Performance of personalized ventilation in a room with an underfloor air distribution system: transport of contaminants between occupants

R. Cermak*, A.K. Melikov

International Centre for Indoor Environment and Energy, Technical University of Denmark, Denmark

ABSTRACT
Studies have documented that personalized ventilation, which provides clean air at each office workplace, is able to improve substantially the quality of air inhaled by occupants. However, the interaction between the airflow generated by personalized ventilation and the airflow pattern outside the workplaces has not been studied in detail. This paper presents a study on the performance of a personalized ventilation system installed in a full-scale test room with an underfloor air distribution system. Transport of human-produced airborne pollutants (in real life they can be infectious agents) between two occupants was examined using a tracer gas. Two breathing thermal manikins were used to simulate occupants. The results show that the tested combination of personalized and underfloor ventilation was not able to decrease the concentration of the human-produced airborne pollutants in air inhaled by the exposed manikin. The main conclusion is that the design of the personalized ventilation system and the interaction of personalized airflow and room airflow should be carefully considered in order to achieve minimal transport of pollution between occupants.

INDEX TERMS
Task/ambient conditioning; Ventilation; Contaminant distribution; Personal exposure

INTRODUCTION
Studies have documented that personalized ventilation (PV), which provides clean air at each office workplace, is able to improve substantially the quality of air inhaled by occupants (Faulkner *et al.*, 1999; Melikov *et al.*, 2002). Kaczmarczyk *et al.* (2002a) showed that clean outdoor air supplied from PV at temperatures several degrees below room air temperature is perceived as fresh and more acceptable than the same air supplied isothermally. As the cooling ability of small amounts of cold air supplied by PV is low (compared to the typical cooling requirements of non-residential buildings), an integration of PV with a supplementary conditioning system is necessary.

The results of medical research presented by Smith (1990) have shown that even sub-clinical respiratory virus infections of colds and influenza can have a negatively adverse effect on occupants' performance even during the incubation period of the illness and after the clinical symptoms have gone. Virulent agents can be dispersed from respiratory tract infections during coughing, sneezing or talking. Bjørn and Nielsen (1996) studied personal exposure to air exhaled by another person in a displacement-ventilated room.

The interaction between the airflow generated by PV, occupants (free convection flow around the body and respiration) and the airflow pattern outside the workplaces has not been studied in detail. The design of PV as well as the parameters of the supply airflow (volume, temperature, direction, etc.) may have an impact on the distribution of contaminants at workplaces and in a room. Faulkner *et al.* (1993) documented that task/ambient ventilation supplying air at high flow rates causes mixing of the indoor air. No data on performance of PV in regard to transport of contaminants between persons are available to our knowledge.

* Corresponding author. E-mail: cermak@mek.dtu.dk

PV can be easily installed in conjunction with a raised (access) floor system. At the same time, the raised floor can be used to provide additional conditioning for the space. Underfloor air distribution (UFAD) systems, which deliver supply air through floor diffusers, typically incorporate two distinct vertical zones—a mixing zone within the lower levels of the space and displacement-type flow in the upper zone (Loudermilk, 1999). If the mixing zone encompasses only a short vertical distance, the UFAD systems may employ a horizontal discharge strategy closely resembling displacement ventilation throughout the space.

In the present study, PV was installed in a full-scale test room with an underfloor air distribution system. The performance of the coupled systems in regard to transport of exhaled air (in real life it can contain infectious agents) between two occupants facing each other was examined for several schemes of occupants' adjustment of airflow rate from the PV units. See also related paper by Melikov *et al.* (2003).

METHOD

A typical office with two identical workplaces was simulated in a climate chamber ($4.7 \times 4.8 \times 2.6$ m^3). Figure 1 shows the experimental set-up of the office. The UFAD system supplied air through four swirl diffusers that were positioned beside the workplaces, not to affect directly the occupants nearby. An exhaust outlet was located in the ceiling in the centre of the room. There were six 42-W fluorescent light fixtures evenly distributed over the ceiling. The walls were made of thermally insulated chipboard. One of the walls was single glazed. The air temperature in the laboratory hall where the chamber was built was kept at 25°C during the experiments in order to reduce heat transfer through the walls. The chamber was carefully sealed prior to the experiments.

