PERSONALIZED VENTILATION
State of the art and Performance in practice

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Abstract
The thermal environment and air quality in buildings affects occupants' health, comfort and performance. The heating, ventilating and air-conditioning (HVAC) of buildings today is designed to provide a uniform room environment. However, large individual differences exist between occupants in regard to physiological and psychological response, clothing insulation, activity, air temperature and air movement preference, etc. Environmental conditions acceptable for most occupants in rooms may be achieved by providing each occupant with the possibility to generate and control his/her own preferred microenvironment. Furthermore, HVAC systems should be designed to protect occupants from airborne transmission of infectious agents that may be present in exhaled air. Personalized ventilation is a new development in the field of HVAC and has the potential to fulfil the above requirements.

This paper reviews existing knowledge on personalized ventilation (PV) and on human response to it. The performance of two types of air terminal devices for personalized ventilation system in conjunction with either mixing or displacement total-volume ventilation system is discussed.

Keywords: individual control, personalized ventilation, human response, performance in practice

1. Introduction

Requirements for temperature and air movement in spaces are prescribed in the present standards [1, 2]. The requirements are based on average values for a large group of occupants. However, occupants' physiological and psychological responses to the indoor thermal environment almost always differ due to differences in clothing, activity, individual preferences for air temperature and movement, time response of the body to changes of the room temperature, etc. The thermal insulation of the occupants' clothing may vary from 0.4 clo to 1.2 clo or even more and the metabolic rate may range between 1 met and 2 met due to differences in occupants' physical and mental activities [3]. Individual differences in preferred air temperature may be as great as 10°C [4]. Occupants' preferences for air movement (air velocity) may differ more than four times [5]. It is therefore not surprising that thermal discomfort is often reported by a large percentage of occupants in offices even when the thermal environment complies with the recommendations in the standards.

Building materials, office machines, electronic equipment as well as occupants and their bioeffluents and exhaled air are some of the pollution sources in rooms. Personal computers pollute room air as well [6]. It has been shown that poor air quality causes SBS (Sick Building Syndrome) symptoms such as increased prevalence of headache, decreased ability to think clearly, etc., and affects occupant's performance [7, 8]. Large individual differences between occupants in rooms in regard to perceived air quality exist as well [9].

Mixing and displacement room air distribution are the main principles of total volume mechanical ventilation (TV) that are applied today in buildings. The clean air supplied far from the occupants is more or less polluted and warm by the time it is inhaled. Numerous laboratory measurements and CFD predictions suggest that air quality is better in rooms with displacement ventilation. However, a recent field study in rooms with displacement ventilation found that almost 50% of occupants were dissatisfied with the air quality [10, 11]. The air quality perceived by the occupants will improve when more fresh air is supplied to the space. This, however, will increase air velocity in the occupied zone and may cause draught discomfort for some occupants. Total volume ventilation does not account for individual differences between occupants and provides only limited or no personal control at all over their microenvironment.

The European guidelines CEN 1752 "Ventilation for Buildings – Design Criteria for the Indoor Environment" [12] defines three categories of indoor environment. It suggests that the highest quality of indoor environment, Category A, may require individual control of the microenvironment of each occupant in a space. ASHRAE standard 55 [2] also suggests individual control under some conditions. In this case personalized ventilation can be applied.

2. Personalized ventilation – state of the art

The main idea of personalized ventilation (PV) is to provide clean and cool air close to each occupant. Thus PV in comparison with TV has two important advantages: first, its potential to improve the inhaled air quality and second, each occupant is delegated the authority to optimise and control temperature, flow rate (local air velocity) and direction of the locally supplied personalized air according to his/her own preference, and thus to improve his/her thermal comfort conditions.

The supply air terminal devices (ATD) used for PV are located close to the breathing zone of occupants. ATDs of different design, allowing control of airflow rate and some of them for control of flow direction, have been tested (Figure 1): two small nozzles (PEM) placed at the back corners of a desk and generating two symmetrical jets or two linear diffusers placed at the front desk edge generating two jets, one toward the occupant's body (HDG) and the second vertically (VDG), directed slightly away from the occupant [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24], ATD (MP) with a rectangular or circular opening mounted on a movable arm-duct which allows for changes of the distance between the ATD and the person as well as the direction of the personalized flow [21, 25], a flat ATD mounted on the top of a PC monitor (CMP) allowing for change of personalized flow direction in a vertical plane [21], a small nozzle integrated with the flexible support of a commercially available headphone supplying air very close to the mouth and the nose [25], or combinations of some of these ATDs [26]. Several other designs, such as a round nozzle attached to the chest blowing air against the face [27], a displacement ATD placed below the desk [28, 29], a ventilation tower system [30], a partition integrated fan-coil unit [31, 32, 33, 34] and other designs have all been tested.

