New air terminal devices with high efficiency for personalized ventilation application

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ABSTRACT
Two air terminal devices (ATD) for personalized ventilation (PV) were developed: Round Movable Panel (RMP) and Headset-Incorporated Supply (Headset). The performance of the ATDs was tested at three combinations of room air temperature and supply personalized air temperature: 23/23°C, 23/20°C and 26/20°C, respectively, and at different flow rates of personalized air, ranging from 5 to 15 l/s for RMP and from 0.18 to 0.5 l/s for Headset. A breathing thermal manikin was used to evaluate the inhaled air quality achieved with the developed ATDs as well as the performance in regard to thermal comfort. The results revealed that inhaled air consisting of 100% personalized air was achieved with the RMP and up to 80% with the Headset. The change in room temperature that would have affected whole-body heat loss equivalently ranged from less than 0.5–2.2 K for RMP and almost 0 K for the Headset.

INDEX TERMS
Air quality; Thermal comfort; Individual control; Diffuser; Ventilation

INTRODUCTION
Total-volume ventilation and air-conditioning of rooms is the method most frequently used today in practice to provide a comfortable indoor environment. Mixing and displacement ventilation principles are mainly applied. However, the clean air is supplied too far from the occupant and by the time it reaches his/her breathing zone it is already mixed with the room air, resulting in substantial rates of dissatisfaction (Naidenov *et al.*, 2002). An important disadvantage of the total volume ventilation is that it does not account for the large individual differences that exist between occupants as regards perceived air quality and preferred thermal environment (occupants are exposed to almost uniform environment). Moreover, they may have very limited control over the environment, which in most cases is not sufficient to account for individual preferences.

The PV system, providing 100% clean outdoor air at the breathing zone of each occupant and allowing the occupant to tailor and control his/her adjacent environment, is the perfect solution. Research has shown that PV has the potential to improve occupants' thermal comfort (Arens *et al.*, 1991; Tzuzuki *et al.*, 1999) and to provide inhaled air of higher quality compared to total volume ventilation (Faulkner *et al.*, 1999; Melikov *et al.*, 2002; Zuo *et al.*, 2002). Faulkner *et al.* (1999) reported an improved air quality in the breathing zone with PV compared to mixing ventilation. In their work, Melikov *et al.* (2002) achieved up to 60% of personalized air in the air inhaled with a PV air terminal device named vertical desk grill. Zuo *et al.* (2002) tested the concept of supplying the fresh air in close proximity (5–10 cm) to the face, at flow rates as low as 0.1–2.0 l/s, but even at this short distance the maximum measured fraction of fresh air in inhaled air was 61%.

Nevertheless, with the existing PV systems, though giving promising results and much better performance than any of the conventional ventilation systems, the aim of 100% fresh air

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in the air inhaled was not achieved. Thus the main goal of PV was still not satisfied. Clearly there was a need to develop more efficient air terminal devices that could generate personalized airflow that mixes less with the polluted room air on its way to the occupant.

METHODS

Two new air terminal devices were designed and tested (Figure 1). These were named Round Movable Panel (RMP) and Headset-Incorporated Supply (Headset).

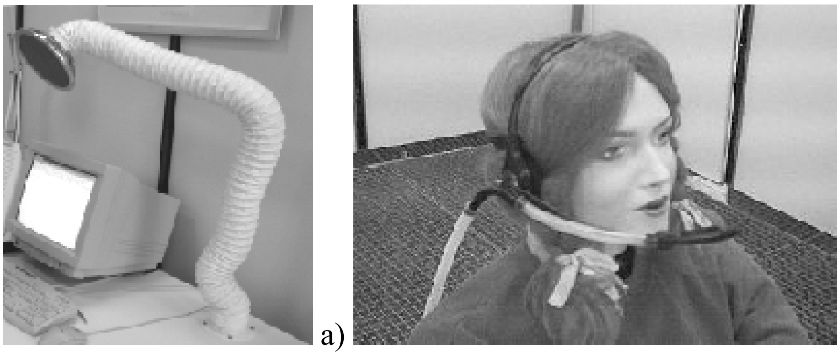
a) b)

Figure 1 (a) The RMP mounted on the movable arm and (b) the Headset.

The RMP was made in a circular shape with a 268 cm^2 discharge area. At the supply opening, a honeycomb plate was used to reduce the turbulence and straighten the air jet and thus improve the ATD's performance. The RMP was connected to an arm mechanism (described by Kaczmarczyk *et al.*, 2002) that allowed for free positioning of the outlet relative to the occupant. In the present experiments, the RMP was always positioned towards the breathing zone, so as to achieve the best air quality performance, i.e. the highest amount of personalized air in the air inhaled. The Headset was made by incorporating a small rectangular nozzle into a commercially available set of headphones, by replacing the microphone piece. Several designs were tested. The Headset had to be light and should not disturb the user. A rectangular shape with dimensions 35 × 8 mm was chosen for the nozzle, so as to cover better the mouth/the nose of the occupant, in order to achieve high performance without blocking the view of the user. A silicon pipe was used to transport the personalized air to the Headset.