Each workplace was equipped with a PV system mounted on a desk, a personal computer and a desk lamp. The air terminal device (ATD) for PV was mounted on a movable arm-duct. This is one of the several first-generation PV systems developed at the International Centre for Indoor Environment and Energy. The design of the movable arm allows for positioning of the ATD at any selected location in front of a person. In the present study, the ATD was fixed at a single location (see Figure 1), which complied with the positioning most often preferred by people in previous experiments (Kaczmarczyk *et al.*, 2002b).

Two breathing thermal manikins, simulating occupants, were seated on office chairs facing each other. The distance between the manikins' nose/mouth was 1.65 m. The manikins consisted of 16 and 23 body segments. Their surface temperature was controlled to be equal to the skin temperature of an average person in thermal comfort. They were dressed in underwear, short-sleeved T-shirt, pants, socks and shoes, giving a total clothing insulation of 0.4 clo (ISO, 1994). The office chair provided an additional insulation of 0.15 clo. The manikins were equipped with artificial lungs that simulated the breathing function of an average person performing light physical work. The breathing cycle consisted of 2.5 s inhalation, 2.5 s exhalation and 1.0 s break. The pulmonary ventilation was 6 l/min. Both manikins exhaled through the nose and inhaled through the mouth. The breathing manikin is described in detail in Melikov *et al.* (2000).