Physical measurements identify a significant decrease of pollution concentration in inhaled air with PV in comparison with TV [17, 18, 19, 21, 22, 23, 24, 25, 27, 35]. The amount of inhaled clean personalized air has been shown to depend on the design of the ATD and its positioning in regard to the occupant, the flow rate (typically from less than 5 L/s up to 20 L/s) and the direction of the personalized airflow, as well as the difference between the room air and the PV airflow temperature, size of target area, etc. [19, 21]. The optimal performance for most of the ATD has not exceeded 50-60% of clean air in each inhalation. Recently highly efficient ATD providing almost 100% clean and cool personalized air in each inhalation have been developed, as shown in Figure 2 [22, 25]. This corresponds to ventilation effectiveness of up to 50-100, which is 1-2 order higher than the ventilation effectiveness in rooms with mixing or displacement ventilation only. The temperature of the inhaled air may be decreased (by up to 6°C as shown in the latter studies) in comparison with mixing ventilation and this will further improve perceived air quality.

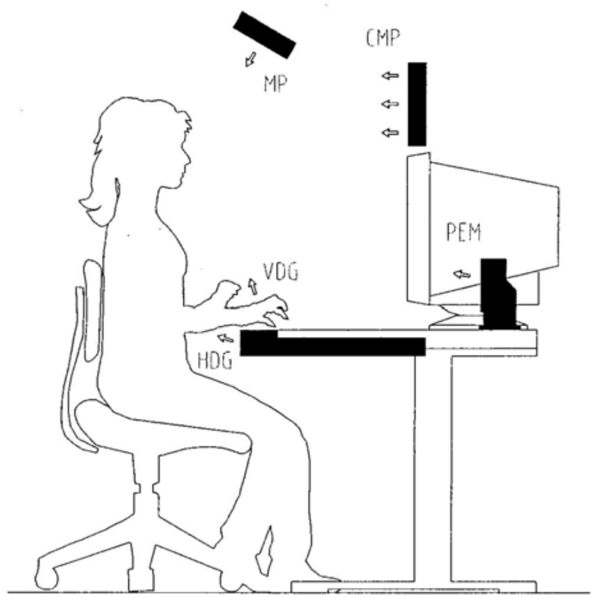

Fig. 1. Personalized ventilation. Examples of tested air supply terminal devices (ATD): Movable Panel (MP), Computer Monitor Panel (CMP), Vertical Desk Grill (VDG), Horizontal Desk Grill (HDG), and Personal Environments® Module (PEM).

Substantial potential of PV for improvement of occupants' thermal comfort has been reported as well [16, 26]. The design of ATD has an impact on uniformity of the body cooling which affects people's thermal comfort [36]. The importance of ATD is discussed later in this paper in relation to air distribution in the vicinity of the human body.

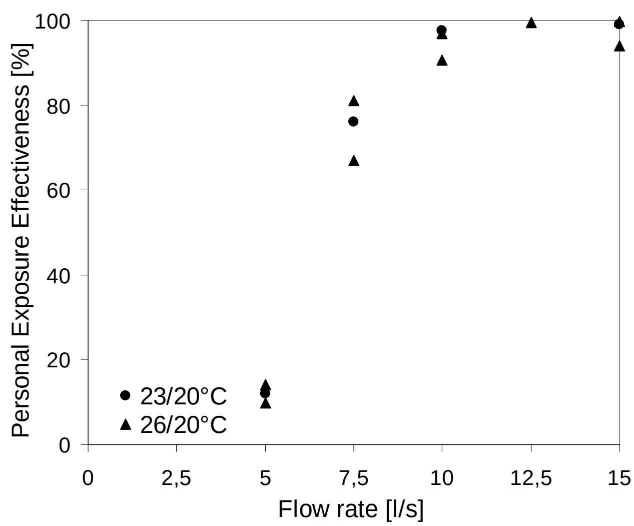

Fig. 2. Personalized exposure effectiveness, i.e. percent of the personalized air in the inhaled air, as a function of flow rate of personalized air: room air temperature of 23°C and 26°C and personalized air temperature of 20°C. Results are obtained with ATD reported in [25].

