Potential IAQ and energy benefits achievable with personalized air supply

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ABSTRACT

In this paper, the very recent laboratory research results on personalized air supply (PAS) from three universities are critically reviewed. Based upon these experimental results, the potential improvements on inhaled air quality versus indoor air quality are analysed in terms of reduced air pollutant levels in the inhaled air. Depending on the configuration of the PAS tested, up to 80% reduction of pollutant levels in the inhaled air can be achieved at the same total ventilation rate of the present mixed ventilation methods. The energy saving benefit is viewed from another perspective, and it can be derived from these experimental studies that equivalent inhaled air quality can be achieved at the airflow rate of merely 30% of the present international standard. Although these two figures are still far below from the ideal, they clearly indicate that significant breakthrough in inhaled air quality and energy saving can be achieved with PAS studied so far. Further improvement of PAS will also be discussed.

INDEX TERMS

Ventilation rate; Personal exposure; Personal control; Ventilation system; Ventilation effectiveness

INTRODUCTION

High air quality in a space can be achieved by decreasing the pollution sources, by increasing the ventilation rate or by cleaning the air. In many ventilated rooms, the outdoor air supplied is of the magnitude of 10 l/s person, which is the current standards and guidelines such as the ASHRAE standard 62 (ASHRAE, 1999) and the recent CR 1752 (CEN, 1998). Of this air, only 0.1 l/s person, or 1%, is inhaled. The rest, i.e. 99% of the supplied air, is not used. And the 1% of the ventilation air being inhaled by human occupants is not very clean. It is polluted in the space by bioeffluents, emissions from building materials and sometimes even by environmental tobacco smoke before it is inhaled. What really counts is the quality of the air that the occupants breathe. Recently, a new air supply method named 'personalized air' was proposed (Fanger, 2000), which is to supply air of high quality directly to the breathing zone of each individual. Personalized air supplied to the breathing zone of each individual is a promising concept, allowing a quality of the air for breathing that is optimal for human perception and productivity.

Inspired by Prof Fanger's ideology, developmental research were carried out vigorously in three universities in Europe(Technical University of Denmark, TUD), America (Lawrence Berkeley National Lab, Berkeley, UBNL) and Asia (The Hong Kong Polytechnic University, HKPolyU) to test a variety of air supply methods, and to find the practical designs (Melikov *et al.*, 2001; Cermak *et al.*, 2002a,b; Faulkner *et al.*, 2002; Zuo *et al.*, 2002; Zuo, 2003). Encouraging performances are already achieved, and different system designs are already available. In this paper, we give a critical review of these developments, with the aim to reveal the most likely application potentials and energy and IAQ benefits, and to identify further research needs.

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TESTING METHODS AND RESULTS

Testing Methods

The test methods and major results are summarized in Table 1. All the experimental studies were carried out using heated thermal manikins The manikin consists of 16 body segments that could be heated and individually controlled in order to maintain a surface temperature equal to the skin temperature of an average person in thermal comfort at a given actual activity level (Melikov *et al.*, 2000). In both TUD and HKPolyU's studies, a respiration machine was included to simulate the respiration of a human lung, and it was actually the inhaled air quality that was directly measured. The air transporting system, which consists of two pumps and two valves, controls the frequency of breathing including duration of exhaled, e.g. the simulated pulmonary ventilation. In TUD's test, both temperature and humidity control were imposed onto the exhaled air to more closely simulate the actual exhaled flow from a lung. In HKPolyU's test, the inhaled and exhaled flows are isothermal. In LBNL's study, no respiration was included; but the age of air in the breathing zone was measured.

Table 1 Summary of developmental works on PAS done by the three research groups

Research groups	Positions of ATD	Supply air rate	Outlet velocity	Testing methods	Performance indices used[a]	Achievable
TUD (Melikov *et al.*, 2001)	Five positions at desktop	Up to 25 l/s	Not reported[b]	Respiration; Thermal manikin	Personal exposure effectiveness ε_p	Maximum ε_p: 0.75 at flow rate of 20 l/s
LBNL (Faulkner *et al.*, 2002)	Nozzle at desk front edge	3.5–6.5 l/s	0.30–0.56 m/s	Thermal manikin	ACE (air change effectiveness) based on ages of air at the breathing zone	ACE: 1.4–2.7
HKPolyU (Zuo *et al.*, 2002)	Microphone position	0.1–3 l/s	0.01–1.10 m/s	Respiration; Thermal manikin	Pollutant exposure reduction efficiency η_{PER}; Fresh air utilization efficiency η_u	Maximum η_{PER}: 0.80 at the flow rate of 3 l/s

[a]It can be approved that ε_p and η_{PER} are numerically equal to each other, and also equal to the fraction of unmixed fresh air in the inhaled air.
[b]Air velocity distribution around the breathing zone were measured and reported using the PIV technique (Cermak *et al.*, 2002a,b).

