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Control of airborne infectious diseases in ventilated spaces

Peter V. Nielsen*

Department of Civil Engineering, Aalborg University, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark

We protect ourselves from airborne cross-infection in the indoor environment by supplying fresh air to a room by natural or mechanical ventilation. The air is distributed in the room according to different principles: mixing ventilation, displacement ventilation, etc. A large amount of air is supplied to the room to ensure a dilution of airborne infection. Analyses of the flow in the room show that there are a number of parameters that play an important role in minimizing airborne cross-infection. The air flow rate to the room must be high, and the air distribution pattern can be designed to have high ventilation effectiveness. Furthermore, personalized ventilation may reduce the risk of cross-infection, and in some cases, it can also reduce the source of infection. Personalized ventilation can especially be used in hospital wards, aircraft cabins and, in general, where people are in fixed positions.

Keywords: airborne disease; cross-infection; ventilated spaces; room air distribution; indoor environment

1. INTRODUCTION

More and more people are spending many hours in an indoor environment. It is important to minimize the amount of pollutants that people are exposed to in order to provide a good air quality, and to minimize the danger of cross-infection in hospital wards, aircraft, buses, trains and everywhere where people are together. The cross-infection problem was clearly demonstrated in the worldwide severe acute respiratory syndrome (SARS) outbreak in 2003 (Li *et al.* 2004*a*,*b*), where it was shown that the danger was especially pronounced in the hospital environment (Li *et al.* 2004*a*; Qian *et al.* 2007). A further discussion of the importance of an effective ventilation system, and the possibility to protect people from airborne infection was given in a literature review by Li *et al.* (2007), where it was concluded that there is strong and sufficient evidence of a connection between ventilation and control of air-flow directions in buildings and the transmission and spread of infectious diseases such as measles, tuberculosis (TB), chicken pox, anthrax, influenza, smallpox and SARS.

When cross-infection and ventilation systems are discussed, it is important to categorize the different principles (table 1). Mechanical ventilation and natural ventilation are two different principles for the supply and distribution of the air into a building. Mechanical ventilation can support all the room air distribution principles mentioned in this article, while natural ventilation often generates a room air distribution that can either be described as mixing flow or as displacement flow. Mixing flow occurs if the temperature difference between indoors and outdoors is small and the flow rate is large. A large temperature difference and a small flow rate generate displacement flow. This article covers the movement of airborne infection in the room air distribution in both types of air supply systems. All situations discussed in this article are cases where the room or the hospital ward is cooled by the air from a ventilation system.

Different air-distribution systems such as mixing ventilation, vertical ventilation and displacement ventilation offer different possibilities in the protection of people from airborne pollutants. The pollutants are almost fully mixed in the occupied zone in a room ventilated by mixing ventilation or vertical ventilation, and they are removed by a diluting process (Nielsen 2007). If the source of pollution is also a heat source, then displacement ventilation offers possibilities to work with two zones, a low zone with clean air, and an upper zone with pollutants. It is possible to design a system with low exposure of people as discussed by Skistad *et al.* (2002), but in certain situations both a very low and a high exposure may also exist in rooms with displacement flow as shown by Bjoern & Nielsen (2002) and Qian *et al.* (2004).

Flow with displacement effect can also be obtained in a room ventilated by ceiling-mounted diffusers with large inlet areas. The air distribution in the room is mainly controlled by buoyancy forces from the heat sources, but the flow from the terminal can be characterized as a displacement flow with a downward direction in areas without thermal load. The displacement flow, which exists in different areas of the room, may indicate the possibility of obtaining improved protection in those areas, but the effect is not very large (Nielsen *et al.* 2007*a*).

*pvn@civil.aau.dk

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Table 1. Air supply systems and air-distribution systems.

ventilation systems	room air distribution systems
mechanical ventilation	mixing ventilation vertical ventilation displacement ventilation personalized ventilation
natural ventilation	mixing ventilation displacement ventilation

A reduction of cross-infection can be obtained by personalized ventilation (PV). Experiments with PV together with vertical ventilation from ceiling-mounted terminals show an increased efficiency of personal protection from a factor of 5 up to 35 (Nielsen *et al.* 2007*a*,*b*, 2008*a*). PV systems have been intensively studied during recent years (see Melikov *et al.* 2002, 2003; Melikov 2004).

2. SIMULATION OF CROSS-INFECTION IN BUILD ENVIRONMENT

This article describes the cross-infection caused by the movement of airborne particles (bacteria and viruses) in room air flow, and how the problem can be minimized and eventually be controlled by the ventilation system and the air-distribution systems.

The experiments are carried out by tracer gas. Tracer gas is not influenced by buoyancy, and the results are therefore only valid for the situation where bacteria and viruses are transported on droplets (droplet nuclei) smaller than 5–10 μm. Droplet nuclei smaller than 5 μm exhibit a settling velocity below 1 m h^{-1} in still air, and can therefore follow a person's exhalation flows and the ambient air flows in, for example, a hospital ward. Large droplets are also part of the cross-infection process, but they settle either on surfaces close to the source of the infection, or evaporate, decrease in size and follow the air flow as droplet nuclei. Tracer gas is therefore especially useful for simulation of the movement of airborne infection at large distances outside infected people's microenvironment. Furthermore, the transport of fine particles is important because they may be much more readily inhaled than coarser particles as shown by Wells (1955).