Only limited knowledge on human response to PV is available [37, 38, 39, 40, 41, 42]. Human response to PV combined with only one type of TV, namely mixing ventilation (MV) has been reported. The results obtained in the room air temperature range 23°C-28°C reveal that PV providing clean outdoor air improves perceived air quality compared to MV (Fig. 3). The effect increases when the personalized air is cool. The acceptability of inhaled air provided by a PV increases at higher background room air temperature [38, 41]. The differences in regard to acceptability of the inhaled air decrease over time due to adaptation but remain always higher with PV than with MV alone. SBS symptoms, such as headache, decreased ability to think clearly, etc. remained significantly less intense with PV than with MV alone (Fig. 4). The PV increases the well-being and self-estimated performance of users. The advantage of PV was maintained under transient conditions, when occupants simulating office work moved away from and back to workstations equipped with PV [41]. People can clearly distinguish the performance of PV systems with different design and can rank them according to perceived air quality, thermal comfort and ergonomics [26, 39]. At room air temperature below 23°C and low odour intensity the performance of PV with regard to health and comfort may be different. PV may not improve perceived air quality significantly in comparison with TV and may cause draught discomfort but it still may remain important for occupants' health (SBS symptoms). Under these conditions, and in general, the importance of the background pollution level on the performance of PV is not known.

PV improves peoples' thermal comfort [26, 37, 39, 40, 41]. The acceptability of the thermal environment with PV compared to without PV significantly improves at room temperature above 23°C. Control over supplied airflow rate, i.e. local air velocity, obviously makes it possible to avoid draught discomfort. However at room air temperature above 26°C the cooling capacity of the personalized flow targeting a relatively small body surface area may not be enough to provide some people with thermal comfort without causing draught discomfort, although it significantly improves whole body thermal comfort [41, 42]. People prefer personalized airflow with constant rather than fluctuating velocity [43].

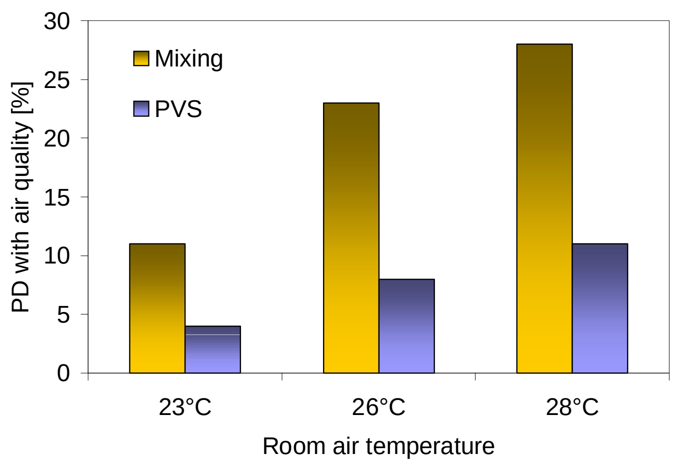

Fig. 3. Percent dissatisfied persons (PD) with air quality in a room with mixing ventilation alone (left bars) and when provided with PV at room air temperature of 23, 26 and 28°C. Personalized air temperature is 20°C. Occupants are provided with individual control of personalized flow rate. The total amount of air supplied to the room (only clean air) is the same with mixing ventilation alone and with PV combined with mixing ventilation. Results reported in [41].

Personalized air supplied close to the face may cause increased eye blinking [44] and skin irritation and may thus be felt uncomfortable. No significant difference in subjects' eye blinking interval was found in a recent as yet unpublished human subject study comprising combinations of personalized air temperature between 23°C and 26°C and room air temperature in the range 23°C – 29°C. The subjects were provided with control over the flow rate and the direction of personalized air and were able to avoid this type of discomfort. Only few subjects wearing contact lenses reported discomfort. This effect needs to be studied.

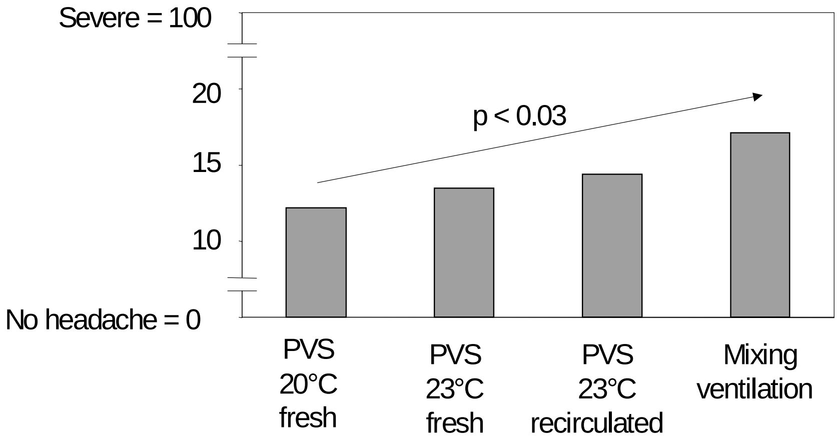

Fig. 4. Reported SBS symptoms. Intensity of headache. The most pronounced symptoms of headache are reported for mixing ventilation. The intensity of the headache is reduced steadily, firstly by providing individual control with PVS (23°C, re-circulated), secondly by providing outdoor air with PVS (23°C, fresh), and finally by decreasing the temperature of provided personalized outdoor air with PV (20°C, fresh). Results reported in [37].

