The impact of a personalized ventilation system on indoor air quality at different levels of room air temperature

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ABSTRACT
The performance of a Personalized Ventilation (PV) system with regard to air quality perceived by people was studied at three room temperature levels: 23, 26 and 29°C. Thirty human subjects participated in the experiment. The system supplied both isothermal (23, 26, 29°C) and non-isothermal (23°C) outdoor air from an outlet attached to a moveable arm. The subjects were delegated with control of both airflow velocity and its direction. Physical measurements performed with a breathing thermal manikin were used to explain the results from the human subject experiments. The results show that the inhaled air quality was perceived significantly better with the PV system than with mixing ventilation only. The measurements performed with the breathing manikin showed that around 30% of the air inhaled by the subjects was outdoor air provided by the present PV system. Therefore the quality and the temperature of the room air had a large impact on the perceived air quality even with the tested PV system. Further development of PV outlets is recommended to improve the air delivery efficiency.

INDEX TERMS
Personalized ventilation (PV); Perceived air quality; Individual control; Local discomfort

INTRODUCTION
Indoor air quality (IAQ) is increasingly recognized as one of the important factors for the promotion of people's comfort and welfare (Yuan *et al.*, 1998). Results of human subject experiments showed that good air quality perception helps to improve occupants' productivity (Wargocki, 1999, 2000; Lagercrantz, 2000). It has been reported that occupant comfort, performance and overall satisfaction increases when they are delegated with control of their own microenvironment (Kroner and Stark-Martin, 1994; Bauman *et al.*, 1998). Therefore, the development and employment of HVAC systems should aim at the delivery of clean air directly to the occupants with some level of individual control.

The concept of personalized ventilation (PV) meets these requirements better than conventional mixing ventilation or displacement ventilation. By supplying fresh air directly at occupants' breathing zone, the PV system is expected to improve the air delivery efficiency significantly. Besides, this system makes it feasible for each occupant to adjust for the preferred airflow direction and velocity (Fanger, 1999; Melikov, 1999). Studies have documented that the employment of PV helps to improve air quality perception and reduce SBS symptoms at low room temperature (Kaczmarczyk *et al.*, 2002; Zeng *et al.*, 2002).

It has been shown that the enthalpy of air has an important impact on the perception of air quality. Cool and dry air, e.g. air with low enthalpy, is perceived as better than warm and humid air (Fang *et al.*, 1998). This study aims to identify the appropriate room air temperature range for applying a PV system with regard to air quality perception.

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METHODOLOGY

The study was carried out in an office room ($L \times W \times H = 6 \times 6 \times 3$ m^3) divided into two parts by a partition. Six PV system terminals were mounted at six work stations established on one side of the partition. Each of these terminals consisted of an outlet attached to a moveable arm. The subjects were able to freely move and rotate the outlet and thus modify the airflow direction. They were allowed to control the airflow rate (airflow velocity) from the PV system by modulating the power of a small fan mounted in the system. Heaters, humidifiers and pollution sources (used carpet) placed behind the partition were used to control the thermal environment and the background air quality in the room. Six experimental conditions, specified in Table 1, were generated and studied: one experiment with mixing ventilation only and five experiments with personalized ventilation. The relative humidity of both room air and personalized air was kept 30% during the experiments.

Table 1 Experimental conditions (PV—personalized ventilation, MV—only mixing ventilation)

Number of experiment	Experimental condition	Personalized air temperature (ºC)	Room air temperature (ºC)
1	PV 23ºC/23ºC	23	23
2	PV 23ºC/26ºC	23	26
3	PV 26ºC/26ºC	26	26
4	PV 23ºC/29ºC	23	29
5	PV 29ºC/29ºC	29	29
6	MV 26ºC	–	26

Thirty human subjects, 16 males and 14 females, divided into five groups of six persons participated in the experiment. The total volume of fresh air supplied into the room was 90 l/s. When a subject adjusted the airflow rate lower than the designed maximum rate of 15 l/s/person, the complementary amount was supplied into the room through a by-pass duct. In this way the pollution level of the background air in the room was kept constant. During the experiment with mixing ventilation (MV) only, Table 1, exp. 6, the PV system was stopped. The fresh air (90 l/s) was supplied behind the partition and well mixed with the room air to achieve uniform environment in the space.

The experimental procedure for each of the experimental conditions was identical: subjects entered the room and answered questions about perceived air quality. Then they sat at the workstations and performed different typical office tasks in three sessions. During the first 30 min they were engaged in proof reading, followed by 35 min of addition task. Then the subjects moved away from the stations to a table placed in the centre of the room for a 5 min break, followed by 45 min of text typing at the PV stations. After that the subjects left the stations and sat around the table in the middle of the room for the last 15 min.

