Advanced Ventilation for Better Health

Arsen K. Melikov

Abstract In this paper the need for change of the present practice of building ventilation is discussed. Results on the importance of ventilation for the health of building occupants are presented to justify the need for change of the focus from room ventilation to ventilation for occupants. The present ventilation design based on ventilation rate has to be complimented with ventilation design based on ventilation air distribution. The performance of advanced ventilation methods providing optimal room air distribution is compared with the present mixing ventilation. The importance of proper design of advanced ventilation and its implementation and operation in practice is highlighted. The need for updating the present standards and considering new standards responding to the developed advanced ventilation methods is concluded.

Keywords Ventilation · Health · Mucous layer · Exposure · Design · Occupants

1 Ventilation of Buildings and Health of Occupants

The primary goal of building ventilation is to provide occupants with clean air for breathing. The importance of the ventilation for occupants' health has been documented during the years [1]. Several studies have reported illness and sick leave prevalence reduction with the increase in the amount of clean air, often outdoor air, supplied to occupied spaces (Fig. 1).

Beside the cleanliness of indoor air, its temperature and relative humidity is important for occupants' health and comfort. Therefore often the ventilated air is conditioned in order to maintain room temperature and humidity in comfortable ranges. Figure 2 reveals the importance of air temperature and relative humidity for eye tear film quality. Results reported by Melikov et al. [3] are summarised in the figure. The number of samples of tear film crystallization in the case of healthy eyes (good quality) and unhealthy eyes (bad quality) for 30 subjects exposed to combinations of

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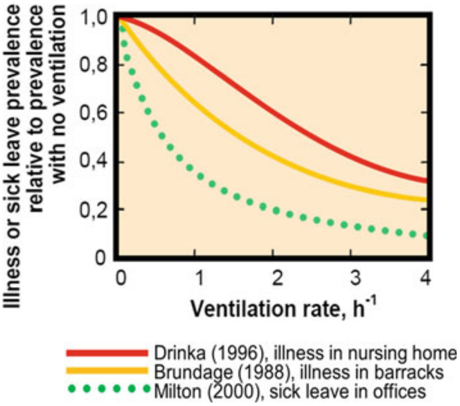
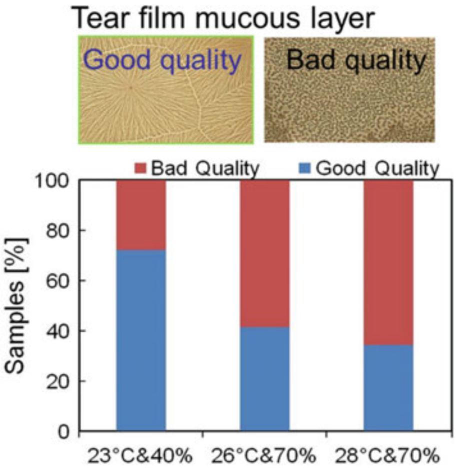
Fig. 1 Positive effect of increased ventilation rate on health [2]



three air temperatures and two relative humidity levels are shown. The results in the figure reveal a decreasing trend in the tear film quality with increase in air temperature and humidity. The percent of tear film mucous layer samples rated as good quality is significantly higher ($P < 0.05$) for the neutral condition (72% at 23 °C) as compared with both higher temperature and humidity conditions (41% at 26 °C and 70%; 34% at 28 °C and 70%).

Fig. 2 Percent of samples with good and bad tear film mucous layer quality collected from 30 persons exposed to different combinations of room air temperature and relative humidity [3]



