Impact of airflow interaction on inhaled air quality and transport of contaminants in rooms with personalized and total volume ventilation

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ABSTRACT
The impact of airflow interaction on inhaled air quality and transport of contaminants between occupants was studied in regard to pollution from floor covering, human bioeffluents and exhaled air, with combinations of two personalized ventilation systems (PV) with mixing and displacement ventilation. In total, 80 l/s of clean air supplied at 20°C was distributed between the ventilation systems at different combinations of personalized airflow rate. Two breathing thermal manikins were used to simulate occupants in a full-scale test room. Regardless of the airflow interaction, the inhaled air quality with personalized and mixing ventilation was higher or at least similar compared to mixing ventilation alone. In the case of PV combined with displacement ventilation, the interaction caused mixing of the room air, an increase in the transport of bioeffluents and exhaled air between occupants and, at low flow rates of personalized air a decrease in the quality of the inhaled air compared to displacement ventilation alone. The PV system supplying air against the face improved the ventilation efficiency in regard to the floor pollution up to 20 times and up to 13 times in regard to bioeffluents and exhaled air, compared to mixing or displacement ventilation alone.

INDEX TERMS
Task/ambient conditioning; Individual control; Personal exposure; Air quality; Air movement

INTRODUCTION
The environment in buildings to which occupants are exposed has an effect on their health, comfort and productivity. Large individual differences exist between occupants in rooms in regard to their activity and preferred air temperature and velocity; differences in regard to perceived air quality exist as well (Summer, 1971). Providing occupants with individual control of their microenvironment has been significantly associated with a lower prevalence of health and indoor climate complaints (Jaakola *et al.*, 1989) and improved self-reported work efficiency (Raw *et al.*, 1990).

Total volume ventilation, aiming for a uniform environment within the occupied zone, does not account for individual differences between occupants and provides only limited control of their microenvironment. Clean air supplied far from the occupants is more or less polluted by the time it is inhaled. The PV, aiming to provide clean air, unmixed with the polluted room air, direct to each occupant allows for individual control of temperature, flow rate and direction of the personalized air. It decreases the pollutant concentration and temperature of the inhaled air (Melikov *et al.*, 2002; Bolashikov *et al.*, 2003). Kaczmarczyk *et al.* (2002) reported a significant decrease of SBS symptoms and an improvement of perceived air quality and self-reported performance of people using PV.

Building materials, office machines as well as occupants with their bioeffluents and exhaled air are some of the pollution sources in rooms. Occupants, in order to avoid draught discomfort, may use PV at small flow rates and at a temperature only a few degrees cooler than the room air temperature. Therefore, total volume ventilation in combination with PV has

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to be applied in rooms with a high heat and/or pollution load. The quality of air inhaled by each occupant and the transport of airborne infectious agents between occupants and pollution within the occupied zone depend on the interaction of personalized airflow with the free convection flow around the occupant's body, the airflow generated by a total volume system and the transient flow of exhalation. Movement of occupants, thermal plumes from heated office equipment, downdraught from cold windows, flows generated by fans built into office equipment, etc. may also have an impact on the interaction.

This paper presents a study on the impact of different airflow interaction patterns generated by combinations of two PV combined with mixing and displacement ventilation on inhaled air quality and transport of contaminants between occupants (see also related paper by Cermak and Melikov, 2003). The performance of the systems is studied in regard to three different pollution sources: floor covering, human bioeffluents and exhaled air.

METHOD

An office room ($4.8 \times 5.4 \times 2.6$ m^3) with two identical workstations with PV systems (WS1-PV1, WS2-PV2) was simulated in a large hall (Figure 1). Each WS consisted of a desk with personalized air terminal devices, a breathing thermal manikin simulating an occupant (75 W), a desk lamp (55 W), a personal computer with a monitor (143 W) and an upholstered office chair. Six fluorescent light fixtures were evenly distributed over the ceiling (36 W in total). The office area, 12.7 m^2 per occupant, was close to the area of 14.3 m^2 recommended in the standards and guidelines (CEN 1752, 1998). The manikins, positioned to ensure similar exposure to the total volume ventilation, were used to assess quality of the air inhaled by occupants (Melikov *et al.*, 2000). The manikins were dressed in summer clothing (0.44 clo), which together with the chair insulation gave a total insulation of 0.59 clo (ISO 7730, 1994).