Personalized Air Systems (PAS)

In both TUD and LBNL, the PAS tested can be classified as desktop systems, where the air supply nozzles are integrated with the working desks. In TUD (Melikov *et al.*, 2001), five different positions of the air supply nozzles were tested, with air supply flow rate ranging from 5 to 20 l/s. Three supply air temperatures are tested, with supply/room air temperature combinations of 20/20°C, 20/26°C and 23/26°C. In LBNL's study (Faulkner *et al.*, 2002), the air supply nozzle is positioned at the front edge of the desk, and tested as one component of the task ventilation system. Air jets can be positioned horizontally towards the office worker or tilted up more towards the breathing zone to an angle of 45°, or downward from the horizontal with an angle of –15°. The supply airflow rates tested are 3.5, 4.8 and 6.5 l/s, respectively, and the supply air temperature is 17°C, about 5–6°C less than the ambient room temperature.

In HK PolyU, microphone-like air supply nozzles are tested (Zuo *et al.*, 2002; Zuo, 2003).

The supplied nozzle is located at the chin position (Figure 1). This position is conceived with three considerations: (a) this is probably the closest position possible without causing much inconvenience to an office worker; (b) the mixing between the exhaled air and the PAS supply jet may be minimal, taking into account the buoyancy effects to the exhaled jet; (c) the nozzle can be integrated with the seat (Niu, 2002), and flexibly adjusted by the user, and movable as the office worker makes slight movement. The supplied airflow rates were tested at seven different conditions, ranging from 0.1 to 3 l/s, and the supply air temperature and humidity was close to ambient room air conditions.

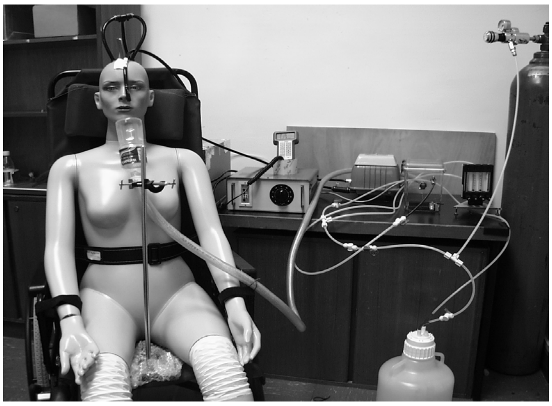

Figure 1 Testing of the microphone position ATD using a thermal manikin (Zuo *et al.*, 2002).

Indices Used to Quantify the Performances

Based upon the ages of the air in the breathing zone, Faulkner *et al.* (2002) used the air change effectiveness (ACE) at the breathing zone to quantify the performance of the tested air supply method.

Melikov *et al.* (2001) introduced a new index, personal exposure effectiveness ε_p, to quantify the inhaled air quality, which is expressed as the percentage of personalized air in inhaled air,

$$\varepsilon_{\mathrm{p}} = \frac{C_{\mathrm{e}} - C_{\mathrm{i}}}{C_{\mathrm{e}} - C_{\mathrm{s}}} \tag{1}$$

where C_e is pollutant concentration in the inhaled air without personalized ventilation, C_s is the pollutant concentration in the supplied air and C_i is the pollutant concentration in the inhaled air. $\varepsilon_p = 0$ means the supply air and ambient air were perfectly mixed; $\varepsilon_p = 1$ means inhaled air contains only personalized air.