2 Room Air Distribution and Exposure

In buildings, pollution is generated by numerous sources (building materials, office equipment, occupants, infiltrated outdoor pollution, etc.). Source control is often applied for reduction of pollution generation, e.g. development and use of low pouting building materials. In buildings occupants are a major source of pollution. Human body is source of bio-effluents (odours), particles emitted as a result of hair breakage and shedding of epidermal cells, aerosols of different size in the exhaled air, skin oil and its oxidation products, etc. Most of the generated pollution is airborne and is transported by the airflows around the human body and in the rooms. Therefore, air distribution around human body and in rooms is of major importance for exposure of occupants to the generated pollution. The air distribution in rooms is the result of a complex interaction of flows including the free convection flow that exists around the human body and the thermal plume above the body, the transient flow of breathing, the supplied ventilation airflow, buoyancy flows generated by warm/cold objects and surfaces such as window surfaces, office equipment, etc. Figure 3 illustrates an example of possible in practice interaction of a supplied ventilation flow with an upward buoyancy flow generated by the occupant and warm window. The complex airflow interaction in spaces changes in time due to changes in strength and location of heat sources, occupants' movement, etc. Therefore, often the airflow distribution and transport of pollution in occupied spaces is not in steady state. Thus, the exposure of occupants to indoor generated pollution is not constant and often its determination is not accurate.

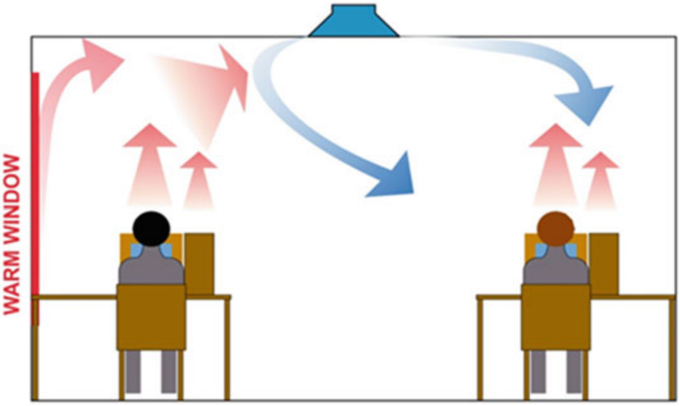


Fig. 3 The interaction of room airflows changes in time and affects occupants' exposure to the indoor environment

3 Present Ventilation Practice

At present mixing air distribution (known also as ventilation by dilution), is most commonly applied in practice [4]. This air distribution strategy is inefficient (Fig. 4). Some of the reasons are: the clean and conditioned air is supplied far from occupants and is mixed with the warm and polluted room air (can carry germs exhaled by sick people) when it reaches the occupants; it is difficult to remove pollution at the source location (occupants, building materials, office equipment, etc.) before it is mixed with room air; often the air distribution pattern enhances the transport of pollution generated outside of the occupied zone (e.g. from wall surfaces, etc.) into the occupied zone; temperature, velocity and contaminant distribution in spaces are determined by the complex flow interactions that are difficult to control; cleaning, conditioning and transportation of huge amount of supply air is needed to ventilate the entire volume of spaces (including unoccupied areas!) and this increases the energy use; large air handling units and bulky duct systems that take space and increased initial costs are used; flexibility in space use is curtailed; the aim is to achieve uniform temperature and velocity in the occupied zone and the environment is designed for an "average occupant" while in reality large differences exist between people with regard to the preferred environment; uniform environments may not be preferred by many people, etc. [5]. In many buildings, the quality of the indoor environment is mediocre even though the ventilation is performing as intended. This is frustrating for engineers and a challenge for the HVAC industry.