Air exhaled from a person (potential source of infectious agents), human bioeffluents and floor covering (carpet, linoleum, etc.) were simulated as office pollution sources. One of the manikins was 'polluting' and the other manikin was 'exposed' (Figure 1). The exposed manikin (WS2-PV2) was located behind the polluting manikin (WS1-PV1), i.e. facing its back, in order to simulate the highest transport of polluted air from one person to another when PV1 was in operation. The manikins exhaled through the nose and inhaled through the mouth at 6 l/min (2.5 s inhalation, 2.5 s exhalation and 1.0 s break). The exhaled air of the polluting manikin was traced with a constant dose of 0.135 ml/s sulfur hexafluoride (SF_6). The temperature of air exhaled by the manikins was adjusted to ensure density close to the density of air exhaled by people (1.144 kg/m^3): 36°C for the polluting manikin (clean air + SF_6) and 34.4°C (clean air) for the exposed manikin. Relative humidity of the exhaled air was 15%. Human bioeffluents were simulated by a constant dose (0.113 ml/s) of dinitrogen oxide (N_2O), released under the clothing of the polluting manikin at the armpits and the pelvic region. The temperature of N_2O was similar to the surface temperature of the manikin. Carbon dioxide (CO_2), simulating pollution from floor covering, was released from 64 points distributed uniformly over the entire floor (19.9 ml/s). Tests ensured that the density of CO_2 did not affect the concentration measurements. The concentrations of CO_2, SF_6 and N_2O were measured in the supply and exhaust air and the air inhaled by the manikins under steady-state conditions by a gas monitor based on photo-acoustic infrared detection method.

Two PV systems with different air terminal devices, namely round movable panel (RMP) and vertical desk grill (VDG) were employed in various combinations with mixing and displacement ventilation. The RMP, with a circular outlet and a diameter of 190 mm, has recently been developed and is a highly efficient air terminal device that can be positioned at any selected location in front of a person (Bolashikov *et al.*, 2003). The VDG has an opening (20×220 mm) located at the front desk edge and is equipped with two blades allowing for directing of the personalized airflow. It is mounted on a plenum box attached underneath the desktop. The positioning of RMP and VDG (Figure 1) was identified as most often preferred by people. A round swirl diffuser placed in the centre of the ceiling, ensuring uniform air supply to all sides, was used for the mixing ventilation. A semicircular air distribution unit (radius of planar projection 250 mm and height of 1000 mm) placed on the floor at one of the long walls of the office was used for the displacement ventilation. The air from the office was extracted uniformly through four circular ceiling diffusers.