An office workplace consisting of a desk with the ATD mounted was simulated in a climate chamber ($5 \times 6 \times 2.5$ m^3). Ventilation air was supplied through the entire floor and exhausted through the ceiling. The velocity generated by the total volume ventilation system of the chamber was lower than 0.06 m/s. A breathing thermal manikin was used to simulate a human performing light sedentary work (Melikov *et al.*, 2000). The surface temperature of the 23 body segments was controlled to equal the skin temperature of an average person in thermal comfort. An artificial lung was used to simulate the breathing cycle: 2.5 s inhalation, 2.5 s exhalation and 1 s break, and a flow rate of 6 l/min. In most of the experiments the manikin inhaled through the nose and exhaled from the mouth, except for the Headset, where the reverse combination was also studied.

Two ambient temperatures were tested in the climate chamber, namely, 23 and 26°C (the room air temperature was equal to the mean radiant temperature). The personalized air was provided at two temperatures, 20 and 23°C, thus comprising one isothermal (23/23°C) and two non-isothermal cases (23/20 and 26/20°C). The flow rates ranged from 5 to 15 l/s for RMP and from 0.18 to 0.5 l/s for the Headset. The impact of the distance between the occupant and the tested ATDs was also studied: for RMP this was in the range 20–50 cm and at 10 l/s supply rate, while for the Headset it was 2 and 6 cm away from nose/mouth. During all the conditions tested the manikin was dressed at a total clothing insulation of 0.66 clo.

Personal exposure effectiveness (ε_p) expressed as the percentage of personalized air in the air inhaled was used to measure the air quality performance of the devices developed (Melikov *et al.*, 2002). A constant amount of the tracer gas, sulphur hexafluoride (SF_6), was mixed with the air in the chamber; the tracer gas was added to the air supplied to the chamber. The concentration of the gas was measured at three points using a multi-gas monitor, and a multi-gas doser and sampler: in the chamber ($C_{I,0}$), in the air supplied by the personalized ventilation system (C_{pv}) and in the air inhaled by the manikin: sampled from the lungs (C_I). The ε_p was calculated as:

$$\varepsilon_p = \frac{C_{I,0} - C_I}{C_{I,0} - C_{PV}} 100\% \qquad (1)$$

The inhaled air temperature was measured by a fast thermo-bead sensor (time constant of 0.18 s) mounted in the nose or mouth of the manikin. Only the temperature recorded during the inhalation period (2.5 s) was used to evaluate the air quality performance of the tested outlets. Heat loss from the whole body as well as from the sections of the manikin were measured and converted to equivalent homogeneous temperature (EHT) as described by Tsuzuki *et al.* (1999). The velocity field and the turbulence intensity of the airflow from the ATDs were measured using an omni-directional low velocity thermal anemometer with high sensitivity. When steady-state conditions were reached the inhaled air temperature was measured for 3 min, the heat loss from the segments of the manikin for 5 min and the SF_6 concentration was sampled ten times (in order to obtain an average value).

RESULTS AND DISCUSSION

The basic requirement for developing the new outlet was that its user should inhale directly from the potential core region of the personalized air jet. Therefore, a jet with a wider and longer core of clean air with constant velocity and temperature was aimed at. The theory of free jets defines that with the same cross-section of the outlet, a circular jet has a longer core in comparison with a jet from a rectangular outlet cross-section, as used in the previous design (Kaczmarczyk *et al.*, 2002). An important advantage of having the target area of the jet in the core region is the high velocity, which makes it possible for the personalized air to penetrate the free convection flow around the human body. At the height of the head the free convection flow is turbulent, with a thick boundary layer having maximum velocities of 0.18 m/s (Cermak *et al.*, 2002).

Round Movable Panel (RMP)

The RMP had a round opening with a diameter of 0.185 m. The mean discharge velocity for the tested flow rate ranging from 0 to 15 l/s, varied from 0 to 0.56 m/s, which corresponded to Re from 0 to 6790. The measurements along the centre line of the personalized air jet showed that at a distance of up to 0.4 m from the outlet the mean velocity was still above 90% of its initial value and the turbulence intensity did not exceed 10%. Therefore, it can be estimated that the core region length is about 0.4 m. The long core region with low turbulence, led to high air quality performance of this ATD. Under all the conditions tested the personal exposure effectiveness (ε_p) for the RMP increased with increasing supply air flow rate, starting from less than 15% at 5 l/s up to 100% at 15 l/s (Figure 2). Under the non-isothermal conditions, at 5 l/s the ε_p is around 10% and at 10 l/s it is approximately 95%. In the isothermal case (23/23°C) the ε_p also reaches about 100%, but at flow rates below 12 l/s.