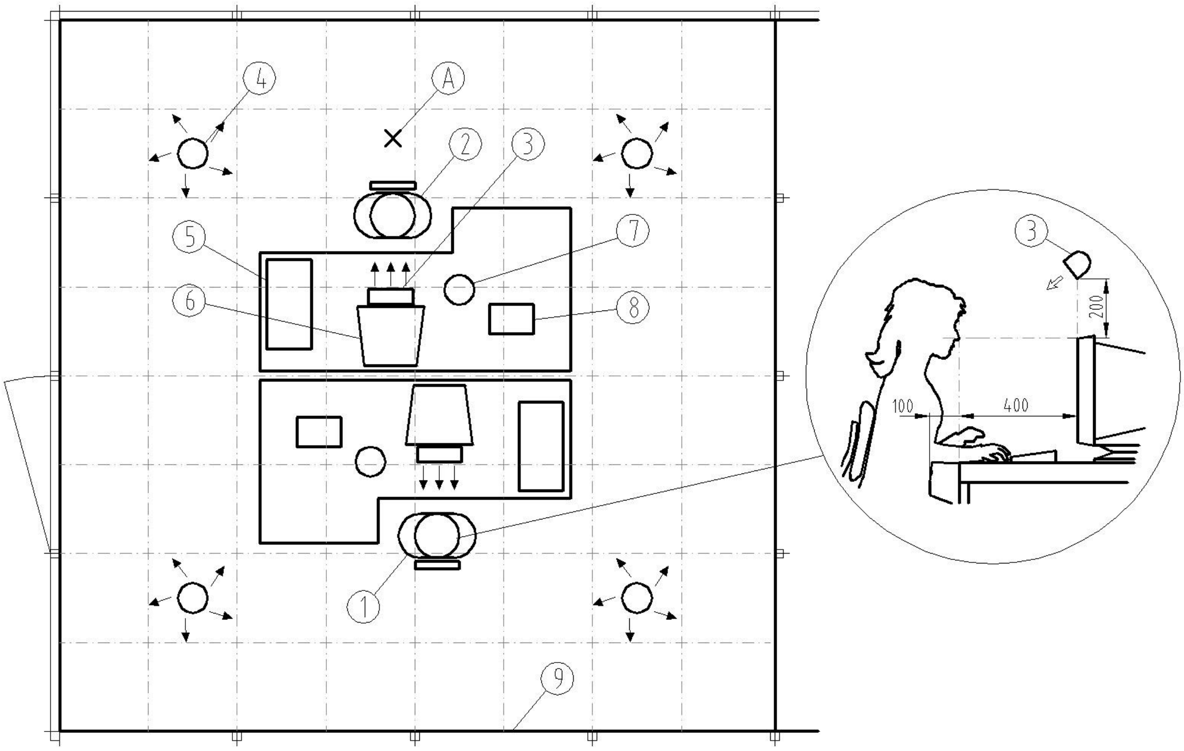

Figure 1 Experimental set-up of the office: (1) polluting breathing thermal manikin, (2) exposed breathing thermal manikin, (3) air terminal device for PV, (4) floor-based air diffuser, (5) computer tower below the desk—75 W, (6) 14 in. CRT computer screen on the desk—45 W, (7) desk lamp—0.5 m above the desk surface—25 W, (8) non-heated printer simulator, (9) glazed wall, (A) concentration measurement position.

A constant dose of sulphur hexafluoride (SF_6) was used to mark air exhaled by one of the manikins (referred to as the polluting manikin). The exhaled air was considered as a source of airborne infectious agents. The concentration of SF_6 in the exhaled air was 1500 ppm. The air was heated to 36°C in order to ensure density that is close to the density of air exhaled by people (1.144 kg/m^3). Relative humidity of the exhaled air was about 15%. The SF_6 concentration was measured in air inhaled by the other manikin (referred to as the exposed manikin). Furthermore, the concentration was measured at several heights behind the exposed manikin as shown in Figure 1. The location (marked as A) was selected as representative of the workplace. At least 20 measurements were taken at each point under steady-state conditions, then averaged and analysed. A gas monitor based on the photo-acoustic infrared detection method of measurement was used.

The performance of the PV system was tested at two airflow rates, namely 10 and 20 l/s, and compared with the performance of the UFAD system. The total amount of air supplied to the office with the PV plus the UFAD system was kept constant at 70 l/s. The supply air temperature of 20°C was identical for both systems. The thermal environment in the occupied zone of the room outside the workplaces was comfortable (ISO, 1994).

RESULTS AND DISCUSSION

The tracer-gas concentration in the supply air, the air inhaled by the exposed manikin and in the exhaust is shown in Table 1. Five studied conditions given by the combination of the supply airflow rates are listed in the table. The case when both PV units were switched off is considered as a reference.

Table 1 Concentration of pollutants (SF_6) in the supply air, the air inhaled by the exposed manikin and in the exhaust

	Supply airflow rate (l/s)			SF_6 concentration (ppm)		
Exp.	PV *Polluting manikin*	PV *Exposed manikin*	UFAD	Supply air	Inhaled air	Exhaust air
1	-	-	70	0,03	0,51	2,04
2	-	10	60	0,03	0,67	2,10
3	-	20	50	0,03	1,54	2,04
4	10	10	50	0,03	1,47	2,04
5	20	20	30	0,03	1,85	2,04

The results show that the tracer-gas concentration in the inhaled air increased when PV was applied. The concentration in the inhaled air was as much as 3.6 times higher when both the PV units operated at 20 l/s/person (Exp. 5) than in the reference case (Exp. 1). The concentrations decreased when the PV unit of the polluting manikin was switched off (Exps. 2 and 3), but they were still higher than in the reference case. The results indicate that the tested combination of personalized and underfloor ventilation systems increased the transport of exhaled air between the persons. If the exhaled air contained infectious agents such as viruses (attached to fine particles) or bacteria, the coupled system would increase the risk of infection for the occupants.