Tracer gas concentration cannot be directly used as a measure of health risk, but it can give an indication of this risk. The health risk can be estimated from the Wells–Riley model which, among other things, gives a link between the concentration in a person's inhalation and the connected risk of infection (Riley *et al.* 1978; Qian *et al.* 2006*b*). All the measurements and discussions in this article are based on steady-state conditions; however, the Wells–Riley model will introduce the time as a parameter, as, for example, the number of infected cases over a period of time.

All the experiments described in this article have also been made in a test room without people in motion. The activity level in the room will, in practice, have a great influence over the concentration distribution in the room, and it is found that mixing ventilation is considerably more robust in this respect compared with displacement ventilation (Brohus *et al.* 2008). Door opening can also disturb the concentration distribution in the room (see Tang *et al.* 2005).

The cross-infection process based on transport of tracer gas through the air, and the effect of the different air-distribution systems and source level can be explained from figure 1. The figure shows, as an example, a situation in a hospital ward with a source patient (manikin S) and a target patient (manikin R). The source has the level of S and represents the respiratory activity of a potentially infectious patient, or related medical procedures such as the use of nebulizer. The source does not represent the effect of coughing, as mentioned later. The target manikin inhales a concentration expressed by c_{exp}, $c_{\mathrm{exp,PV}}$ or $c_{\mathrm{exp,tot}}$. The room is supplied with an air-flow rate of q_o and the concentration in the exhaust of the room c_{R} is thus

$$c_{\mathrm{R}} = \frac{S}{q_o}. \tag{2.1}$$

The ventilation index at the position of manikin R's inhalation zone ε_p is

$$\varepsilon_p = \frac{c_{\mathrm{R}}}{c_p}, \tag{2.2}$$

where c_p is the concentration in manikin R's breathing zone. A ventilation index larger than 1 means that the air in manikin R's breathing zone is less contaminated when compared with the exhaust concentration, and an index smaller than 1 means that the air is more contaminated than the exhaust air. The ventilation index is close to 1 for many air-distribution systems which indicates full mixing, but it can be higher, for example displacement ventilation, and sometimes also smaller than 1 under disadvantageous conditions as discussed later, for example, for displacement ventilation. Equation (2.2) is only valid for steady-state conditions. Disturbances as walking, opening and closing of doors, using electronic equipment with fan cooling will reduce ε_p to a value close to 1 as long as they are occurring.

The concentration c_p is also the concentration c_{exp} in the target patient's (manikin R) inhalation. From equations (2.1) and (2.2) it is possible to show that c_{exp} is equal to

$$c_{\mathrm{exp}} = \frac{1}{q_o} \cdot \frac{1}{\varepsilon_p} \cdot S. \tag{2.3}$$

The use of PV for the target patient (manikin R) leads to a definition of a personal exposure index $\varepsilon_{\mathrm{exp,PV}}$ with respect to the PV system, where $c_{\mathrm{exp,PV}}$ is the inhaled concentration with PV:

$$c_{\mathrm{exp,PV}} = \frac{1}{q_o} \cdot \frac{1}{\varepsilon_p} \cdot \frac{1}{\varepsilon_{\mathrm{exp,PV}}} \cdot S. \tag{2.4}$$

If the PV system influences or modifies the flow field established by the general air distribution system (mixing system, displacement system, etc.), the

Figure 1. Two patients (life-size manikins) in a hospital ward. One patient is the source of airborne infection, and the other patient is the target.

expression for the exposure is given by

$$c_{\mathrm{exp,tot}} = \frac{1}{q_o} \cdot \frac{1}{\varepsilon_{\mathrm{exp,tot}}} \cdot S. \tag{2.5}$$

In the case of steady state, equations (2.3)–(2.5) show that the concentration of any airborne infection from the source manikin can be reduced by

(i) using high ventilation rate q_o to dilute the infected particles to a low level of concentration;
(ii) using high ventilation index ε_p in the patients' occupation zone;
(iii) working with PV which has a high exposure index $\varepsilon_{\mathrm{exp,PV}}$ or $\varepsilon_{\mathrm{exp,tot}}$; and
(iv) reducing the contaminant emission S of the source.

Disturbances may, while they are occurring, reduce the ventilation index to a value close to 1. In all, it is most efficient to work with systems that both can handle a high flow rate and have a high ventilation index. It is also efficient to work with PV and to reduce the emission source of the disease. These ideas are addressed in the following four sections.

3. HIGH VENTILATION RATES

The importance of high ventilation rates, in the form of fresh air in a hospital ward and in other indoor environments, has been considered for many years. Benjamin Franklin (1970) writes to a friend about observation of the spread of influenza, and Florence Nightingale (1860) writes in *Notes on Nursing*: 'The very first canon of nursing . . . is this . . . to keep the air he breathes as pure as the external air, without chilling him'.

A traditional treatment of TB was to keep the patients in open air during the daytime (Cook 1999). This treatment was given because fresh air was considered to be healthy. It also had the effect that there was a low concentration level of infection in the surroundings, corresponding to an extremely high level of the ventilation rate q_o. