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Personalized ventilation

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 fulfill the above requirements. This paper reviews existing knowledge on performance of personalized ventilation (PV) and on human response to it. The airflow interaction in the vicinity of the human body is analyzed and its impact on thermal comfort and inhaled air quality is discussed together with control strategies and the application of PV in practice. Performance criteria are defined. Recommendations for design of PV that would be in compliance with the criteria are given. Future research needed on the topic is outlined.

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Key words: Individual control; Personalized ventilation; Design strategies; Human response.

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Practical implications

Personalized ventilation can improve occupants' comfort, decrease SBS symptoms and reduce the risk of transmission of contagion between occupants in comparison with total volume ventilation. However in order to perform efficiently in rooms in practice, the design (air distribution, control, etc.) has to be carefully considered together with type of occupant activity (occupancy rate, occupied density, etc.).

Introduction

Requirements for temperature and air movement in spaces are prescribed in the present standards (ISO 7730, 1994, ASHRAE 55, 2004). 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 (ASHRAE, 2001). Individual differences in preferred air temperature may be as great as 10°C (Grivel & Candas, 1991). Occupants' preferences for air movement (air velocity) may differ more than four times (Melikov et al., 1994). 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 (Bakó-Biró et al., 2002). It has been shown that poor air quality causes sick building syndrome (SBS) symptoms such as increased prevalence of headache, decreased ability to think clearly, etc., and affects occupant's performance (Wargocki et al., 1999; Lagercrantz et al., 2000). Large individual differences between occupants in rooms in regard to perceived air quality exist as well (Summer, 1971).

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 (Naydenov et al., 2002; Melikov et al., 2004). 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.

At present the indoor environment is designed for an "average" person. The European guidelines document (CEN CR 1752) "Ventilation for Buildings—Design Criteria for the Indoor Environment, 1998) 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 (2004) also suggests individual control under some conditions. In this case personalized ventilation can be applied.

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 optimize 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 (Fig. 1a): 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 (Sodec & Craig, 1990; Arens et al., 1991; Bauman et al., 1993; Faulkner et al., 1993, 1999, 2002; Tsuzuki et al., 1999; Cho et al., 2001; Melikov et al., 2002, 2003; Cermak & Melikov, 2003, 2004), 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 (Melikov et al., 2002; Bolashikov et al., 2003), a flat ATD mounted on the top of a PC monitor (CMP) allowing for change of personalized flow direction in a vertical plane (Melikov et al., 2002), a small nozzle integrated with the flexible support of a commercially available headphone supplying air very close to the mouth and the nose (Bolashikov et al., 2003), or combinations of some of these ATDs (Kaczmarczyk et al., 2004). Several other designs, such as a round nozzle attached to the chest blowing air against the face (Zuo et al., 2002), a displacement ATD placed below the desk (Loomans, 1999; Izuhara et al., 2002), a ventilation tower system (Hiwatashi et al., 2000), a partition integrated fan-coil unit (McCarthy et al., 1993; Jeong & Kim, 1999; Chiang et al., 2002; Levy, 2002) and other designs have all been tested.