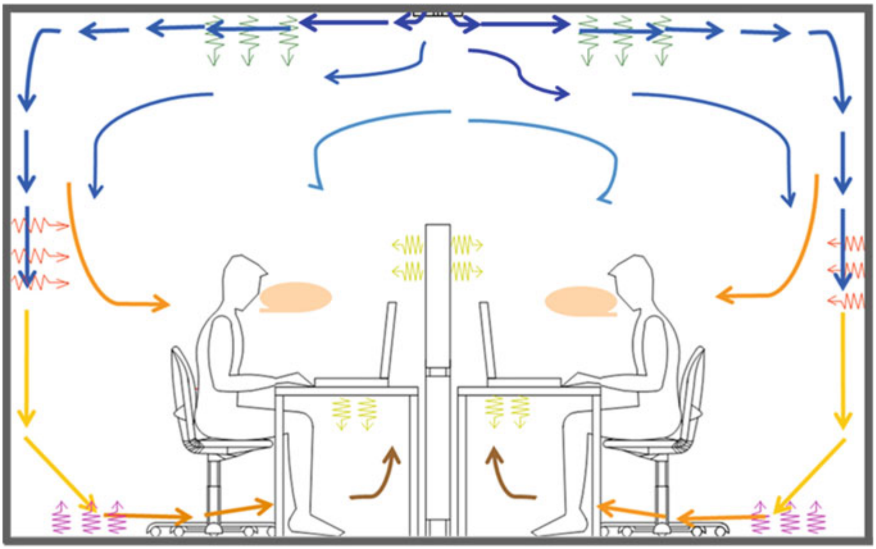


Fig. 4 In rooms with mixing ventilation the distribution of supplied clean ventilation air is not efficient

4 Present Ventilation Design Practice

The first step in the ventilation design is to determine the amount of clean air supply needed to ensure certain air quality level in spaces. For this purpose the ventilation rate is calculated. Comfortable thermal environment is maintained by conditioning and/or increase of the supplied air, use of radiant systems, elevated air movement at high room temperatures (e.g. use of cooling fans), etc. Energy use is also of concern, though often the required indoor environment is achieved by increase of the supplied ventilation air instead of pollution (contaminants and heat) control.

One of the methods for calculation of the ventilation rate is based on the perceived air quality (PAQ) by the occupants [6]. Typically occupants are the major (only) source of CO_2 in spaces. CO_2 is easy to measure. It is used as a proxy of room generated pollution assuming complete room air mixing (often not present in rooms in practice!). The ventilation rate that will ensure CO_2 concentration in occupied space at a certain level above the outdoor CO_2 concentration is calculated. The CO_2 concentration levels correspond to categories of indoor environment (three or four categories) defined by different percent of occupants dissatisfied with the perceived air quality. However, this procedure is based on the impact of indoor pollution on perceived air quality without taking into account the impact of the temperature and humidity of the inhaled air. Research has documented that increase of the inhaled air temperature and relative humidity has negative impact on the PAQ [7]. Warm and humid clean air is perceived as unpleasant while cool and dry polluted air may not be perceived as unpleasant. The importance of air movement for the PAQ is not considered in the standards either. It is documented that acceptability of PAQ and freshness of the air improved when air movement from front, i.e. against the face, is applied [8]. The elevated air movement diminishes the negative impact of increased air temperature, relative humidity and pollution level on PAQ. The degree of improvement depends on the pollution level, the temperature and the humidity of the room air. At a low humidity level of 30% an increased velocity could compensate for the decrease in perceived air quality due to an elevated temperature ranging from 20 to 26 °C (Fig. 5). The study also reports that at air temperature of 26 °C, increased air movement is able to compensate for an increase in humidity from 30 to 60%, but not to 70%. The elevated velocity of recirculated polluted room air (by a cooling fan) does not decrease the intensity of SBS symptoms, but the movement of clean, cool and dry air does. Energy-saving strategy of improving occupants' comfort in rooms by moving room air at high velocity and maintaining room temperature high at reduced supply of outdoor air or by a decrease of indoor air enthalpy should be cautiously implemented in buildings because the pollution level may still cause negative health effects.

The above discussion makes clear that the indoor air quality requirements in the present standards based on perceived air quality are incomplete and need to be updated.

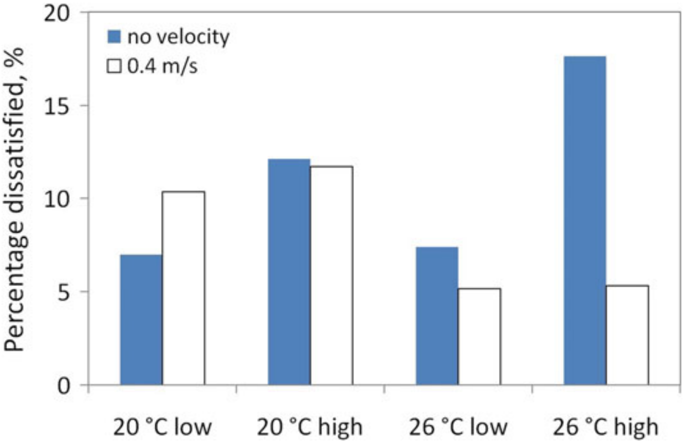


Fig. 5 Percentages dissatisfied people with PAQ exposed to still air (velocity <0.05 m/s) and air movement from front (velocity 0.4 m/s) at combinations of air temperature (20 and 26 °C) and pollution level (low and high); 30% relative humidity

5 Next Development: Advanced Ventilation

Achieving high indoor air quality at reduced energy consumption is an important goal of the ventilation design. Increase of the ventilation rate is suggested in the standards and the guidelines in order to improve indoor air quality. In the case of the present mixing ventilation (ventilation by dilution), the increase of the ventilation rate will dilute the indoor pollution, will reduce its concentration and will improve inhaled air quality but the energy used for conditioning and transportation of the ventilation air will increase. The energy use will decrease if the ventilation rate is reduced but this will lead to decrease of the indoor air quality. Thus, in the case of mixing ventilation the energy saving strategy based on reduction of clean ventilation air is dangerous because it will affect occupant's health negatively and will decrease their work performance.

Are indoor environment designers really at crossroads? Is it possible to design an indoor environment that improves health, comfort, performance and saves energy compared to our present practice? This would create shared values for employees, in terms of their well-being and comfort, for employers, in terms of increased performance and reduced energy use, and for society, in terms of fewer sick leave days, decreased healthcare costs, and energy conservation. However, for the reasons discussed in the previous section, it is not possible to achieve such a win–win solution with the present mixing ventilation strategy. A new approach in the indoor environment design is needed. Clean air distribution instead of ventilation rate and micro-environment around each occupant instead of the entire room should be in the focus. More advanced heating, cooling, and ventilating methods and technological solutions must be developed. Ventilation design should focus on advanced air distribution based on the following main principles [5]: remove/reduce the air pollution and the generated heat (when not needed) locally; provide clean air, also heating and cooling (where, when, and as much as needed), make possible active control of the air distribution; involve each occupant in creating his/her own preferred microenvironment, reduce energy use. The development of advanced air distribution methods has already started. Several solutions have been reported in the literature and some of them have been implemented in practice. In the following sections of the chapter, the performance of two advanced air distribution methods, namely displacement ventilation and personalised ventilation will be compared with the performance of mixing ventilation.

6 Displacement Ventilation: Impact of Occupant Activities

Displacement ventilation aims at replacing polluted room air without mixing with the supplied clean ventilation air. Typically the clean and cool ventilation air is supplied with low velocity from relatively large diffusers located on the wall near to the floor. Compared to mixing ventilation the use of displacement air distribution for comfort ventilation is relatively new. It has been studied intensively during the last 35–40 years. Detail description on its performance under different conditions, most of them steady-state conditions, is provided in the literature [9]. The performance of displacement ventilation under non-steady state conditions, e.g. moving room occupants, has been studied little. It follows the performance of displacement ventilation and mixing ventilation is compared with regard to airborne cross-infection (e.g. COVID 19) based on results from physical measurements under realistic conditions in a room with walking persons [10]. An office room with two workstations was arranged in a full-scale test room. Two breathing thermal manikins (body size of average Scandinavian woman) were used as sedentary occupants at the workstations. Tracer gas was added to the air exhaled by one of the manikins simulating infected occupant. The tracer gas concentration in the inhaled air was measured without the walking person in the room and with one and two walking persons. In the case of walking persons in the rooms, three possible practice situations were studied: person walking along the desks on the side of the air supply diffuser, person walking along the desks on the side opposite to the diffuser and two walking persons along the desks—one on the desk side near the diffuser and one on the side opposite to the diffuser (Fig. 6). During the experiments 80 L/s of the treated outdoor air at 20 C was supplied to the room by the DV, aiming at an exhaust air temperature of 26 °C. Details of the experiments are reported by Halvoňová and Melikov [10]. In the following the focus is on assessment of airborne transmission.

Figure 7 shows the concentration of the tracer gas exhaled by the front (infected) manikin in the air inhaled by the manikin seated behind (simulating occupant exposed to the infected air exhaled by the front manikin). The inhaled tracer gas concentration normalized to the case of complete mixing room air distribution is shown. The

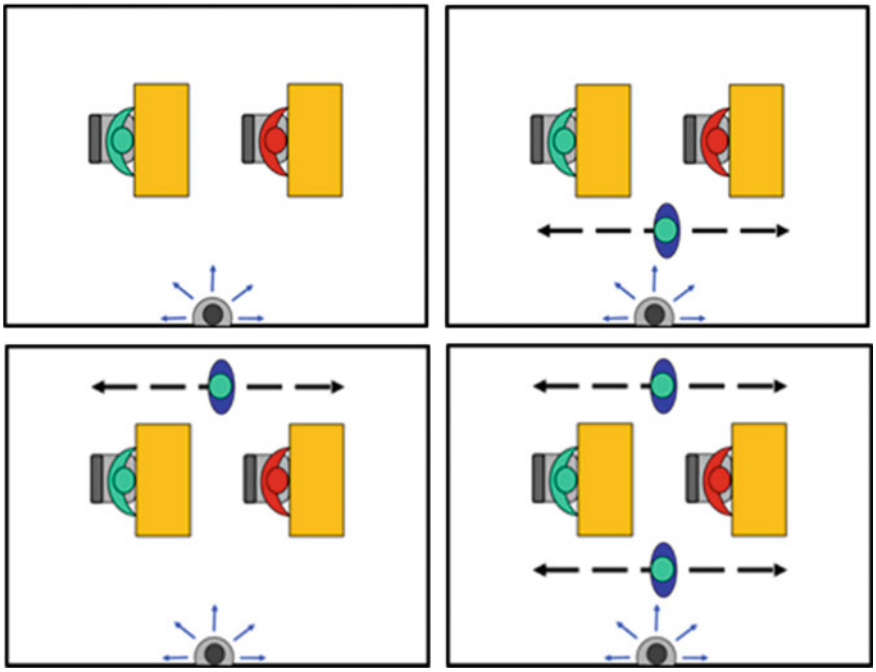


Fig. 6 Studied cases: without walking person; one walking person along the desks on the side of the air supply diffuser; one person walking along the desks on the side opposite to the diffuser; two walking persons along the desks—one on the desk side near the diffuser and one on the side opposite to the diffuser. The manikin simulating infected occupant exhaling tracer gas is seated in front (indicated with red colour)

results are expected and reveal that first, under steady-state conditions (i.e. without moving person), the normalized concentration with displacement ventilation is much lower compared to complete mixing ventilation, i.e. the air inhaled by the exposed manikin is much cleaner with displacement ventilation than with mixing ventilation and second, the walking person causes air mixing and disturbs the superior performance of the displacement ventilation.

In practice the activity of the room occupants is different. In some rooms walking occupants are present often while in other rooms they do not. It is documented that in rooms with displacement ventilation the flow disturbed by the walking person is re-established in a short time after the walking event. The intake fraction (iF) index defined as the ratio of the mass intake of the infected air to the mass exhaled infected air (%) introduced by Bennett et al. [11] is used to assess the impact of the walking person on airborne cross-infection. The iF is calculated for the results presented in Fig. 7 assuming four hours of work for two seated occupants and 10 min walking event (one or two other occupants) during each hour. The results are shown in Fig. 8. The results reveal that the intake fraction for the all studied conditions with displacement ventilation is much lower than in the case of complete mixing.