In HKPolyU, two new indices were introduced. A pollutant exposure reduction efficiency, $\eta_{PER,}$ is defined to express the percentage of pollutant level reduction in the inhaled air from the ambient room air. If we assume that the pollutant in the supply air is zero, the index η_{PER} is defined as:

$$\eta_{\mathrm{PER}} = (C_{\mathrm{a,P}} - C_{\mathrm{L,P}})/C_{\mathrm{a,P}} = (1 - C_{\mathrm{L,P}}/C_{\mathrm{a,P}}) \tag{2}$$

where $C_{a,P}$ is pollutant concentration in ambient air and $C_{L,P}$ is pollutant concentration in inhaled air. Numerically, η_{PER} is equal to the fraction of fresh air in inhaled air, which is in turn defined as ventilation coefficient η_f and can be calculated from the measured tracer gas concentrations:

$$\eta_{\mathrm{f}} = V_{\mathrm{F,L}}/V_{\mathrm{L}} = (C_{\mathrm{f}} - C_{\mathrm{a}})/(C_{\mathrm{L}} - C_{\mathrm{a}}) \tag{3}$$

where $V_{F,L}$ is the fresh air volume in the inhaled air V_L, C_f is tracer gas concentration in fresh air, C_a is tracer gas concentration in ambient air and C_L is tracer gas concentration in inhaled air. Although the new index, η_{PER}, is numerically equal to ε_p, introduced by Melikov *et al.* (2001), it can be shown later that the definition of the pollutant exposure reduction efficiency

η_{PER} can be more conveniently used to assess the benefits of PAS in comparison with the total volume ventilation system.

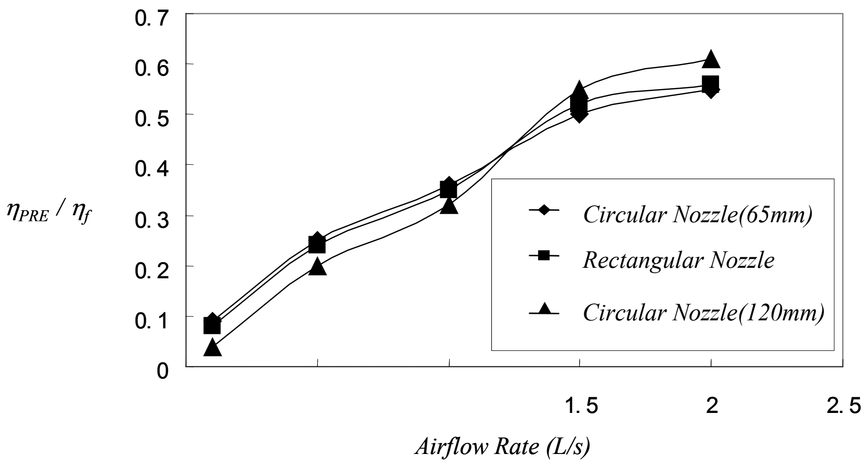

Figure 2 Variation of η_f with supply airflow rates of three different air nozzles (Zuo *et al.*, 2002).

RESULTS

Figure 2 shows the pollutant exposure reduction achieved in HKPolyU's test (Zuo *et al.*, 2002). The η_{PER} and η_f increases as the supplied airflow rate increases from 0.1 to 2 l/s. The effective area of the rectangular nozzle is the same as that of the circular nozzle with the 65 mm diameter, and their η_f curves have no obvious differences. It appears that the η_f curves are becoming flat as airflow increases further from 1.5 l/s. This may indicate that increasing supplied airflow with a given supply air nozzle will have limited effects on increasing the efficiency. Whereas, for the circular nozzle with a large diameter of 120 mm, the slope of the curve in the range of 1.5–2 l/s appears to be higher, indicating that further increasing of supplied airflow may still have obvious effect on the increasing of η_f. Comparing the curves of the circular nozzle with 65 mm diameter and 120 mm diameter, it may be concluded that the larger nozzle area could achieve larger η_f at higher supplied airflow rates, but that at lower supplied airflows, the smaller nozzles perform better. In later studies, a value of η_{PER} as high as 0.8 was achieved at the air supply rate of 3 l/s (Zuo, 2003).

In TUD's investigation, similar trends were observed, except that the equivalent values of ε_p were achieved at much higher flow rates, at the range of 10–20 l/s (Melikov *et al.*, 2001). This is obvious since the distances between the nose and the ATDs integrated into the desk are larger. The maximum ε_p is about 0.75, achieved at the flow rate of 25 l/s. It is important to observe that, for some of the ATDs tested, a value of nearly 0.5 of ε_p was achieved at the airflow rate of 10 l/s, which is the current standard ventilation rate. As will be analysed later in this paper, this is still a significant achievement.

Human Subject Evaluation of PAS

In TUD, using human subjects, the effects of PAS on perceived air quality were assessed (Kaczmarczyk *et al.*, 2002), and a reduction of 20% of PD% was achieved. It appears that similar studies should be carried out with the chin-position PAS method.

ANALYSIS OF THE BENEFITS OF PAS

The Reduced Exposure to Indoor Air Pollutants

Assume that the emission rate of indoor pollutants is $\dot{E}$, and the total ventilation rate is Q. With the introduction of personal ventilation (PA) rate Q_P, the background ventilation is reduced to $Q_B = Q - Q_P$, i.e. the total ventilation rate remains the same as in a conventional design. According the current ventilation standard, Q is typically around 10 l/s.

Assume a well-mixed condition in the room, the indoor air pollutant level in the room air will be

$$C = C_s + \dot{E} / Q \tag{4}$$

where C_s is the pollutant level in the supply air. C would be the pollutant concentration in the inhaled air with the conventional air supply methods.

With the introduction of personalized air supply, concentration pollutant levels in the room will remain the same. The concentration of pollutants in the inhaled air C_{in} becomes

$$C_{in} - C_s = (1 - \eta_{PER})(C - C_s) = (1 - \eta_{PER})\dot{E} / Q \tag{5}$$

where η_{PER} is the pollutant exposure reduction efficiency of the air supply method. According to our test results, η_{PER} ranges from 9 to 80% at the range from 0.1 to 3 l/s of Q_P (Zuo, 2003). This means that at the same total ventilation rate, 80% of reduction of indoor air pollutants in the inhaled air is achieved when 3 l/s of the total ventilation air is delivered through the personalized air supply nozzle. In the case of desktop located PAS ATDs, and if all the 10 l/s ventilation air is supplied via the PAS nozzles, a 50% reduction can still be achieved (Melikov, 2002).

The Reduced Total Ventilation Rate to Achieve Equivalent Inhaled Air Quality

The benefit of the new air supply method can be alternatively quantified by demonstrating that the ventilation rate can be much reduced to achieve the same inhaled air quality. Let us assume that the total ventilation rate Q is reduced 3 l/s, all of which is delivered via the chin-position PAS nozzle. Let us assume that $\dot{E}$ remains the same, the indoor air pollutant level will be raised due to the reduced ventilation rate according to Eqn (4), when compared with the case when Q = 10 l/s:

$$C' = C_s + \dot{E} / (0.3Q) \tag{6}$$

However, with the PA system, the pollutant concentration, according to Eqn (5), in the inhaled air would be

$$C_{in} - C_s = (1 - \eta_{PER})(C' - C_s) = (1 - \eta_{PER})\dot{E} / (0.2Q) \tag{7}$$

Since η_{PER} is equal to 80% at Q_p = 3 l/s with the chin-position ATD, from Eqn (7), we will have

$$C_{in} = C_s + \dot{E} / Q \tag{8}$$

Comparing (8) and (4), we can see that $C_{in} = C$. That is to say, equivalent inhaled air quality is achieved at the total ventilation rate of merely 30% of the conventional system. This means that the PA method can save 30% of ventilation air, which means significant saving of energy used in air conditioning, especially for hot–humid climates and cold climates, where cooling/heating, and/or (de-) humidification of outdoor air constitute a large percentage of the total energy use.

In summary, the benefits of the PA system can be quantified in both improved inhaled air quality and reduced energy use in air conditioning. Depending on circumstances, the designer may choose to bias towards one of the two benefits, but the overall performances will always be significantly better than that of the current whole space ventilation strategy.

CONCLUSIONS

It appears that, even when the supply air nozzles are located very close to the chin of the tested thermal manikin, certain mixing between the supply air and the ambient air has occurred as quantified by the two newly defined indices, namely the fresh air utilization efficiency η_u and the pollutant exposure reduction efficiency η_{PER}. But the pollutant exposure reduction and air utilization are still many times higher than the conventional general ventilation system, which indicates that the system can be very promising in those work places where occupants are sitting in a fixed position for prolonged period. As high as 80% reduction of exposure to indoor air pollutants can be achieved with one of the supply methods tested, at the current ventilation level of 10 l/s, which should be considered as a great breakthrough in ventilation technology. Practical designs to realize the supply methods have also become available.

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