People learn, exercise successfully and benefit from their control over the flow velocity and direction and positioning of an ATD [26, 38, 41]. A tendency to make fewer changes in the positioning over elapsed time has been observed. The freedom of control over direction and flow rate of personalized air is important for lowering the risk of draught sensation and to improve occupants' satisfaction. Personalized airflow toward the face is preferred over airflow towards the abdomen, although airflow from the side has been used as well. The preferred flow rate ranges from 3 to 20 L/s (local air velocity range 0.2 – 1.2 m/s). Factors such as ergonomics, appearance, easy control, etc. are also important for subjects' ranking of the performance and acceptance of PV systems of different design [26, 39].

The spread of respiratory tract infections between people, such as the common cold and influenza, occurs by surface contact (i.e. face-to-face contact), large-droplet sprays (cough, sneeze) and also by transmission through contaminated air, i.e. infectious aerosols exhaled by occupants [45]. In this respect PV, when properly applied, has greater potential to prevent transmission of contagion between occupants compare to TV. The research on this topic is at an early stage, but available knowledge suggests that in rooms with mixing ventilation the use of PV will always protect the occupants from airborne transmission of infectious agents and will be superior to mixing ventilation alone [22]. In rooms with displacement ventilation, however, PV promotes mixing of the exhaled air with room air [22, 35]. A similar effect may occur in rooms with underfloor ventilation [23, 24]. In real life this may lead to an increase of the risk of transmission of airborne infectious agents to occupants who are not protected by high efficiency PV, e.g. occupants who are not at their workstation.

The number of secondary infections that arise when a single infectious case is introduced into a population where everyone is susceptible can be defined as reproductive number, R_{A0} [45]. An infectious agent can spread in a given population, if $R_{A0} > 1$. The larger the value of R_{A0} the more likely is the infection to reproduce rapidly. Fig. 5 presents R_{A0} at two ventilation rates of outdoor air, of which one corresponds to the ventilation rate of 10 L/s outdoor air required by present guidelines and standards [12, 46]. It is assumed a presence of 30 persons in the room (chosen arbitrarily) and the time of exposure of 8 hours. The generation rate of infectious doses (influenza), i.e. the average infectious source strength of an infected occupant, is 100 quanta/hour. In the case of mixing ventilation alone and a supply rate of 10 L/s per person, there is likelihood that 7 out of 30 occupants acquire influenza after an 8-hour exposure. The number of possibly infected person decreases to just 2 (1 already and 1 secondary infected) if the ventilation rate is increased to 40 L/s per person. The use of PV enables the occupants to efficiently protect themselves from infections ($R_{A0} < 1$) at much lower flow rate. However, in rooms with stratified flows, i.e. displacement and underfloor ventilation the use of PV by the sick occupant may increase the risk of infections for occupants not protected by PV [47].

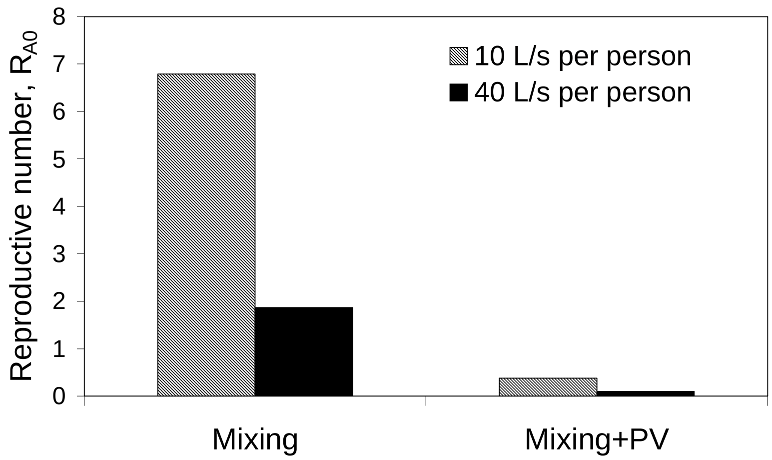

Fig. 5. Reproductive number, R_{A0}, in a room with mixing ventilation alone and mixing ventilation combined with PV. In case of mixing + PV minimum of 10 L/s·person and maximum of 15L/s·person of outdoor air is supplied through the PV and the rest through the mixing ventilation.