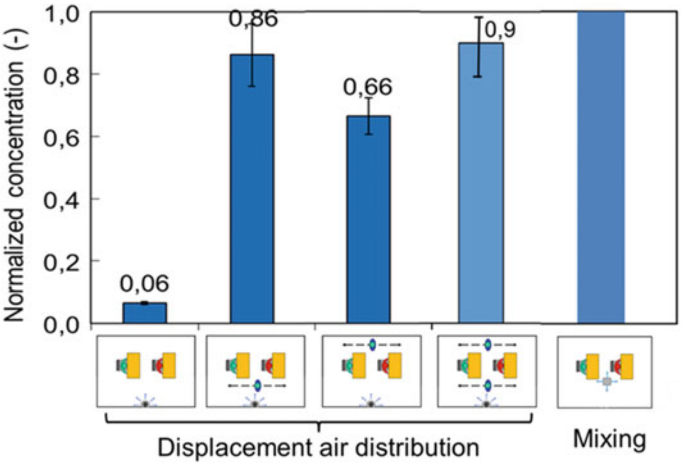


Fig. 7 Impact of disturbance due to walking person on the performance of displacement ventilation

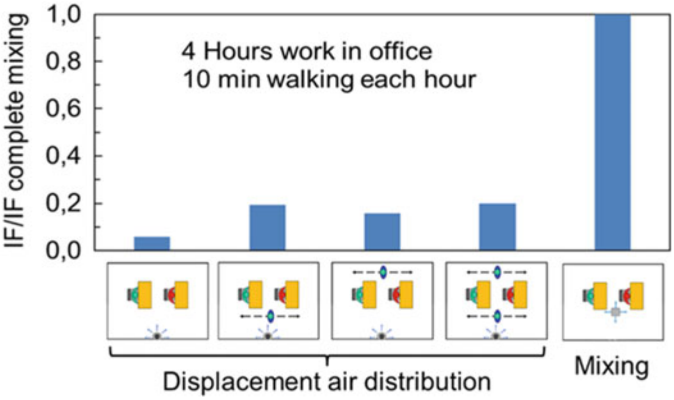


Fig. 8 Impact of walking on the intake fraction

Thus, with regard to airborne transmission displacement air distribution is superior to mixing air distribution.

7 Personalized Ventilation

Personalized ventilation (PV) is an advanced air distribution method aiming at clean air supply close to the breathing zone of the user [12]. Figure 9 shows the principle of the desk installed in personalized ventilation. The user can control the direction and the flow rate of the supplied personalized air and in some cases its temperature and

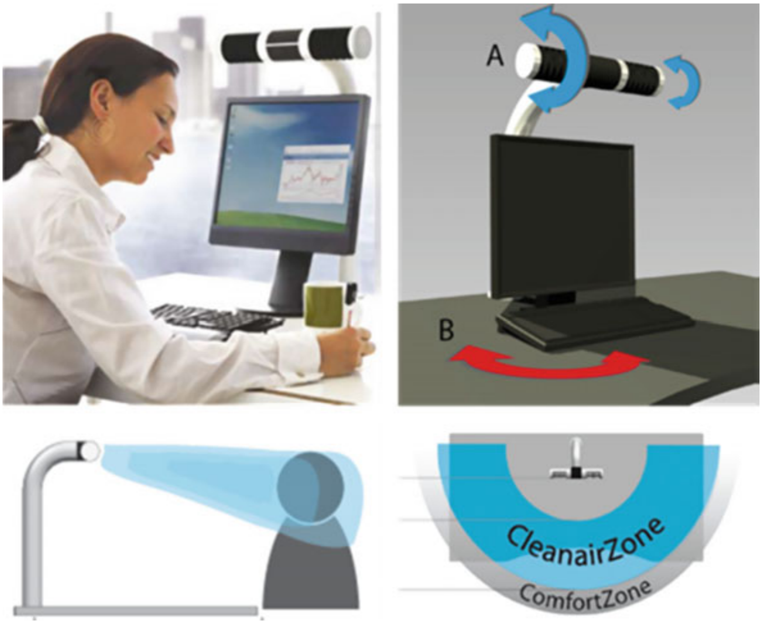


Fig. 9 Desk installed personalized ventilation (curtesy to Exhausto AS, Denmark)