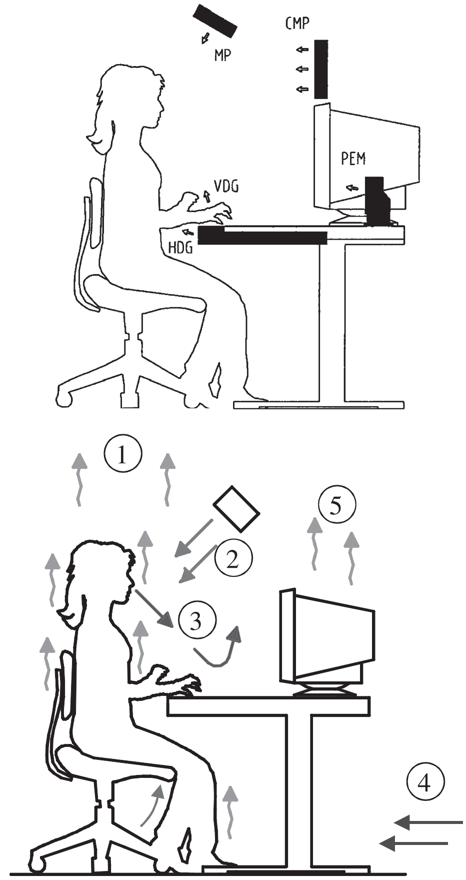

Fig. 1 Personalized ventilation. (a) Examples of tested air supply terminal devices (ATD): Movable Panel (MP), Computer Monitor Panel (CMP), Vertical Desk Grill (VDG), Horizontal Desk Grill (HDG), and Personal Environments® Module (PEM) (b) Airflow interaction around human body: ①—free convection flow, ②—personalized flow, ③—respiration flow, ④– ventilation flow, ⑤—thermal flow.

Physical measurements identify a significant decrease of pollution concentration in inhaled air with PV in comparison with TV (Faulkner et al., 1993, 1999, 2002; Melikov et al., 2002, 2003; Zuo et al., 2002; Cermak & Melikov, 2003, 2004; Cermak et al., 2004; Bolashikov et al., 2003, etc.). 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^{-1} up to 20 l s^{-1}) 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. (Faulkner et al., 1999; Melikov et al., 2002). 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, making it possible to increase the ventilation effectiveness 20 times or more compared with mixing ventilation (Bolashikov et al., 2003; Melikov et al., 2003). 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. Substantial potential of PV for improvement of occupants' thermal comfort has been measured as well (Tsuzuki et al., 1999; Kaczmarczyk et al., 2004). The design of ATD has an impact on uniformity of the body cooling which affects people's thermal comfort (Forejt et al., 2004). The importance of ATD is discussed later in this paper in relation to air distribution in the vicinity of the human body.

Only limited knowledge on human response to PV is available (Kaczmarczyk et al., 2002a, 2002b, 2004; Zeng et al., 2002; Kaczmarczyk, 2003; Yang et al., 2003). 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 23–26°C reveal that PV providing clean outdoor air improves perceived air quality and decreases SBS symptoms compared with MV. 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 (Kaczmarczyk et al., 2004; Yang et al., 2003). 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. 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 move away from and back to workstations equipped with PV. 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 (Kaczmarczyk, 2003; Kaczmarczyk et al., 2004). At room air temperature below 23°C and low odor 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 (Kaczmarczyk et al., 2002a, 2004; Zeng et al., 2002; Kaczmarczyk, 2003; Yang et al., 2003). The acceptability of the thermal environment with PV compared with 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 (Yang et al., 2003; Sekhar et al., 2003a). People prefer personalized airflow with constant rather than fluctuating velocity (Yang et al., 2002).

Personalized air supplied close to the face may cause increased eye blinking (Wyon & Wyon, 1987) 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 23–26°C and room air temperature in the range 23–29°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.

People learn, exercise successfully and benefit from their control over the flow velocity and direction and positioning of an ATD (Kaczmarczyk et al., 2002b, 2004; Yang et al., 2003, etc.). 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^{-1} (0.2–1.2 m s^{-1}). 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 (Kaczmarczyk, 2003; Kaczmarczyk et al., 2004).

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. This will increase non-uniformity of velocity and temperature fields to levels that do not comply with the requirements in the standards (Arens et al., 1991). Spatial differences in air pollution levels from occupants, office machines, etc. will occur as well (Faulkner et al., 1993; Cermak & Melikov, 2003; Melikov et al., 2003). This will affect occupants' personal exposure, especially in rooms with displacement ventilation (Cermak et al., 2004). The distribution of contaminants depends on the type and operation of PV, the airflow pattern generated by TV as well as on the type and location of the contaminant sources.

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 (Roy & Milton, 2004). In this respect PV, when properly applied, has greater potential to prevent transmission of contagion between occupants compare with 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 (Melikov et al., 2003). In rooms with displacement ventilation, however, PV promotes mixing of the exhaled air with room air (Melikov et al., 2003; Cermak et al., 2004). A similar effect may occur in rooms with underfloor ventilation (Cermak & Melikov, 2003, 2004; Cermak et al., 2004). 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.

PV has also a potential for energy savings (Sekhar et al., 2003b). This area, however, needs to be studied further.