3. Performance of personalized ventilation in conjunction with mixing and displacement ventilation – case study

A large office with several workstations can be one of the most typical applications of the PV principle in practice. Some occupants, provided with individual control, may adjust their PV system to deliver a small flow rate and at a temperature only a few degrees cooler than the room air temperature or they may even switch it off in order to avoid draught, while other occupants may use their PV at high flow rates in order to cool their body. Therefore in order to keep an acceptable background environment, total volume ventilation in combination with PV can best be applied in rooms with high heat and/or pollution loads. Localized airflows created by PV at workstations will affect the background environment. The personalized flow will affect non-uniformity of velocity and temperature fields mainly at the workplace. Spatial differences in air pollution levels from occupants, office machines, etc. will occur as well [17, 22, 23]. This will affect occupants' personal exposure, especially in rooms with stratified air distribution, i.e. displacement and underfloor air distribution [24, 35]. The distribution of contaminants depends on the type and operation of PV, the airflow pattern generated by total volume ventilation system as well as on the type and location of the contaminant sources. In the following some results from study [48] on performance of personalized ventilation in conjunction with mixing and displacement ventilation are discussed.

Method

A mock-up of a typical office with two identical workplaces (Fig. 6) was built in an environmental chamber (length x width x height = 5.4 m x 4.8 m x 2.6 m). Each workstation consisted of a desk with an air terminal device (ATD) for PV, a personal computer and a lamp. The walls and the floor of the chamber were made of wooden chipboard, the ceiling of gypsum tiles. One of the walls was single glazed. Air temperature outside the chamber was controlled to be close to the temperature inside the chamber in order to reduce the heat transfer through the walls. The chamber was sealed prior to the experiments.

Two types of ATDs for PV were tested (Fig.7). The round movable panel (RMP) mounted on a movable arm-duct attached to the desktop had a round discharge opening with diameter of 0.185 m. The front panel was fitted with a flow straitener. The construction of the movable arm-duct allowed for changing the position of the panel and the angle of the supply jet. The vertical desk grille (VDG) consisted of a discharge slot (20 mm x 220 mm) located on the front desk-edge. The slot was equipped with vanes that directed air vertically to the breathing zone. The positioning of the ATDs defined personalized flow direction as shown in Fig. 7, i.e. the positioning most often preferred by people. The positioning was identical for the two manikins and it did not change during the study.

A swirl type ceiling diffuser was used for mixing ventilation. The diffuser was suitable for the variable air volume application and its performance optimal between 30 and 110 L/s. A semicircular unit with a radius of planar projection of 0.25 m and a height of 1 m was used for displacement ventilation. The unit was fitted with nozzles, which ensured the spread of the air mainly along the walls and only minimally directly to the occupied zone of the room. The near zone of the displacement unit, defined as a horizontal distance from the wall to the place in a room where the maximum velocity decreases to 0.2 m/s, was predicted and experimentally verified as being no longer than 0.7 m. The air was exhausted by means of four circular return grilles mounted on the ceiling (Fig. 6).

Two breathing thermal manikins, shaped as 1.7 m tall average women, were used to simulate occupants. The manikins' body was divided into several individually heated segments with surface temperature controlled to be equal to the skin temperature of an average person under thermal neutrality. The manikins were dressed with underwear, short-sleeved T-shirt, pants, socks and shoes, giving a total clothing insulation of 0.45 clo (estimated) and were seated on upholstered office chairs (providing thermal insulation of 0.15 clo).

Each manikin was equipped with an artificial lung that simulated the human breathing function [49, 50]. The breathing cycle consisted of 2.5 s inhalation, 2.5 s exhalation and pause, which was at 0.9 s and 1.1 s, respectively, in order to prevent synchronization of the manikins. The breathing frequency was 10 per minute and the pulmonary ventilation was 0.6 L per breath. The exhaled air was heated to a density that was close to the density of air exhaled by people (1.144 kg/m^3). The air was exhaled through the nose (most typical breathing pattern) and inhaled through the mouth. Providing the manikin sat upright, the two jets emerging from the nostrils with a diameter of 8 mm were declined 45° from the horizontal plane, and 30° from each other. The width and the height of the oval mouth opening were 25 and 5 mm, respectively. A fast response sensor mounted in the mouth of each manikin was used to measure the inhaled air temperature.

The number and distribution of heat sources (Fig. 6) corresponded to a typical office. The total sensible heat gain was 580 W (22.5 W/m^2) and identical for all experiments.

Floor covering and occupants with their bioeffluents and exhaled air were selected as the most common contaminant sources in offices. A constant emission of different tracer-gases was used. The floor covering was realized by means of a rectangular grid of tubing, from which carbon dioxide (CO_2) was released over the entire floor area. The tubing was perforated every 0.6 m creating an array of 8x8 dosing points. Air exhaled from the front manikin was marked with sulphur hexafluoride (SF_6). The bioeffluents were simulated with nitrous oxide (N_2O), released at three locations (armpits and a pelvis region) under the clothing of the front manikin. Therefore, the front manikin acted as a source (referred in the following as polluting manikin), while the back manikin was exposed (referred as exposed manikin).

Experimental condition

The performance of the two types of PV in conjunction with mixing and displacement ventilation (4 combinations) was examined. Four scenarios were tested for each combination: (1) both manikins using PV, (2) front (polluting) manikin using PV while back (exposed) manikin did not or (3) vice versa, (4) neither of the manikins using PV, i.e. total-volume ventilation alone. In total, 80 L/s of clean air (= 4.3 air changes per hour) was distributed between the personalized and the total-volume ventilation system (Table 1). The personalized airflow rate was either 7 L/s or 15 L/s per person – the combinations of airflow rates for the two manikins (Table 1) were used to identify the results. The temperature of air supplied from both personalized and total-volume ventilation was fixed at 20°C, aiming at the exhaust air temperature of 26°C. The recirculation of exhaust air to the supply air was not utilized in order to increase sensitivity of the tracer-gas measurements. All experiments were performed under steady-state conditions.

Measured quantities and measuring equipment

Tracer-gas concentration, temperature and velocity were measurement at two positions near the two workplaces (Fig.6). The velocity and temperature were measured at 8 heights (0.05, 0.1, 0.2, 06, 1.1, 1.4, 1.7 and 2.2 – displacement ventilation and 0.1, 0.35, 0.6, 0.85, 1.1, 1.4, 1.7, and 2.2 – mixing ventilation). The concentration measurements were performed at six heights – 0.1, 0.6, 1.1, 1.4, 1.7 and 2.2 m. Inhaled air temperature and concentration were measured for the two manikins. The supply and exhaust air concentrations, temperatures and airflow rates were monitored as well.

A multi-channel anemometer with 16 omni-directional low velocity sensors was used to perform the velocity and temperature measurements. The characteristics of the instrument complied or were superior to those recommended in the standards [51, 52, 2]. The concentrations of the three tracer-gases were measured with a multi-gas monitor based on the photo-acoustic infrared detection method of measurement. The instrument had only six channels. Therefore, concentration measurements were performed in groups of six.

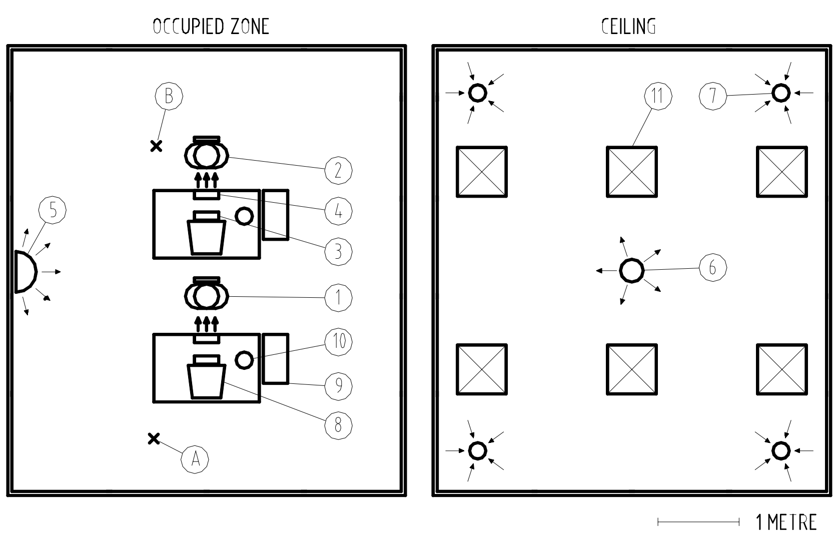

Fig. 6. Office plan: (1) front thermal manikin – 23 sections, (2) back thermal manikin – 16 sections, (3) Personalized ventilation – RMP, (4) Personalized ventilation – VDG, (5) Displacement ventilation supply, (6) Mixing ventilation supply, (7) Exhaust, (8) 17” computer monitor – 70 W, (9) Computer tower – 75 W, (10) Desk lamp – 55 W, (11) Ceiling light fixture – 6 W, (A)-(B) Measurement positions.

