MEASUREMENTS AND PREDICTION OF INHALED AIR QUALITY WITH PERSONALIZED VENTILATION

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ABSTRACT
This paper examines the performance of five different air terminal devices for personalized ventilation in relation to the quality of air inhaled by a breathing thermal manikin in a climate chamber. The personalized air was supplied either isothermally or non-isothermally (6°C cooler than the room air) at flow rates ranging from less that 5 L/s up to 23 L/s. The air quality assessment was based on temperature measurements of the inhaled air and on the portion of the personalized air inhaled. The percentage of dissatisfied with the air quality was predicted. The results suggest that regardless of the temperature combinations, personalized ventilation may decrease significantly the number of occupants dissatisfied with the air quality. Under non-isothermal conditions the percentage of dissatisfied may decrease up to 4 times.

INDEX TERMS
Personalized ventilation, Perceived air quality, Inhaled air temperature, Improved IAQ practices and technologies, Offices

INTRODUCTION
Previous research has shown that air temperature, air humidity and the level of air pollution influence the perception of air quality. Fang et al. (1998a, 1998b) confirmed earlier studies and found that the odour intensity of air did not change significantly with temperature and humidity; however, air is perceived less acceptable with increasing temperature and humidity. This impact decreases with an increasing level of air pollution. A linear correlation was found between acceptability and enthalpy of the air in the case of facial exposure as well as of longer 20-min whole-body exposure.

The concept of personalized ventilation suggests supplying clean air directly and gently into a person’s breathing zone. It is assumed that occupants’ satisfaction and productivity can be increased as a result of improved air quality and preferred thermal environment. Therefore, the system aims to ensure both a high quality of the inhaled air and individual thermal control for the occupants.

In order to improve the quality of the inhaled air, clean personalized air should reach the breathing zone unmixed with the polluted room air. The velocity should be low in order to avoid draught. Because of the positive influence of low air temperature on the perception of air quality, it would seem to be advantageous to supply cool air. In this case, however, the jet of personalized air may not reach directly the occupant’s breathing zone due to buoyancy forces, which are proportional to the temperature difference between the personalized and room air. Furthermore, an interaction of the personalized airflow with the free convection

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flow around a human body and the flow of respiration may have a significant impact on both the portion of the personalized air inhaled and the temperature of the inhaled air. The direction of the air supply in relation to the occupant, determined by the air terminal device, is an important parameter as well.

A study on the performance of five different supply air terminal devices in regard to temperature of the inhaled air and the portion of the personalized air inhaled was designed and performed. The results of the experiments were further used to assess the quality of the inhaled air as perceived by occupants.

**METHODS**

Five different air terminal devices (ATDs) were developed and studied. They are schematically shown in Figure 1. The movable panel (MP) is made up of a grill mounted on a movable arm. The arm allows the direction of the personalized airflow in relation to the occupant to be changed within a wide range. However, the direction of the airflow remained unchanged in the present experiments pointing the breathing zone of the occupant from front and above. A grill attached to a computer screen forms the computer monitor panel (CMP). The vertical desk grill (VDG) and the horizontal desk grill (HDG) were mounted at the edge of a desk, providing respectively a vertical and a horizontal flow of personalized air direct to the breathing zone or against the occupant’s body. The last air terminal device, the personal environments® module (PEM) consists of two nozzles mounted at the two back corners of the desk. This device, described in detail in Tsuzuki et al. (1999), is available on the market, and was provided for testing by the manufacturer.

![Figure 1. Air terminal devices studied: MP (Movable Panel), CMP (Computer Monitor Panel), VDG (Vertical Desk Grill), HDG (Horizontal Desk Grill), PEM (Personal Environments® Module).](image)

A typical office workplace consisting of a desk with mounted air terminal devices was simulated in a climate chamber (5x6x2.5 m\(^3\)). Ventilation air (partly recirculated) was supplied through the entire floor and exhausted at the ceiling. The air velocity generated by the ventilation system of the chamber was lower than 0.06 m/s. The chamber is described in detail in Kjerulf-Jensen et al. (1975).
A clothed breathing thermal manikin consisting of 16 body segments was used to simulate a human being. The surface temperature of the body segments was controlled to be equal to the skin temperature of an average person in thermal comfort. The manikin was equipped with an artificial lung that simulates the breathing function of an average sedentary person performing light physical work. The breathing cycles consisted of inhalation (2.5 s), exhalation (2.5 s) and break (1.0 s); the breathing frequency was 10 times per minute. The volume of the exhaled/inhaled air was 6 L/min. The air was exhaled from the nose with a temperature of 34°C and a relative humidity of 95%. The manikin inhaled through the mouth. The manikin is described in detail in Melikov et al. (2000).