Occupant-related performance criteria

The performance of PV can be assessed based on the following criteria related to occupants' health, comfort and productivity:

- Improvement of inhaled air quality (providing clean air at low enthalpy);
- Improvement of thermal comfort without causing draught discomfort;
- Protection from and minimizing of airborne transmission of infectious agents;
- Minimal disturbance of the microenvironment of neighboring workplaces and the room background environment;
- Independence of its performance of occupant's movement and body posture at the workstation;
- Easy control.

Some of these criteria often contradict each other when applied to the design of PV systems. In practice the criteria will be prioritized, based on a compromise that can be different from case to case. Other criteria, such as ergonomics, appearance, energy efficiency, initial installation cost, maintenance, etc., are also important for the application of PV in practice.

Occupant-based design considerations

The optimal performance of PV in regard to the above specified criteria depends, inter alia, on two important factors: first, the aerodynamic characteristics of the personalized flow of clean and cool air and second, the interaction of this flow with the free convection flow around the occupant's body, the ventilation flow generated by the TV and the transient flow of exhalation (Fig. 1b). The performance of PV will always be reduced when these factors are not considered. Unfortunately this is the case for most of the present PV designs that are able to provide only a small fraction of personalized air in inhalation. In the following these two factors are analyzed and when possible the conditions that will lead to optimal performance of PV in regard to occupants' thermal comfort, inhaled air quality and protection are outlined. Thermal plumes from heated office equipment and flows generated by fans in the equipment, downdraught from cold windows, etc. may also have an impact on the performance of PV. However, in most cases, this impact is secondary and will therefore not be discussed here.

Types of Airflow

Free convection flow around the human body In a calm comfortable environment an upward free convection flow exists around the human body (Homma & Yakiyama, 1987; Melikov & Zhou, 1996; Ozcan et al., 2003). The airflow is slow and laminar with a thin boundary layer at the lower parts of the body and becomes faster and turbulent with a thick boundary layer at the height of the head. Body shape and posture, room air temperature, etc. define the mean velocity in the free convection flow which may be as high as 0.25 m s^{-1} and the thickness of the boundary layer may measure 0.2 m or more. This flow induces and transports air (as well as pollution if present) from lower heights in the room to the breathing zone (Holmberg et al., 1990; Homma & Kim, 1992; Brohus

& Nielsen, 1996). Thus, in rooms, a large portion of the air that is inhaled by sedentary and standing persons is from the free convection flow.

Personalized flow The personalized flow is typically a free jet issued from a circular or rectangular opening or a nozzle. The first region of the jet, the potential core region (the other three are known as characteristic decay region, axisymmetric decay region and terminal region) contains a core of almost unmixed supply air with constant velocity and low turbulence intensity. The length of the potential core region is typically 4–5 opening diameters for an ATD with a circular opening. In the case of a rectangular outlet it is 4–5 times the length of the smaller side, i.e., a circular outlet will generate a jet with a much longer potential core region than a rectangular outlet with the same cross-section area. A jet from an outlet with a square cross-section transforms quickly into a circular jet with relatively high initial turbulence intensity. Non-uniform velocity field at the outlet and high initial turbulence intensity enhances the transport of momentum across the jet, generates velocity fluctuations, causes mixing of clean and polluted air in the boundary layer and decreases the length of the potential core. The core length increases with the Reynolds number (*Re*). For $Re > 3 \times 10^4$ the core length is independent of *Re*. The velocity distribution in a non-isothermal jet is similar to that in an isothermal jet, but the change in the diffusion characteristics of the jet due to buoyancy forces should be considered. The buoyancy effect increases when the temperature difference between jet air and surrounding air increases. It decreases as the supply velocity (i.e., flow rate) increases.

Ventilation flow Mixing ventilation may generate a ventilation flow with a different pattern, depending on the location and type of the air supply devices, supply air temperature, type and location of heat sources, etc. Clean air supplied at high velocity promotes mixing in the room. Air velocity decreases in the occupied zone, where it is comparable with the velocity of thermal flows generated by heat sources. Pollution generated inside the room is mixed with the room air and is inhaled by occupants. In rooms with displacement ventilation the supplied clean air spreads over the floor at relatively high velocity and low turbulence intensity. The free convection flow transports clean air from low heights (if not polluted from carpet, etc.) as well as entrains surrounding air and moves it to the breathing zone where it is inhaled. Vertical temperature gradient and pollution concentration gradients develop as a result in the occupied zone.

Respiration flow The breathing cycle consists of inhalation, exhalation and pause. The dynamics of the inhalation flow very close to the nose and to the mouth are similar (Haselton & Sperandio, 1988). The velocity in nostrils/mouth can be relatively high; however, it decreases rapidly with the distance from the face and already at 2–3 cm it is rather low.

The flow of exhalation depends on the breathing mode (nose/mouth, mouth/nose, etc.), respiration flow rate (which depends on activity level, body weight), nose and mouth shape (different from person to person), body and head posture, etc. The exhalation generates jets with relatively high velocity, 1 m s^{-1} and more, which can penetrate the free convection flow around the human body, effectively rejecting exhaled air from the flow or air that may subsequently be inhaled. The exhaled air has a temperature of approximately 34°C and a relative humidity close to 100%. For a seated person performing office work, two independent jets emerging from the nostrils are deflected 30–50° downward from the horizontal axes. The jets flow 20–30° apart and thus do not collapse but diffuse in the room. The mouth opening typically has a larger cross-section area than the nose, thus generating a jet with lower momentum that in a calm environment moves upward.

Inhaled air quality

The most important advantage of PV in comparison with TV is its potential to provide clean, cool and dry air at inhalation. The highest quality of inhaled air will be achieved when the flow of clean and cool personalized air penetrates the free convection flow and reaches an occupant's face unmixed with the surrounding polluted room air and the free convection air, which is typically polluted and warm. In order to achieve this, the potential core region of the personalized flow should be employed. The freedom of occupant's movement and the necessity for a good visual environment requires a relatively large distance between the occupant and the ATD, i.e., a long potential core region with a large cross-section, which can be ensured by a circular jet with uniform velocity field and low initial turbulence intensity. The ATD should allow for changes of airflow direction in order to account for buoyancy effects, i.e., drop of the personalized flow initially directed toward the face, as well as for occupants' preferences.

The interaction of the personalized flow with the free convection flow is the second important consideration for the inhaled air quality. The interaction and the penetration are influenced by many factors: strength of the free convection flow and thickness of its boundary layer, the characteristics of the invading personalized flow (mean velocity, velocity profile, turbulence intensity, direction, temperature, etc.), body posture, shape and height of the body part exposed to the invading flow, clothing design, etc. Personalized flow transverse to the free convection flow has the highest potential to provide clean air at inhalation (Melikov et al., 2003). Personalized flow from highly efficient ATDs (ensuring less mixing of personalized air with the surrounding air) directed against the face with a mean velocity of 0.3 m s^{-1} is able to completely penetrate the free convection flow and to provide 100% clean and cool air in inhalation (Bolashikov et al., 2003). The buoyancy effect (drop in colder personalized flow) may play an important role for penetration. At low room air temperature the free convection is strong and therefore the minimum velocity needed for penetration is high. As will be discussed in the following, this requirement is unfavorable from a thermal comfort point of view since it increases the risk of draught. In this case isothermal personalized flow may perform better. When supplied upward at the chest, i.e., as a flow assisting the free convection flow, clean personalized air is mixed with the warm and polluted free convection air. Thus the inhaled air is diluted but not completely free of pollution. Its temperature is relatively high and this decreases the perceived air quality. In this case the ventilation flow is important: displacement flow will ensure cleaner free convection air (if carpets and other sources do not pollute the air at lower heights) and thus better inhaled air quality. Personalized airflow from above opposing the free convection flow will promote intensive mixing and will decrease the inhaled air quality, unless it is strong enough to peel off the free convection flow. This however, may pose draught discomfort. The location of the pollution source(s), which as already discussed should not be in the vicinity of the personalized flow, is another important factor to be considered.

Personalized flow with a large target area will compensate for occupants' movement at the desk. This, however, requires larger flow rates in order to achieve the minimum velocity needed for penetration. Otherwise the buoyancy effect will dominate and this may decrease the performance of PV. The airflow interaction will affect pollution concentration, temperature and humidity of the inhaled air. It will also generate different velocity at the face region. The impact of air velocity on the inhaled air perception is not completely understood. Minimum air speeds for avoidance of perception of stuffiness still need to be identified (Wyon, private communication). In this respect draught discomfort as well as eye and skin irritation should be considered.