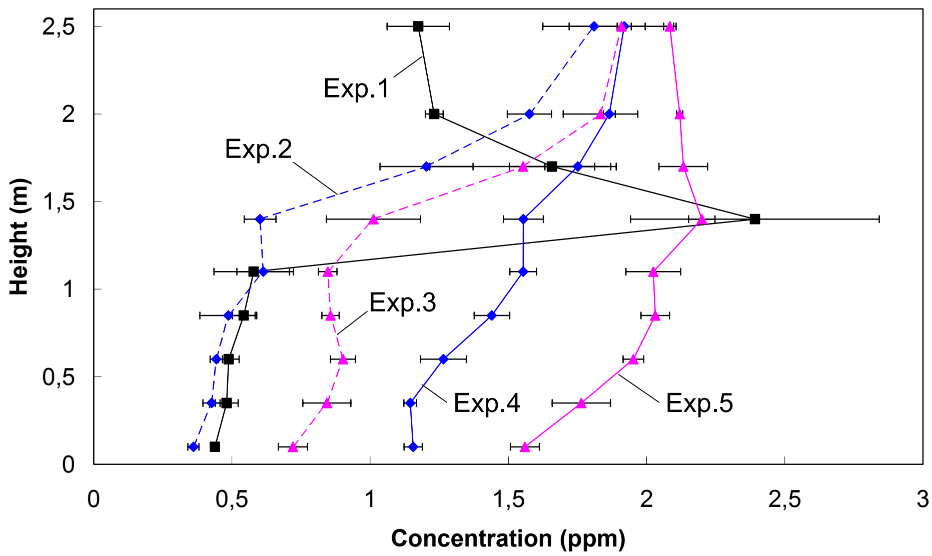

Figure 2 Tracer-gas concentration profiles measured 0.3 m behind the exposed manikin (position A, Figure 1) under the five conditions tested (see Table 1). Standard deviation based on repeated measurements is provided.

Tracer-gas concentration profiles were measured throughout the room and analysed in order to reveal the reason for the concentrations increasing when PV was employed. Figure 2 shows the profiles measured behind the non-polluting manikin at a distance of 0.3 m. The profile for the reference case (Exp.1) shows a clear concentration peak measured at a height of 1.4 m. Air temperature, measured additionally at several positions in the room (not presented here), showed vertical distribution typical for the UFAD systems, with a mixing zone near the floor and displacement (stratified) zone above it up to the ceiling (Loudermilk, 1999). Bjørn (2002) reported that in rooms with displacement ventilation, air exhaled through the mouth spreads in a horizontal layer due to the temperature stratification. The results in Figure 2 (Exp. 1) suggest that the exhaled air passed by the desks, being displaced upward by the thermal plumes of both the computer screens and the exposed manikin. The concentration measurements with exhalation through the nose (Figure 2) and exhalation through the mouth (not reported in this paper) did not show large differences. Nevertheless, the tracer-gas concentration in the inhaled air was very low in this case (0.51 ppm, Table 1). However, it is difficult to conclude with certainty, whether the breathing zone was simply submerged in the low concentration (mixing) zone or the free convection movement around the body moved the cleaner air upward.

The tracer-gas concentration profiles in Figure 2 show that the room airflow pattern changed completely when the PV was applied. Two distinct vertical zones with a mixing and displacement type of flow can be recognized in the profiles when only one of the PV units was used (Exps. 2 and 3). These profiles are similar to a profile that one would expect in a room with the UFAD system only. The two zones of the vertical distribution of the concentration in the flow gradually disappeared when the PV unit of the polluting manikin was switched on (Exps. 4 and 5). The tracer-gas concentration in the occupied zone increased substantially. Consequently, the concentration in the inhaled air increased as well (Table 1). In this respect, it is reasonable to believe that a complete mixing of indoor air would develop if the PV supplied air at higher rates. Furthermore, the location of the PV systems in a room and the extent of their use (flow rate and direction) will have an impact on the uniformity of the flow field in the occupied zone, e.g. velocity, temperature and concentration distribution. The comparison of the contaminant concentration in the inhaled air and in the room air clearly shows that the concentration in the inhaled air, and hence the inhaled air quality, depends directly on the level of contaminants in the room. The entrainment of room air into clean personalized airflow is the reason. It can be concluded that a PV system has to be extremely efficient in delivering clean air to the breathing zone of each occupant (i.e. little room air is entrained by the personalized airflow). Otherwise, any combination of the PV system and total-volume ventilation system that promotes mixing of the exhaled air from the occupants with the room air will increase the level of inhaled pollution generated by other occupants.