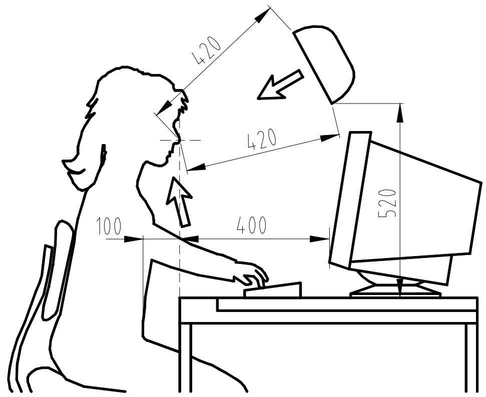

Fig. 7. Details of the positioning of the Round Movable Panel and the Vertical Desk Grille.

Table 1. Experimental conditions.

Supply airflow rate, L/s		
PV Polluting manikin	PV Exposed manikin	Mixing or displacement
0	0	80
0	7	73
0	15	65
15	0	65
15	7	58
15	15	50

Criteria for assessment

The performance of the systems was evaluated with regard to inhaled air quality (concentration and temperature), the thermal environment in the workplaces and the velocity, temperature and contaminant concentration within the occupied zone. In this paper only the results in regard to air quality are discussed. The overall results of this study, including the characteristics of the personalized flow are reported in [48].

The concentration of contaminants in inhaled air were expressed in term of their normalized values, defined respectively as $(x_I - x_S)/(x_E - x_S)$. I, S and E subscripts designate inhaled, supply or exhaust air, respectively. A normalized concentration or temperature of 0 corresponds to the air supplied by either the personalized ventilation and/or the total volume ventilation, while a value of 1 corresponds to the exhaust air. Due to a large number of experimental data only the results for the exposed manikin are presented in this article.

Results

Table 2 presents the concentration of contaminants in the air inhaled by the exposed manikin. The concentration close to the exhaust air concentration was obtained in regard to all three contaminants with only mixing ventilation and in regard to the floor contaminant with displacement ventilation alone. With displacement ventilation alone, a large portion of the inhaled air was from the lower levels (transported by the free convection flow around the manikin's body). Therefore the concentrations of the human-produced contaminants in inhaled air were about 6 times lower than the concentrations at the exhaust.

The primary aim of PV is to provide as high air quality for occupants as possible. In order to ensure a high air quality, the personalized airflow (1) had to be strong enough to penetrate the free convection flow around the body, and (2) had to be delivered clean, i.e. not mixed with the surrounding polluted air. The RMP generated a long initial region with a core of clean, unmixed air, which reached the manikins' face. At a rate of 15 L/s, the velocity at the face of 0.48 m/s was high enough to penetrate the free convection flow, thus providing clean air in the inhalation (Table 2, RMP, conditions 0-15 and 15-15). Because of its high efficiency, the concentrations of the three contaminants were extremely low and comparable. Only a small difference was found when PV was used in conjunction with mixing ventilation and in conjunction with displacement ventilation. At a lower rate of 7 L/s, the flow from the RMP was too weak to destroy completely the free convection flow. In addition, the flow dropped toward the desk due to buoyancy and caused local mixing. As a result, the inhaled air concentrations were similar or even lower than those obtained with displacement ventilation alone (Table 2, RMP, conditions 0-0 and 15-7).

The VDG generated a flow with a short and narrow core region (proportional to the length of the small side of the opening). Because the face of the manikin was located in the fully developed region of the jet, the clean personalized air was already mixed with the polluted room air. The inhaled air concentrations were thus higher with the VDG than with the RMP at a rate of 15 L/s. The characteristics of the flow did not change at 7 L/s. Therefore the inhaled air concentrations were similar at the two airflow rates from the VDG. At 7 L/s, however, the VDG outperformed the RMP in combination with both mixing and displacement ventilation.

Discussion

As compared to mixing ventilation alone, the use of PV in conjunction with mixing ventilation decreased greatly the concentration of pollution in the inhaled air. The inhaled air quality was higher with the RMP than with the VDG at a personalized flow rate of 15 L/s. The improvement was similar in regard to the three pollution sources. Hence, PV will always be able to protect occupants from pollution and thus increase the quality of inhaled air in rooms with mixing air distribution.

In rooms with displacement ventilation, the performance of PV will depend on the type and location of the contaminant source. A passive and plane contaminant source located on the floor, e.g. carpet, PVC or linoleum, is exposed directly and therefore mixes with the clean air current from the wall-based terminal. Therefore, an improvement of the inhaled air quality in regard to the floor contaminant can always be expected when PV is applied.