A 'breathing' thermal manikin and tracer gas (SF_6) measurements was used to identify the amount of personalized air inhaled by subjects (Melikov *et al.*, 2000). The measurements were conducted in a chamber where SF_6 concentration in room air and personalized air was separately controlled. The posture of the manikin and the positioning of the PV outlet was adjusted to represent the average condition identified during the human subject experiments. The room air temperature and the personalized air temperature were the same as in the human subject experiments (Table 1). An index, personal exposure effectiveness ε_p, expressed as the percentage of personalized air in inhaled air, was used to quantify the performance of fresh air delivery in this system (Melikov *et al.*, 2002):

$$\varepsilon_{\mathrm{p}} = \frac{C_{\mathrm{r}} - C_{\mathrm{in}}}{C_{\mathrm{r}} - C_{\mathrm{PV}}} \tag{1}$$

where C_r is the SF_6 concentration in room air, ppm; C_{in} is the SF_6 concentration in the inhaled air, ppm; and C_{PV} is the SF_6 concentration in the personalized air, ppm. This index is equal to 100% when all the inhaled air is personalized air from the PV system and zero when no personalized air is directly inhaled, such as under mixing ventilation condition.

RESULTS AND DISCUSSION

Figure 1 shows the comparison of air quality acceptability in case of mixing ventilation and personalized ventilation. The result is presented as percentage of dissatisfied (PD). It shows that the air quality is initially perceived significantly better with personalized ventilation than with mixing ventilation ($p < 0.005$). After working at the station for more than 30 min, the subjects become slightly adapted to the air pollution and the PD value decreased compared to the first impression. But the air quality was still significantly better with personalized ventilation than with mixing ventilation ($p < 0.0001$).

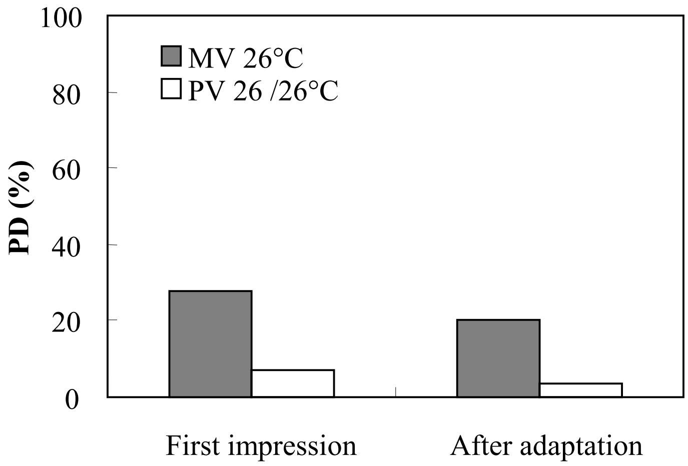

Figure 1 Air quality perception at MV and PV systems.

The airflow rate selected during the experiment by the subjects was recorded to analyse fresh air delivery efficiency. The airflow rate was in average selected at 13 l/s under PV 26/26ºC condition. Figure 2 shows the personal exposure effectiveness for the tested PV system. The efficiency increases with increasing airflow rate from the PV system, indicating that the stronger the airflow, the easier the flow reaches the breathing zone and drives away the free convection airflow around human body. However, the effectiveness is much lower than 100% due to mixing of personalized air with the room air polluted mainly by the carpet and the occupants. Personal exposure effectiveness of 33% was measured for the average airflow rate of 13 l/s as selected by the subjects participating in the experiment at 26°C. The results shown in Figures 1 and 2 were obtained under isothermal conditions (26°C). Therefore the improvement in the air quality as perceived by the subjects was due to the inhaled portion of clean personalized air (33% of the inhaled air). The sensation of air movement may have had an additional effect for better perception of the air movement with PV.

The velocity measurements near the face of the thermal manikin identified local air velocity as high as 0.75 m/s. This velocity cannot explain why very few subjects reported uncomfortable draught sensation with the localized flow at the face. During the measurement, the position of manikin and the outlet of the PV were fixed to have a distance of 0.30 m between the face and the outlet. However, draught sensitive persons have probably selected a lower velocity and/or moved the outlet to a longer distance from the face.

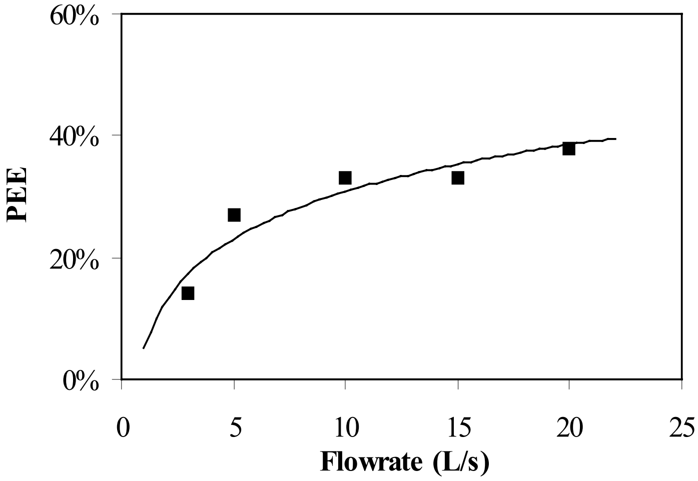

Figure 2 Air delivery efficiency of PV system: personal exposure effectiveness (PEE) as a function of the flow rate from the outlet.