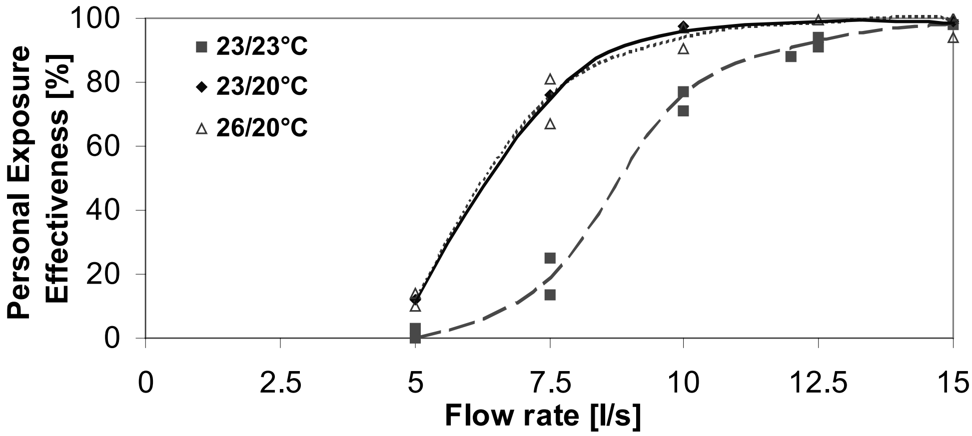

Figure 2 Personal exposure effectiveness (ε_p) as a function of the supply flow rate. RMP; conditions 23/23°C, 23/20°C and 26/20°C; distance 40 cm.

At 5 l/s and 40 cm from the outlet, the calculated air velocity was less than 0.15 m/s, so the strength of the invading personalized airflow was not sufficient to penetrate the free convection flow; thus almost no personalized air was inhaled by the manikin. At 7.5 l/s, the non-isothermal flow (26/20°C and 23/20°C) with increased momentum (mean velocity of 0.32 m/s at target area), enhanced additionally due to downward acceleration caused by buoyancy forces, was able to penetrate the free convection flow at the face and increase the ε_p. An increase in ε_p was not observed under the isothermal condition (23/23°C), because the velocity enhancement effect of the buoyancy forces was not present and the flow was not strong enough to penetrate and destroy the free convection flow at the manikin's head.

The air in the core of the supplied jet was not only free from the room pollution, but it also retained its supply temperature. Therefore, under non-isothermal conditions, the RMP also reduced the inhaled air temperature to a greater extent (up to 6 K at 26/20°C) compared to any of the existing designs (Melikov *et al.*, 2002), while at 23/23°C it had almost no influence (less than 1 K).

The air quality performance of the RMP (ε_p and inhaled air temperature) depends on the distance between the outlet and the manikin's face. For the interval 20–50 cm at 26/20°C and 10 l/s, ε_p decreased from 100 to 75%, and the difference in the inhaled air temperature from the reference condition (without PV), decreased from 6.5 to 5 K. For the isothermal case (23/23°C) the ε_p decreased from 90 to 31% (at 0.40 m ε_p was as high as 77%); the inhaled air temperature was influenced only slightly, by 0.6 K.

A high performance of the RMP in regard to thermal comfort was also identified. Under conditions 26/20°C the ATD reduced the whole-body equivalent temperature of the thermal manikin by a maximum of 2.2 K at the highest flow rate tested, namely 15 l/s. At 23/23°C the cooling of the whole body was almost negligible: the corresponding reduction in the equivalent temperature was less than 0.5 K. But for all conditions the head was the part with the lowest measured equivalent temperature: at 26/20°C and 15 l/s it dropped 10 K below its value at a room temperature of 26°C and no PV. This is explained with the positioning of the outlet, which was always aimed to yield the highest possible air quality performance. Thus substantial thermal asymmetry between head and feet was induced. But the cooling of the face may not be disadvantageous, especially at relatively high room air temperatures, above 24°C, since research has identified that the head is an efficient dissipater of heat generated from the body (Melikov *et al.*, 1994).

The results suggest that RMP could be a good solution in buildings with poor air quality and elevated heat loads, providing a high quality microenvironment for each occupant. A possible problem at high flow rates may be the excessive cooling of the face.