Thermal comfort

The impact of the personalized airflow on occupants' thermal comfort is the second important consideration for design of PV. Human response to air movement is not completely understood although it has been extensively studied mostly under isothermal conditions. Under other identical conditions, the cooling effect of the air movement increases with the increase of the turbulence intensity (Lee et al., 1991). The turbulence intensity is defined as the standard deviation of velocity fluctuations divided by the mean velocity. Therefore the risk of draught discomfort increases when airflow temperature decreases and mean velocity and turbulence intensity increase (Fanger et al., 1988). Local heat loss from the body is influenced by the airflow direction (Mayer & Schwab, 1988). Airflow from the front causes least draught discomfort (Mayer & Schwab, 1988; Toftum et al., 1997). Fluctuating flow may cause draught discomfort at comfortable temperatures and may improve people's thermal comfort in warm environments (Fanger & Pedersen, 1977; Zhao & Xia, 1998; Zhou et al., 2002).

The personalized airflow is defined by its temperature, mean velocity, turbulence intensity, direction and target area size. The skin temperature and the rate of change of skin temperature, i.e., temperature of the cold thermal receptors, determine an occupants' thermal sensation, which therefore depends on the extent to which the free convection flow is penetrated by the invading personalized flow. At comfortable room air temperature a transverse invading flow from the front of the body with a mean velocity as low as 0.1 m s^{-1} will substantially disturb the free convection flow and above 0.2 m s^{-1} will peel it off (Brohus & Nielsen, 1994; Hyldgaard, 1994; Bjørn et al., 1997). Melikov and Zhou (1996) reported that a horizontal isothermal airflow from behind with a mean velocity of 0.1 m s^{-1} and a turbulence intensity of 10% was able to decrease the air temperature near the skin surface by 4°C and to increase the local heat flux by 22%. The minimum air velocity (momentum) needed for the penetration that will ensure a high quality of inhaled air, may cause draught discomfort. Here the temperature of personalized air is important. The results reported by Kaczmarczyk et al. (2004) and recent as yet unpublished results of human subject experiments with highly efficient personalized air terminal devices (performed at the Technical University of Denmark) reveal that in the comfortable range of room air temperature, 23– 26°C, personalized air supplied at 20°C will not cause draught discomfort.

The penetration is easier when room air temperature increases since the strength of the free convection flow around the human body decreases. This will increase the cooling power of the personalized flow. Airflow is preferred when directed against the face and head region (Melikov et al., 1994; Kaczmarczyk et al., 2004). Face and breath cooling improves thermal comfort in a warm environment (Zhang, 2003). Thus the positive effect of transverse flow against the face on both thermal comfort and inhaled air quality will increase with an increase of the room air temperature.

Fluctuating or pulsating personalized flow may improve occupants' thermal comfort due to increased heat loss from the body and overshooting effect in the thermal sensation but it will also promote mixing and thus decrease inhaled air quality.

As already discussed, a personalized flow with a large target area (large outlet) will improve the performance of PV in terms of an occupants' inhaled air quality and free movement at the workstation. It will also improve occupants' thermal comfort, especially in a warm environment (larger surface of the body will be cooled). However, the minimum velocity needed for penetration, i.e., good inhaled air quality, will increase the minimum flow rate from large outlets. This, together with the large target area, will overcool the body in the comfort range of room air temperature, even under isothermal conditions. The impact of the target area size on occupants' thermal comfort (for the whole body and locally) needs to be studied, since it is correlated with the temperature and velocity of the personalized air, which have an impact on airflow interaction and thus on the inhaled air quality. For occupants who are sensitive to air movement, improvement of both inhaled air quality and thermal comfort may be difficult and will require a compromise. Still, even in this case, the possibility for control of temperature, flow rate and direction of personalized air by the occupants makes PV advantageous as opposed to TV.

Protection of occupants and disturbance of room environment

The airflow interaction, i.e., whether the personalized flow is transverse, assisting or opposing the transient flow of exhalation, the free convection flow and the ventilation flow are of major importance for minimizing mixing in spaces and improving the protection of occupants from airborne transmission of infectious agents.

Droplets larger than 1 μm exhaled during coughing and sneezing with high velocity (up to 50 m s^{-1}) spread over short distances. Viruses of sizes from 0.003 to 0.06 μm normally occurring in colonies and bacteria of 0.4 and 0.5 μm can be carried by these droplets. In the case of PV, their traveling time and distance as well as dispersion, drying, etc. can be affected by the airflow interaction. This may be important for transport of diseases between occupants located in close proximity, i.e., vehicle cabins, theaters, etc. The performance of PV in regard to airborne and large-droplet spray transmission of infectious agents remains to be studied.

Non-uniformity in velocity and temperature field and differences in pollution generated in spaces will depend on the airflow interaction as well as the location of pollution sources. Large non-uniformity will result in considerable variation in occupants' exposures.

Control strategies

The possibility for individual control is one of the most important features of PV. Occupants may be provided with control of temperature, velocity (flow rate) and direction of the personalized flow. The benefits of providing control over the temperature have not yet been quantified. An increase in temperature of personalized flow will require an increase in its velocity in order to keep the same convective heat loss from the body. It remains to be studied to what extend the negative effect of increased temperature on perceived air quality may be compensated for by improvement due to increase in velocity. In practice the PV system can be calibrated separately for each occupant. The set point of the personalized air temperature as a function of the room air temperature can be automatically fixed in order to ensure the minimum flow velocity needed for good air quality, i.e., minimum velocity needed for penetration of the free convection flow, without causing draught discomfort. In simple systems a decrease in personalized airflow will usually result in an increase in air temperature due to increased heat gain from the ducting if flow temperature is less than room temperature. A control system can be used to keep the supply air temperature constant. Other control solutions are possible as well.

The PV may be designed to respond automatically and to ensure occupants' thermal comfort under transient conditions, for example due to slow daily temperature variations in rooms as well as fast changes in the thermal environment when occupant is repeatedly leaving and coming back to the desk. Such control, when properly designed, will decrease the time used by the occupant for control and may increase his/her performance. The system can be switched off or operate with a low personalized flow rate when the occupant is not present at the workplace and this may save energy. ATD controlled to follow the movement of occupants at the workplace can be designed. ATD with automatic control of its positioning can be calibrated to account for changes in the direction of personalized flow due to buoyancy effects, thus ensuring clean air in inhalation. Of course any control solution has to be carefully considered and validated in order to ensure occupants' acceptance.

Individual control may be assumed to have a psychological impact on occupants. Occupants' complaints decrease and their satisfaction with the local environment increases when they are provided with individual control (Bauman et al., 1998).

In practice PV will most often be applied together with TV, which can be operated either as constant (CAV) or variable (VAV) air volume system. The control of the coupled systems may be important for both indoor environment and energy savings. This area has not been studied.

Application of PV in practice

Personalized ventilation has been applied for many years in theatres and vehicle cabins, in most cases in order to improve occupants' thermal comfort. It has also been applied in a few office buildings with underfloor ventilation. Technical solutions related to installation of PV in rooms, together with other types of total volume room air distribution, natural ventilation, etc. remain to be developed together with means for localized air-conditioning at each workplace, e.g., thermoelectric personalized air-conditioner, application of binary ice, etc.

Only limited numbers of laboratory studies of the performance of PV in combination with mixing, displacement or underfloor ventilation have been reported in the literature (Bauman et al., 1993; Faulkner et al., 1999; Levy, 2002; Cermak & Melikov, 2003; Melikov et al., 2003; Cermak & Melikov, 2004; Cermak et al., 2004). Bauman et al. (1998) and Kroner and Stark-Martin (1994) reported field studies of individually controlled environments with PV. Several aspects of the combined performance of PV and TV need to be considered when applied in practice: mode of operation of TV system—CAV or VAV mode; levels of acceptable non-uniformity and pollution level in the background environment that will allow for decrease of the ventilation rate, change of the supply air temperature and energy savings; control strategies of the coupled systems, etc. As was discussed, although PV may improve the indoor environment in regard to SBS symptoms, at low room air temperature and low background pollution level improvement in perceived air quality may not be achieved. This may limit its application in practice due to high installation costs. Occupancy rate, i.e., the time occupants stay in room, as well as occupied density, defined as the ratio of time that occupants stay in a certain region over the total time that occupants stay in a room (Zhao et al., 2003) are other important factors for the application of PV in practice. Yang et al. (2004) demonstrated the importance of the occupied density for the performance of PV in practice under different operation modes of TV, i.e., with and without recirculation of room air, etc. Several other factors, such as office furnishing requirements, architectural requirements, etc. may restrict its application in practice.