Summer and winter conditions, with operative temperatures of 26°C and 20°C respectively, were simulated in the climate chamber (the room air temperature was equal to the mean radiant temperature). Experiments at a constant temperature of personalized air, 20°C, were performed at airflow rates ranging from less than 5 L/s up to 23 L/s. During summer conditions, the manikin was dressed at a total clothing insulation of 0.4 clo (ISO 7730, 1994). During winter conditions the clothing garment provided a total thermal insulation of 1.0 clo. In both cases, the manikin was seated on the office chair providing an additional thermal insulation of 0.15 clo.

The personal exposure effectiveness, $\varepsilon_P$, expressed as the percentage of personalized air in inhaled air, was used to assess the performance of the air terminal devices tested (Melikov et al., 2001). The index is equal to one when 100% of personalized air is inhaled and it is equal to zero when no personalized air is inhaled. It is defined as:

$$\varepsilon_P = \frac{c_{I,0} - c_I}{c_{I,0} - c_{PV}}$$  \hspace{1cm} \text{(1)}$$

where $c_{I,0}$ is the pollutant concentration in the inhaled air without personalized ventilation, $c_I$ is the pollutant concentration in the inhaled air, and $c_{PV}$ is the pollutant concentration in personalized air.

The tracer gas, sulphur hexafluoride (SF$_6$), was used to simulate air pollution in the present study. A constant dose of the tracer gas was used to mark the air in the chamber continuously, while the personalized air was kept free of the tracer gas. Complete mixing of the tracer gas with the air supplied to the chamber was achieved as the tracer gas was dosed to the air far before it entered the room. The concentration of the gas was measured in the air supplied to the climate chamber, in the air supplied by the personalized ventilation system and in the air inhaled by the breathing thermal manikin. Without personalized ventilation, the SF$_6$ concentration in the inhaled air is equal to the SF$_6$ concentration in the air supplied to the chamber. Therefore, the pollutant concentration in the inhaled air without personalized ventilation ($c_{I,0}$; Equation 1) was substituted by the tracer gas concentration in the air supplied to the chamber. All the measurements were taken under steady-state conditions during the last 30 minutes of each experiment, then averaged and analysed. A gas monitor based on the photo-acoustic infrared detection method of measurement was used.

The inhaled air temperature was measured by a fast thermistor mounted inside the mouth cavity of the manikin. During the experiments the inhalation took 2.5 seconds of a 6 seconds breathing cycle; only the temperature measured during the inhalation period was averaged and used. Relative humidity of the inhaled air was not examined in the experiments.
RESULTS AND DISCUSSION

Table 1 shows the personal exposure effectiveness and inhaled air temperature under both winter isothermal and summer non-isothermal conditions. Percentage of occupants dissatisfied with the air quality as defined later in this paper is listed in the table as well. The parameters as a function of two different flow rates of personalized air are shown in the table. Except for HDG and VDG, the first of the two flow rates corresponds to the minimum amount of outdoor air typically required by the ventilation standards and guidelines (ASHRAE Standard 62, 1989; CEN Report CR 1752, 1998) per building occupant today (~10 L/s). Because of the superior performance of HDG and VDG, the performance of these ATDs is shown for a lower flow rate (5 L/s). The second flow rates compared in the table correspond to the minimum flow rate of personalized air needed to achieve maximum personal exposure effectiveness (Melikov et al., 2001). This flow rate is 10 L/s for VDG and HDG, 15 L/s for PEM and 20 L/s for CMP and MP.

Table 1. Personal exposure effectiveness ($\varepsilon_P$), inhaled air temperature ($t_{\text{inhal.}}$) and percentage of occupants dissatisfied with the air quality (PD) of the air terminal devices studied.

<table>
<thead>
<tr>
<th>Air terminal device</th>
<th>Flow rate of pers. air (L/s)</th>
<th>Winter conditions</th>
<th>Summer conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Room air 20°C, 30% RH</td>
<td>Personalized air 20°C, 30% RH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\varepsilon_P$ (-)</td>
<td>$t_{\text{inhal.}}$ (°C)</td>
</tr>
<tr>
<td>HDG</td>
<td>5</td>
<td>0,35</td>
<td>21,3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0,38</td>
<td>21,0</td>
</tr>
<tr>
<td>VDG</td>
<td>5</td>
<td>0,31</td>
<td>21,3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0,48</td>
<td>21,0</td>
</tr>
<tr>
<td>PEM</td>
<td>10</td>
<td>0,31</td>
<td>20,6</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0,34</td>
<td>20,4</td>
</tr>
<tr>
<td>CMP</td>
<td>10</td>
<td>0,05</td>
<td>21,6</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0,7</td>
<td>20,7</td>
</tr>
<tr>
<td>MP</td>
<td>10</td>
<td>0,41</td>
<td>21,3</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0,58</td>
<td>21,1</td>
</tr>
<tr>
<td>Without PV</td>
<td>0</td>
<td>0</td>
<td>21,6</td>
</tr>
</tbody>
</table>

The results show that both the portion of the room air inhaled and the temperature of the inhaled air generally decreased with an increase in the flow rate from the air terminal devices under both isothermal and non-isothermal conditions. Only HDG under summer conditions performed slightly better at the lower flow rate (5 L/s).