Headset

The smaller the distance between mouth/nose and the outlet, the less is the supply air mixed with the polluted room air, and the smaller the supply volume of personalized air needed. The second outlet, named Headset, was developed to comply with these considerations. Its rectangular shape and its small size made it rather difficult to obtain a uniform initial velocity field of the supplied air. The core region, with a length proportional to the small side of the outlet, ended very close to the outlet. The 90% value of the initial velocity was observed at a distance of only about 0.02 m, but the turbulence intensity of the airflow was rather low throughout the measured range (below 10% up to 0.06 m). The results of the experiments, shown in Figure 3, identified that the ε_p obtained for the headset did not depend on the breathing mode. However the ε_p increased with an increase of the flow rate (at 2 cm) and a decrease of the distance; thus ε_p of 84% was achieved at 0.5 l/s and a distance of 0.02 m (v_{max} = 2.17 m/s). Similar to the RMP, the ε_p was the result of the interaction of the personalized flow with the free convection flow at the face.

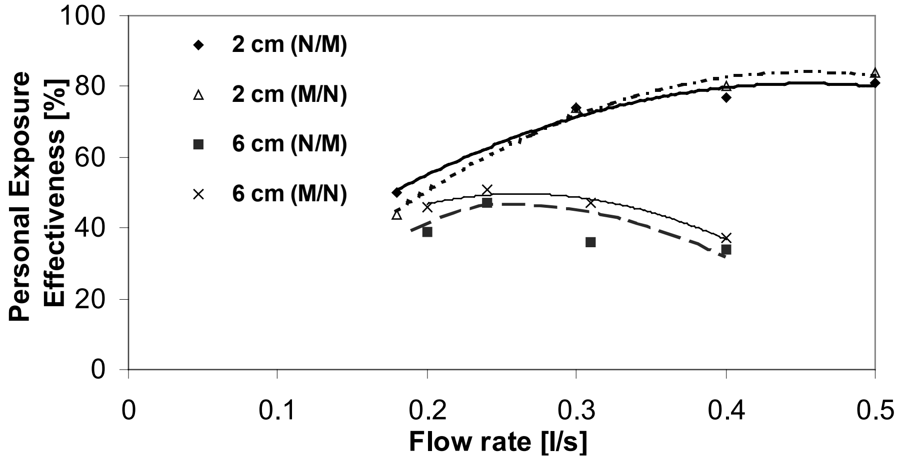

Figure 3 ε_p for Headset as a function of flow rate. Distance from face (2 cm/6 cm) is a parameter. Isothermal conditions 23/23°C; exhalation from mouth/inhalation through nose (M/N) and exhalation from nose/inhalation through mouth (N/M) is compared.

The distance of 6 cm (v_{max} = 1.28 m/s at 0.5 l/s) was longer than the length of the potential core of the flow from the nozzle. Thus the target area was in the fully developed region of the jet where intensive mixing of the personalized and the surrounding air occurred. Therefore relatively low values of ε_p were measured. This made the performance of the Headset quite sensitive to the distance between the nozzle and nose/mouth. The temperature of the air inhaled was reduced by less than 0.5 K because the jet was supplied isothermally (23/23°C), due to heat gains along the silicon tubing connected to the nozzle.

As expected, the thermal performance of the Headset was limited to the facial region of the manikin (the reduction in the equivalent temperature for the face was 2.7 K) and had no effect on the heat loss from the whole body. However, the high velocities measured (v_{max} > 1.2 m/s) could generate certain complaints from the occupants because the pressure of the air supplied, distinct from its cooling effect, can be sensed by humans at velocities higher than 0.5 m/s, while above 1 m/s the resultant sensation may be annoying (McIntyre, 1980).

These results reveal that the Headset has rather limited application in warm environments. At high flow rates people may be disturbed due to its very local impact on the face. This, however, may not be a problem when the Headset is applied at moderate room air temperatures, provided its users have control over the supply velocity by regulating the flow rate.

CONCLUSIONS

Two ATDs for personal ventilation with high performance were developed and tested. With RMP, 100% fresh air in the air inhaled was achieved for flow rates below 15 l/s. The temperature of inhaled air was reduced by the RMP to a maximum value of 6 K compared to the case with no PV present. A maximum cooling of the body corresponding to a decrease in the whole-body equivalent temperature of 2.2 K was achieved at 15 l/s with the RMP. With the Headset the maximum amount of personalized air in the air inhaled changed from 50% (at 6 cm distance from nose/mouth to nozzle) to 84% (2 cm distance) and was achieved at flow rates below 0.5 l/s. The isothermal airflow from the Headset did not affect the whole-body EHT and therefore it will not be able to improve occupants' thermal sensation at high room temperatures.

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