humidity. The characteristics of the supplied flow (e.g. entrainment of the surrounding polluted room air, spread of the jet, etc.) can be controlled by use of air supply diffusers of different designs or by changing the initial characteristics of the supplied flow (velocity distribution, turbulence intensity, etc.). In offices, PV is typically used in conjunction with total volume ventilation [13–15] as well as radiant cooling/heating systems such as chilled ceiling, etc. [16].

Numerous human subject studies have documented that the use of PV reduces SBS (Sick Building Syndrome) and eye symptoms and improves users' perceived air quality, thermal comfort, and performance [3, 17]. Recommendations for design and implementation of PV in practice have been suggested as well [12].

The use of PV is recommended in the recently developed guidelines for reduction of airborne transmission of COVID 19 [18, 19]. Its efficiency is due to breathing clean personalized air before it is mixed with the polluted (infected) surrounding room air. With regard to reduction of airborne transmission the performance of PV is compared with the performance of mixing ventilation in Fig. 10. The reproductive number, defined as a number of secondary infections that arise when a single infectious case is introduced into the population where everyone is susceptible is used [20]. The details of the calculations are presented by Cermak and Melikov [21]. The reproductive number in the case of influenza virus is calculated in the case of an office with ten occupants who work together for eight hours. The calculations include data from physical measurements and available data on characteristics of the influenza virus. Results of clean air supply at a ventilation rate of 10 L/s per

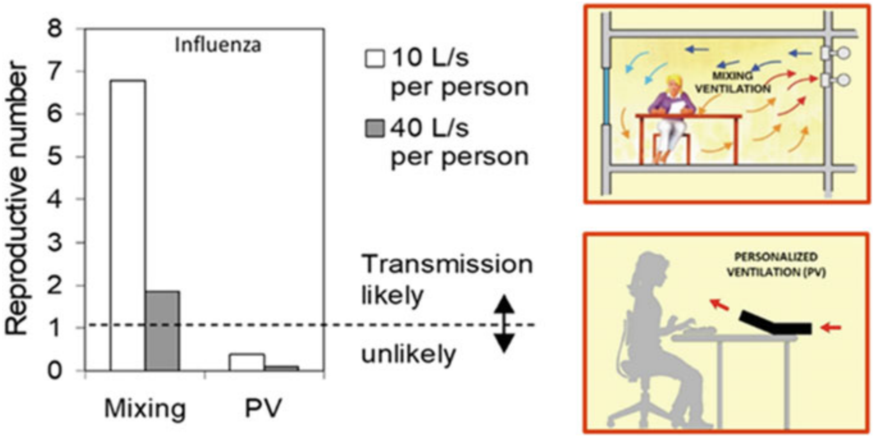
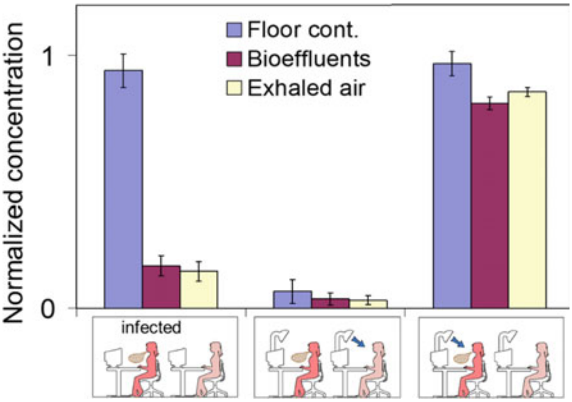


Fig. 10 Reproductive number in the case of office with one infected and nine susceptible occupants working together for 8 h. The reproductive number in case of mixing ventilation and personalized ventilation at two ventilation rates 10 L/s per person and 40 L/s per person is compared [21]

person (as recommended in the present standards [6] as well as four times higher ventilation rate (40 L/s per person) are compared in the figure. It can be seen that in the case of mixing ventilation four times increase of the ventilation rate decreases the number of secondary infections, yet it is likely that at the end of the day, i.e. after eight hours, two occupants will be infected. On contrary, the use of personalized ventilation makes the airborne transmission unlikely already at 10 L/s per person.