The present study showed that the tested combination of the systems did not perform well in regard to the transport of exhaled air between two persons. Nevertheless, there can be many more sources of pollution present constantly in rooms in practice, such as building materials, electronic equipment, etc. The transport of exhaled air in rooms is of concern only when it contains infectious agents, while exposure to pollution from other sources is always important for occupants' health (SBS symptoms) and productivity. Our previous research has shown that PV was able to improve the inhaled air quality when the concentration of contaminants in a room was uniform and constant (Melikov *et al.*, 2002). Such contaminant concentration can be found in rooms with an ideal mixing airflow pattern. In practice, where the distribution of contaminants may not be uniform, the level of improvement of inhaled air quality would most probably depend on the type and location of the pollution source, the design and operation of PV, etc., as well as the airflow pattern in the room.

CONCLUSIONS

The main conclusion of this study is that the interaction of personalized airflow and room airflow should be carefully considered. While decreasing the inhaled concentration of pollution generated by different pollution sources in a room, the PV system may affect the transport of pollution between occupants, e.g. it may increase the exposure to air exhaled by other occupants. Several factors such as the type and location of pollution sources, the design and operation of PV, arrangement of offices, etc., should be considered in future studies.

ACKNOWLEDGEMENT

This research was supported by the Danish Technical Research Council (STVF).

REFERENCES

Bjørn, E. and Nielsen, P.V. (1996). Exposure due to interacting airflow between two persons. *Proceeding of* the *5th International Conference on Air Distribution in Rooms—Roomvent '96,* Yokohama, Vol. 1, pp. 107–114.

Bjørn, E. (2002). Dispersal of exhaled air in stratified surroundings—CFD studies. *Proceedings of the 8th International Conference on Air Distribution in Rooms—Roomvent ´02*, Copenhagen, pp. 285–288.

Faulkner, D., Fisk, P.E. and Sullivan, D.P. (1993). Indoor airflow and pollutant removal in a room with desktop ventilation. *ASHRAE Transactions* **99** (2), 750–758.

Faulkner, D., Fisk, W.J., Sullivan, D.P. *et al.* (1999). Ventilation efficiencies of desk-mounted task/ambient conditioning systems. *Indoor Air* **9**, 273–281.

ISO (1994). ISO 7730:1994(E), Moderate thermal environments—Determination of the PMV and PPD indices and specification of conditions for thermal comfort. Switzerland: International Organization for Standardization.

Kaczmarczyk, J., Zeng, Q., Melikov, A.K. *et al.* (2002a). The effect of a personalized ventilation system on perceived air quality and SBS symptoms. *Proc. of the 9th International Conference on Indoor Air Quality and Climate—Indoor Air '02,* Monterey, Vol. IV, pp. 1042–1047.

Kaczmarczyk, J., Zeng, Q., Melikov, A.K. *et al.* (2002b). Individual control and people's preferences in an experiment with a personalized ventilation system. *Proc. of the 8th International Conference on Air Distribution in Rooms—Roomvent ´02*, Copenhagen, pp. 57–60.

Loudermilk, K. (1999). Underfloor air distribution solutions for open office applications. *ASHRAE Transactions* **105** (1), 605–613.

Melikov, A.K., Cermak, R., Kovar, O. and Forejt, L. (2003). Impact of airflow interaction on inhaled air quality and transport of contaminants in rooms with personalized and total volume ventilation. *Proceedings of Healthy Buildings 2003*, Singapore.

Melikov, A.K., Cermak, R. and Majer, M. (2002). Personalized ventilation: evaluation of different air terminal devices. *Energy and Buildings* **34**, 829–836.

Melikov, A.K., Kaczmarczyk, J. and Cygan, L. (2000). Indoor air quality assessment by a breathing thermal manikin. *Proceedings of the 7th International Conference on Air Distribution in Rooms—Roomvent '00*, Reading, Vol. 1, pp. 101–106.

Smith, A.P. (1990). Respiratory virus infections and performance. *Philosophical Transactions of the Royal Society of London B* **327**, 519–528.