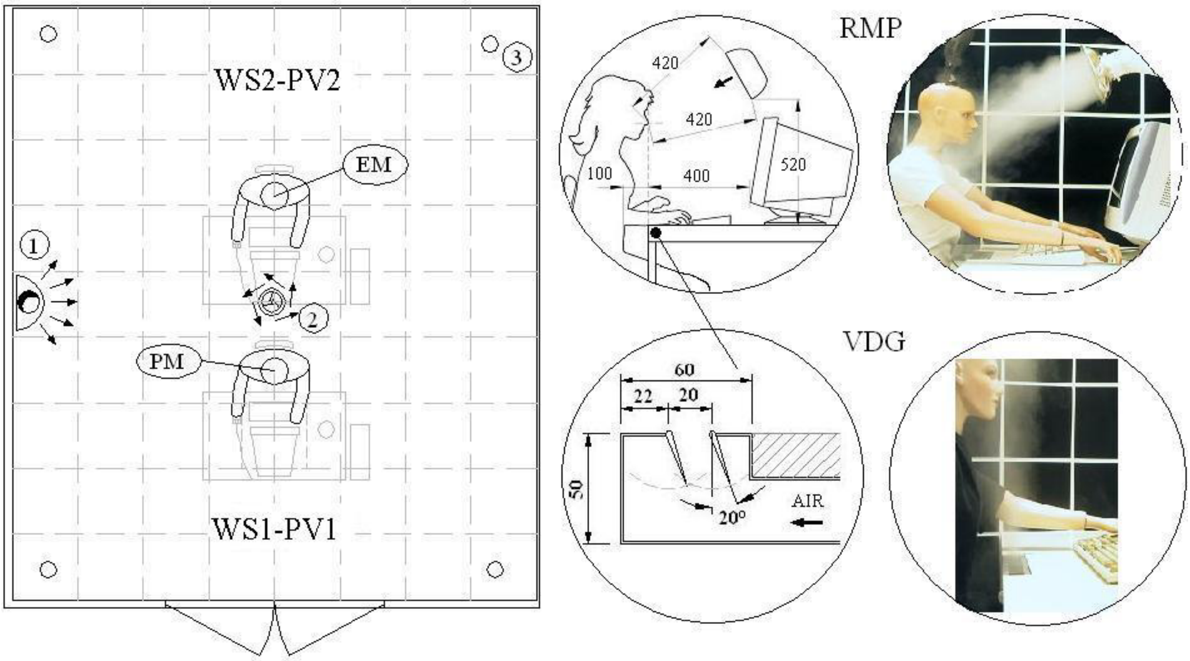

Figure 1 Set-up of the office: PM, polluting manikin; EM, exposed manikin; 1, 2 and 3, air terminal devices, respectively, for displacement and mixing ventilation and for exhaust.

Four combinations were studied: round movable panel with mixing ventilation (RMP + MV) and with displacement ventilation (RMP + DV) and vertical desk grill with mixing ventilation (VDG + MV) and with displacement ventilation (VDG + DV). Clean air at 20°C with a flow rate of 80 l/s was supplied to the room through either the total volume ventilation system alone or from both the PV and the total volume ventilation. Six combinations of flow rate through the two PV were tested: 0 and 15 l/s from PV1 (polluting manikin) and 0, 7 and 15 l/s from PV2 (exposed manikin). The supply air kept an average room air temperature of 26°C. This is the maximum operative temperature recommended in standards (ISO 7730, 1994) and the summer design criteria for Category B recommended in the European guidelines CR 1752 (1998). The air temperature in the hall was kept at 25°C in order to reduce heat transfer through the walls.

Ventilation effectiveness, VE, was used to evaluate and compare the performance of the combined systems. It is given in CR 1752 (1998):

$$\mathrm{VE} = \frac{c_\mathrm{R} - c_\mathrm{S}}{c_\mathrm{P} - c_\mathrm{S}} \qquad (1)$$

where c_R, c_S, c_P are, respectively, the tracer gas concentration in the exhaust (return) air, the supply air and the air inhaled by a manikin. VE = 1 means complete mixing of the supply and room air; when VE > 1 the inhaled air quality is better than in the exhaust and vice versa for VE < 1. The higher is the VE, the more efficient the air distribution system.

RESULTS AND DISCUSSION

Figure 2 presents the VE in the air inhaled by the exposed manikin with mixing and displacement ventilation, and with and without personalized ventilation applied. The results for both the RMP and the VDG are shown in the figure when PV1 and PV2 each provided 15 l/s (the remaining 50 l/s was supplied through the total volume ventilation).