The optimal performance of PV depends on its design and proper implementation in practice. The design recommendations are suggested by Melikov [12]. The performance of PV when implemented in practice under different conditions has been studied as well [10, 13]. Figure 10 summarises some of the results on exposure of the occupants to indoor pollution in the case of PV combined with displacement ventilation as reported by Cermak et al. [13]. The experimental conditions described in [13] can be summarised as following: a full scale test room with two breathing thermal manikins is used to simulate the office with two occupants; different tracer gases are used to simulate pollution generated at floor level (e.g. carpet), body bio-effluents (odour) and infected exhaled air. The arrangement in the office is shown in Fig. 11. The body bio-effluents and infected exhaled air are generated by the manikin seated in front, i.e. polluting manikin (indicated with red colour). Results from three studied scenarios are compared: (1) displacement ventilation operates alone; (2) displacement ventilation is combined with PV used only by the manikin in the back (exposed manikin); (3) displacement ventilation is combined with PV used by the manikin in front (polluting manikin). In total, 80 L/s of clean air (= 4.3 air changes per hour) is supplied either by the displacement ventilation when operating alone or the air is distributed between the personalized ventilation (15 L/s) and the displacement ventilation (65 L/s). The temperature of the air supplied from both personalized and displacement ventilation is fixed at 20 °C. The normalized concentration shown in

Fig. 11 Exposure to floor pollution, body bio-effluents and exhaled air in the case of displacement ventilation alone and in combination with personalized ventilation



the figure is the ratio of the tracer gas concentration in the air inhaled by the exposed manikin minus the tracer gas concentration in the supplied air divided by the tracer gas concentration at the exhaust room air minus the trace gas concentration in the supplied air. For the first scenario when displacement ventilation is used alone the exposure to floor generated pollution is high since the clean air supplied near the floor is mixed with the floor generated pollution and is transported to the breathing zone by the free convection flow around the manikin's body. However, the exposure to the bio-effluents and the exhaled air is low. The use of PV by the exposed manikin in addition to the displacement ventilation (scenario 2) leads to very low exposure to the three pollutions. However, the exposure to the three pollutions increases dramatically when the polluting manikin uses its PV but the PV of the exposed manikin is not used. In this case the personalised flow mixes the pollution generated by the polluting manikin with the room air and thus the exposed manikin inhales polluted room air. The results reveal that when PV is implemented in practice its operation has to be considered carefully in order to obtain optimal performance.

8 Concluding Remarks

The issues discussed in this paper reveal that with the used at present mixing ventilation it is not possible to provide room occupants with high inhaled air quality at reduced energy use. There is need to move the focus from design of room ventilation to ventilation design for occupants. For this purpose the design based on ventilation rate has to be complemented/replaced with design based on ventilation air distribution. Advanced ventilation methods for clean (disinfected) air distribution need to be developed. The methods, when implemented in practice, have to improve inhaled air quality at reduced energy consumption compared to the used at present mixing ventilation. The advantage of this approach is the possibility for implementation of smart control based on the individual needs and activities of each occupant. Development of design guidelines and recommendations for the practical implementation of advanced air distribution methods is important in order to ensure their optimal performance. Advanced ventilation methods based on the existing ventilation systems (air handling unit, ducting system, etc.) but improved room air distribution are easy to be implemented.

The future development of advanced ventilation providing non-uniform clean air distribution in rooms requires substantial revision of the present indoor air quality/ventilation standards based on the assumption of complete room air mixing. Specific requirements for design, implementation and operation of the advanced ventilation methods has to be included in the standards.

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