Figure 3 shows the impact of the air temperature on the air quality perceived by the occupants. The vote at time zero is the assessment of room air by the subjects when entering the room. It is apparent that the assessment is related with air temperature: the PD value is about 8, 25 and 70% for room air temperature of 23, 26 and 29ºC, respectively. In Figure 3, the second vote in time is the first impression to personalized air after subjects sat at the working station. The comparison between the first vote and the second vote shows that the air from PV system was perceived much better than the room air under all experimental conditions. A significant step-up change and step-down change of the PD value occurred at the beginning and the end of the 5 min break when the subjects moved away from the PV to the table in the middle of the room and then back to their work place with PV system (respectively after 65 and 70 min from the start of the experiment). This result confirms that personalized ventilation had a positive impact on occupants' perception of the inhaled air.

Figure 3 shows that background air temperature affects air quality acceptability as well. When room air temperature was not higher than 26ºC, the PD value decreased to 5% after subjects adapted to the environment. The PD value was about 20% after the first impression vote when room air temperature was elevated to 29ºC. It is apparent from the results in Figure 3 that the PD value is almost similar under isothermal and the non-isothermal conditions, Table 1—experiments 2 and 3 and 4 and 5.

Only at room air temperature of 29ºC did a significant difference ($p < 0.05$) in the air quality as perceived by the subjects when they first sat at the workstation with the PV system (second vote in Figure 3) exist between the isothermal and non-isothermal cases (Table 1—experiments 4 and 5). The PD value was 23% at non-isothermal condition (PV 23ºC/29ºC) and 35% at isothermal condition (PV 29ºC/29ºC). Also at the beginning of the break the subjects assessed the air quality in the middle of the room (room air temperature of 29ºC) as better during the non-isothermal experiment than the isothermal experiment. These effects were not observed at room air temperature of 26°C. Differences in the step-change of the inhaled air temperature may be one of the reasons. The tested PV outlet generated airflow with quite high turbulence, promoting mixing of the personalized air with the room air. As a result the inhaled air was polluted and warmed up when inhaled. Nevertheless the results of this study indicate that the impact of air temperature on perceived air quality is stronger for the first impression and diminishes after the adaptation period. This result is different than the result reported by Fang *et al.* (1998).

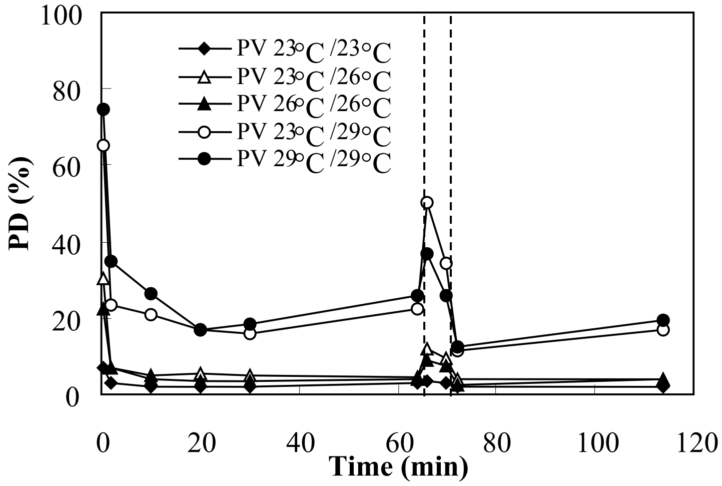

Figure 3 Air quality perception at different room temperatures.

The first subjective impression is used in the CEN guideline as designing criteria. It is required that the PD value should be lower than 20% in moderate environment (CEN 1752, 1998). It was possible to achieve this requirement with the PV system tested in the present study. The PV value was 7% when the room air temperature was 26°C and lower. Using the same outlet Zeng *et al.* (2002) reported PD value of less than 20% at room air temperature of 28°C. However, the results of the present study show that when the room air temperature was as high as 29ºC, the PD increased to 23–35%, e.g. above the requirement in the guidelines. These results show that the PV system is able to improve perceived air quality, but within a range of room air temperature. The improvement from the PV decreases when room temperature is lower than 23ºC, because the quality of the air as perceived by the occupants is already improved due to low enthalpy of the room air. At room air temperature 29ºC and higher, the tested PV was unable to lower PD value below the requirements in the guidelines due to the intensive mixing of the personalized and the room air it generated. Therefore development of outlets for PV that create less mixing is recommended.

CONCLUSION

The tested PV system with an outlet attached to a movable arm improved the perceived air quality significantly compared with conventional mixing ventilation, even at room temperatures up to 29°C. However the PV system had a personal exposure effectiveness (outdoor air delivery efficiency) of only around 30%, which explains why the quality and temperature of the room air had a strong impact on the inhaled air quality. Further development of the PV outlet to significantly improve the delivery efficiency is essential for successful application of PV systems in practice.

ACKNOWLEDGEMENT

This study is part of the research program of the International Centre for Indoor Environment and Energy funded by the Danish Technical Research Council (STVF).

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