With mixing ventilation alone, the airflow with high velocity supplied at the ceiling level generated relatively high turbulence in the occupied zone, thus promoting intensive mixing. Therefore, VE of 1–1.1 in regard to the three pollution cases was obtained for the exposed manikin. With displacement ventilation alone, the flow in contact with the floor assisted the free convection flow around the exposed manikin to transport floor pollution upward to the breathing zone (VE = 1.1) and to protect the manikin from bioeffluents (VE = 6) and exhaled air of the polluting manikin (VE = 6.8). However the free convection flow around the polluting manikin transported its own bioeffluents and exhaled air upward to its breathing zone (VE ≈ 0.2–0.3, not shown in the figure). The VE of the polluting manikin in regard to the floor pollution was the same as for the exposed manikin.

The PV combined with total volume ventilation always improved the inhaled air quality in regard to the floor pollution. The flow rate up to 15 l/s supplied locally by one of the two PV had a rather small impact on the air distribution in the vicinity of the neighbouring manikin, the free convection flow around its body and the inhaled air quality. However, the personalized airflow supplied at 15 l/s in front of the polluting manikin mixed its bioeffluents and exhaled air with the room air. The pollution was then transported to the breathing zone of the exposed manikin by the free convection flow around its body (some differences in regard to the transport of the bioeffluents and exhaled air were identified but they will not be discussed in this paper). Velocity as high as 0.18 m/s has been measured in the free convection flow around the human body at the height of the breathing zone (Cermak *et al.*, 2002). In order to improve the inhaled air quality of the exposed manikin the personalized air: (1) has to be strong enough to penetrate the free convection flow, and (2) has to be clean, and not mixed with the surrounding polluted room air. These requirements are influenced by the direction of the personalized flow.

The RMP, having a circular cross-section and a uniform initial velocity profile with low turbulence intensity, generated a jet transverse to the free convection flow. It had a long initial region with a core of clean, unmixed air, which reached the manikin's face (Bolashikov *et al.*, 2003). The centre line velocity at the target area (the face) of 0.48 m/s at 15 l/s was high enough to penetrate the free convection flow and to provide clean air in inhalation. Therefore, high values for the VE, in regard to the bioeffluents and the exhaled air, respectively, 13.1 and 11.6 in the case of RMP + MV and 33.3 and 26.4 in the case of RMP + DV were obtained. Although large, the difference in VE obtained for the RMP + MV and for the RMP + DV was caused by only a small difference in the amount of inhaled pollution. Still, the higher VE achieved for the RMP with displacement as opposed to mixing ventilation was due to the interaction between the personalized air of the polluting manikin and the polluted free convection flow around its body and the displacement flow in the room. The interaction caused a lower concentration of bioeffluents and exhaled air at the location of the exposed manikin in comparison with the case of mixing ventilation and therefore its personalized air was less polluted (this interaction will be discussed in a separate paper). At a lower flow rate of 7 l/s the airflow from the RMP had a target velocity of 0.2 m/s and was not strong enough to destroy completely the free convection flow at the breathing zone (which existed with both mixing and displacement ventilation). Therefore, relatively low VE, between 1.5 and 1.8, in regard to the three pollution sources was obtained with both mixing and displacement ventilation. The VE was still higher compared to the VE of 1.1 obtained with only mixing ventilation but significantly lower than the VE between 6 and 6.8 obtained with displacement ventilation in regard to the bioeffluents and the exhaled air.

