{p} should be 40.5% with a delivery outlet at a distance of 30 cm and with an air flowrate of 10 L/s. Inputting ε_{p} as 40.5% and P_{MVS} as 21.8% into Eq. (8), the predicted P_{PVS} is 14.6%, which agrees well with the P_{PVS} acquired in the human subject experiment with a difference as 0.2%. Table 2 compares human subject results[6] with predicted P_{PVS} when the room temperature was 23℃, the average distance from the outlet to the occupants was about 30 cm and when the room temperature was 26℃, the average distance was 18 cm. The results agree well with a maximum absolute difference between the predicted P_{PVS} and the human test results of 3%.

Table 2 Comparison of the predicted P_{PVS} from Eq. (12) and P_{PVS} from human tests

Personalized air flow rate (L/s)	Predicted P_{PVS} (%)		P_{PVS} (%)	
	T=23℃	T=26℃	T=23℃	T=26℃
5	7	12	6	12
10	6	9	4	7
15	5	12	4	11
20	7	11	4	9

T is the room air temperature.

3 Conclusions

The perceived air quality with personalized ventilation systems was evaluated using a breathing manikin and human tests. The results show that:

- With the movable outlet, the personal exposure effectiveness (ε_{p}) is affected more by the distance between the movable outlet and the occupant's breathing zone than by the personalized air flowrate.
- With the movable outlet, when the distance between the movable outlet and the occupant's breathing zone is fixed, the personal exposure effectiveness (ε_{p}) does not change much for the personalized air flowrate higher than 10 L/s.
- The perceived air quality expressed as a percentage of dissatisfied occupants for the personalized ventilation systems tested in these experiments was found to be a function of the dissatisfaction with a mixing ventilation system and the personal exposure

effectiveness, ε_p. The relationship agrees well with previous data.

Acknowledgements

This work is a part of a cooperative research program between the International Centre for Indoor Environment and Energy, Technical University of Denmark and the Department of Building Science of Tsinghua University. The authors thank Prof. P. O. Fanger, Prof. A. Melikov, Dr. J. Kaczmarczyk, and Dr. M. Mayer, Technical University of Denmark.

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