The results of the personal exposure effectiveness show that none of the ATDs was able to provide 100% of personalized air in the occupant’s inhalation. A considerable difference in the personal exposure effectiveness was observed for CMP under both summer and winter conditions. Smoke visualization indicated that under non-isothermal summer conditions a low-velocity airflow from CMP dropped on the desk, and the personalized air mixed with the room air. The performance of the other outlets was almost independent of the experimental conditions. Development of the personal exposure effectiveness with the flow rate for the tested air supply devices is reported in Melikov et al. (2001).
In a calm environment, the free convection flow around a human body transports the room air upward to the breathing zone, where it is inhaled. Therefore, the temperature of the inhaled air is higher than the ambient air temperature, as shown in Table 1 (case ‘Without PV’). The results show that the temperature of the inhaled air decreases when personalized ventilation is applied, even with the isothermal air supply. However, under isothermal conditions, the inhaled air temperature is only slightly lower than the inhaled temperature without personalized ventilation, and nearly the same for all the air terminal devices studied. The inhaled air temperature can be decreased substantially by increasing the temperature difference between the personalized air and the room air (summer conditions). Under summer conditions, the ATD with the greatest ability to decrease the inhaled air temperature was VDG. The decrease of inhaled air temperature of MP and PEM is also high, whereas HDG and CMP decrease the inhaled air temperature only slightly. The lowest inhaled air temperature of 23°C (with VDG) was achieved when the temperature difference between the room and personalized air was 6°C. Increasing the temperature difference, the inhaled air temperature may further be decreased; however, this may decrease the amount of personalized air in the inhaled air, due to a buoyancy effect, and may also cause unwanted cooling of the occupant’s body.

The results of the present investigation were used to further assess the performance of the ATDs studied as regards the air quality perceived by the occupant. Fang et al. (1998a) developed a model to predict the acceptability of the inhaled air. According to this model, the air temperature, air humidity and level of air pollution influence the perception of air quality (AQ). A high accuracy of the model can be expected when applied for personalized ventilation, because the model was established for a facial exposure to the air released from diffusers, i.e. similar to the exposure to personalized air. Acceptability of the air, \( Acc \), was correlated to enthalpy of air and expressed as:

\[
Acc = Acc_0 - 0.0247 \cdot (E - 45.39) - 0.0416 \cdot Acc_0 \cdot (E - 45.39)
\]  

(2)

where \( Acc_0 \) is the acceptability of air at 23°C and relative humidity of 50%, and \( E \) is enthalpy of the air in kJ/kg.

The percentage of persons dissatisfied with the air quality, \( PD \), was calculated using a logit curve fitted to the relation obtained by Gunnarsen and Fanger (1992).

\[
PD = \frac{\exp(-0.18 - 5.28 \cdot Acc)}{1 + \exp(-0.18 - 5.28 \cdot Acc)} \cdot 100
\]  

(3)

The results are shown in Table 1. It is assumed that clean personalized air (\( Acc_0 = 0.197 \)) is supplied at a temperature of 20°C and a relative humidity of 30%. The room air of 20 and 26°C is polluted by a carpet (\( Acc_0 = -0.019 \)). Relative humidity is 30% in both cases. Acceptability of the air inhaled with the personalized ventilation (i.e. mixture of the clean air and the polluted air) was considered to be proportional to the portion of the personalized air in the inhaled air. Enthalpy of the air comprised the inhaled air temperature and humidity.

Under winter conditions, there is about 16% of occupants dissatisfied with AQ in a calm environment without personalized ventilation. The percentage of dissatisfied decreased almost twice, to 7-9%, when personalized ventilation was applied (except with CMP terminal). In summer, the benefit from personalized ventilation may be even higher. With VDG, for example, the percentage of dissatisfied with AQ decreases four times in comparison to the
case without PV (from 44% to about 11% at 10 L/s). The results suggest that for most of the air terminal devices (except CMP) the percentage of occupants dissatisfied with the air quality will be reduced up to 70% in comparison to the case without personalized ventilation.

CONCLUSIONS
The major findings of this study are:

- Both the portion of the room air inhaled and the temperature of the inhaled air generally decreased with an increase in the airflow rate from the air terminal devices under both isothermal and non-isothermal conditions.
- The results suggest that regardless of the temperature combinations, personalized ventilation may decrease significantly the number of occupants dissatisfied with the air quality in comparison to a calm environment without personalized ventilation. Under non-isothermal conditions the percentage of dissatisfied may decrease up to 4 times.
- The air terminal device providing the air from the edge of a desk vertically towards the occupant’s face, referred as VDG, is the device with the greatest potential for satisfying the highest number of occupants as regards perceived air quality.

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REFERENCES