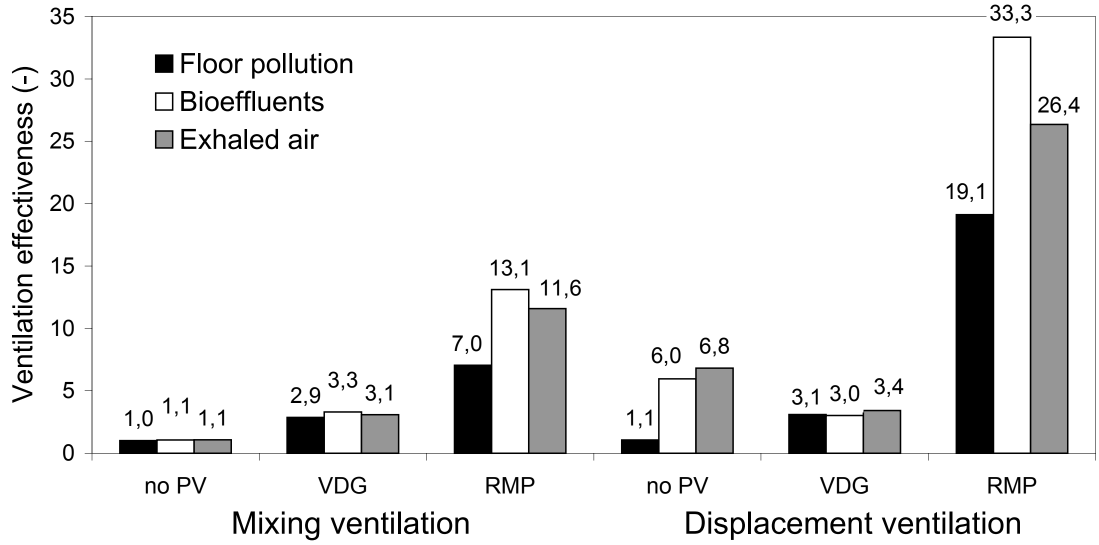

Figure 2 Ventilation effectiveness in the air inhaled by the exposed manikin obtained for the combinations studied. The personalized airflow rate for each, the polluting manikin (PV1) and the exposed manikin (PV2), was 15 l/s.

Due to its rectangular cross-section, the VDG generated a flow with a short core region (proportional to the length of the small side) having the target area (manikin's face) located in the fully developed region of the jet. The personalized air was thus considerably mixed with the surrounding air of the room and the assisting free convection flow. Therefore, when combined with mixing and displacement ventilation, the VDG performed in the same way providing VE of 2.9–3.4 at 15 l/s (Figure 2). The VE measured at 7 l/s was only a little lower—between 2.3 and 2.9 (in regard to the three pollution cases), but higher than with the RMP at 7 l/s (VE = 1.5–1.8). At 7 l/s the VDG generated a flow with a high velocity of approximately 1.1 m/s at the target area (VDG had a smaller cross-section than the RMP), which penetrated the free convection flow. Due to the mixing caused by the personalized flow of the polluting manikin, the VE obtained with the exposed manikin in regard to bioeffluents and exhaled air for the VDG combined with displacement ventilation was again lower than in the case of displacement ventilation alone. The lowest VE for the exposed manikin (VE = 1, floor pollution; VE = 1–1.3, bioeffluents; VE = 1.1–2.1, exhaled air) was obtained when its PV was switched off (under these conditions similar values were also obtained for the RMP combined with displacement ventilation). Only when the PV of the polluting manikin was switched off (no mixing) was the VE of the exposed manikin with PV comparable to the VE of 6–7 obtained with only displacement ventilation. Further research is needed in order to identify whether this will always be the case in rooms in practice where occupants move frequently. Bjørn *et al.* (1997) showed that in rooms with displacement ventilation, walking occupants cause mixing and may increase occupants' exposure to pollutants.

CONCLUDING REMARKS

An important conclusion of this study is that the airflow interaction as well as the location of the pollution source should be carefully considered in order to achieve optimal performance of PV. In rooms with mixing ventilation the use of PV will always protect the occupants from pollution and will increase the quality of the inhaled air. When applied with displacement ventilation, the PV can also improve substantially the inhaled air quality when the pollution source is not located in the vicinity of the personalized flow, e.g. floor pollution. It may however, promote mixing of pollution with room air when the personalized airflow is directed against a pollution source, thus decreasing the quality of the inhaled air. In real life this may lead to the increase of airborne transmission of infectious agents between occupants and decrease the performance of PV in comparison to displacement ventilation alone. This, however, remains to be studied. The present study identified that the flow generated by the RMP at a rate of 15 l/s was more efficient than the VDG.

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