Design recommendations for personal ventilation

Personalized ventilation is a new development in the field of comfort ventilation. Experience from practical applications is therefore not available. The limited knowledge obtained from laboratory studies is not sufficient to outline procedures for the optimal design of PV in practice. Nevertheless the following recommendations can be made:

- Low turbulent personalized flow has to be applied. Therefore ATDs should generate personalized flow with a uniform velocity profile and low initial turbulence;
- The location of an ATD should aim for use of the initial region of the personalized flow;
- ATDs with as large as possible circular or square cross-section are recommended;
- In order to reach high efficiency the momentum of the personalized flow has to ensure penetration of the free convection flow, i.e., a minimum target velocity of 0.3 m s^{-1}. The individually preferred maximum velocity can be as high as 1.5 m s^{-1}, especially at room air temperatures above 26°C;
- ATDs should allow for control of velocity (flow rate) and direction of the personalized flow. Airflow from the front against the face is preferable;
- PV system with ATDs of high efficiency perform well (no draught discomfort) at room air temperature 23–26°C and a temperature of personalized air that is equal or 3–4°C lower than the room air temperature. The performance at lower and higher room air temperatures remains to be studied;
- Airflow interaction in the vicinity of the occupant should be considered carefully in order to provide occupants with high inhaled air quality;
- PV combined with mixing ventilation is always superior to mixing ventilation alone in regard to both occupants' comfort and protection from infectious agents. The performance of PV with other types of room air distribution needs to be studied.

Future research

For many practical applications personalized ventilation can be advantageous compared with total volume ventilation alone. Research is needed in order to explore the potential of PV and ensure its optimal performance. Some of this research is outlined in the following:

Research related to human response

- Human response to non-isothermal and locally applied airflow. Airflow temperature, velocity, size of the target area, etc. should be parameters.
- Impact of air velocity on perceived air quality. Draught discomfort as well as eye and skin irritation should be part of this research.
- Performance of PV in terms of perceived air quality and draught at the low end of the comfortable room air temperature range (20–22°C) and in terms of draught at room air temperatures above 26°C.
- SBS symptoms and productivity with PV.
- Occupants' response to PV under transient conditions, i.e., room air temperature changes, different seat occupancy rates, etc.

- Occupants' compromise between thermal comfort and perceived air quality.
- Field studies of occupants' response to PV (health, comfort and performance).

Research related to air distribution, applicability and energy

- Development of ATDs with high efficiency.
- Investigation of free convection flow and airflow interaction in the vicinity of the human body, including effects of posture, clothing design, etc. in regard to inhaled air quality and thermal comfort.
- Studies of airflow interaction in terms of the transport of pollution within spaces ventilated by PV coupled with TV (mixing, displacement, low impulse downward air distribution, etc., as well as natural ventilation).
- Studies of airborne transmission of infectious agents and dispersion of large-droplet aerosols exhaled by people as a result of airflow interaction in rooms with PV.
- Research on energy issues related to use of PV alone and in combination with total volume ventilation systems.
- Development of technical solutions for installation of PV in practice, e.g., in rooms with natural ventilation and different total volume air distribution, thermoelectric personalized air-conditioner, etc.
- Development of PV systems with high performance (in regard to health, comfort and protection) for use in crowded spaces such as theaters, cinemas, vehicle cabins.

Research related to controllability

- Development and validation of strategies for the control of PV to optimize occupants' subjective responses and performance.
- Development and testing of technical solutions related to occupants' activity.
- Development and validation of control strategies for coupled systems, i.e., PV coupled with TV.

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