PV in conjunction with displacement ventilation will decrease the inhaled air concentration of pollution from a localized source, e.g. it will protect occupants from exhaled air (which may carry infectious agents, tobacco smoke) and bioeffluents generated by other occupants, when it is carefully designed and used to supply clean air to the breathing zone. However, the results of this study presented in [48] reveal that pollution from a source located at the vicinity of used PV, e.g. exhaled air and bioeffluents, will be mixed and transported within the room. The mixing and the transportation, which will depend on the individual adjustments of ATD (in regard to the pollution source) and flow rate, occupants' posture, etc., will increase the pollution concentration in the air inhaled by occupants who do not use their PV systems. The inhaled air quality for these occupants may decrease in comparison with displacement ventilation used alone. In practice, however, the activity of occupants can cause mixing as well. Therefore, if modest, the mixing promoted by PV may not be a serious drawback in real life. Because several occupants can produce virulent agents, while at the same time other occupants can produce unpleasant odor (e.g. tobacco smoke), it is difficult to recommend a layout that would ensure a low exposure of all occupants at any moment.

As reported in [48] PV used in conjunction with displacement ventilation will not affect the distribution of pollution from a source, which is not located in the vicinity of the personalized flow, e.g. copy machines or printers. Neither the use of upward personalized flow from VDG, which acts as a thermal plume, nor the decrease in the displacement ventilation rate (when PV was used) did change the elevation of the interfacial layer between the lower cleaner and upper polluted zone. This is an important result in regard to occupants inhaled air quality. Another consequence is that the calculation method used in the design of displacement ventilation could be applied also for the coupled systems. However, because complete mixing can be expected at high rates of personalized air, design methods of both displacement and mixing ventilation (i.e. two extreme air distribution patterns) should be considered.

4. Future research

For many practical applications personalized ventilation can be advantageous compared to total volume ventilation alone. Laboratory and field studies related to human response, air distribution, applicability in practice, energy savings, controllability, etc., are needed in order to explore the potential of PV and ensure its optimal performance. This is discussed in detail in [53, 54].

Acknowledgement

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Table 2. Inhaled air concentration and temperature for the exposed manikin (normalized values).

Air terminal device	PV airflow rate, L/s		Mixing ventilation			Displacement ventilation		
	Polluting manikin	Exposed manikin	Inhaled floor cont.*	Inhaled bioeffluents*	Inhaled exhaled air *	Inhaled floor cont.*	Inhaled bioeffluents*	Inhaled exhaled air*
-	0	0	0.99 ± 0.07	0.95 ± 0.04	0.93 ± 0.04	0.94 ± 0.06	0.17 ± 0.02	0.15 ± 0.02
RMP	0	7	0.74 ± 0.10	0.69 ± 0.06	0.67 ± 0.05	0.68 ± 0.05	0.23 ± 0.02	0.21 ± 0.02
RMP	0	15	0.15 ± 0.05	0.15 ± 0.02	0.13 ± 0.02	0.07 ± 0.03	0.04 ± 0.01	0.03 ± 0.00
RMP	15	0	1.07 ± 0.06	0.98 ± 0.03	0.98 ± 0.02	0.97 ± 0.07	0.81 ± 0.05	0.85 ± 0.03
RMP	15	7	0.66 ± 0.09	0.58 ± 0.07	0.62 ± 0.07	0.66 ± 0.07	0.56 ± 0.04	0.57 ± 0.02
RMP	15	15	0.14 ± 0.04	0.08 ± 0.01	0.09 ± 0.01	0.05 ± 0.04	0.03 ± 0.02	0.04 ± 0.00
VDG	0	7	0.47 ± 0.04	0.43 ± 0.03	0.41 ± 0.02	0.42 ± 0.04	0.14 ± 0.02	0.10 ± 0.01
VDG	0	15	0.39 ± 0.04	0.38 ± 0.02	0.35 ± 0.02	0.37 ± 0.04	0.18 ± 0.02	0.14 ± 0.01
VDG	15	0	0.98 ± 0.06	0.90 ± 0.06	0.94 ± 0.04	1.04 ± 0.06	0.75 ± 0.03	0.48 ± 0.02
VDG	15	7	0.43 ± 0.05	0.37 ± 0.03	0.41 ± 0.02	0.43 ± 0.04	0.41 ± 0.02	0.35 ± 0.01
VDG	15	15	0.35 ± 0.04	0.30 ± 0.02	0.32 ± 0.01	0.32 ± 0.05	0.33 ± 0.02	0.29 ± 0.01

* Dimensionless

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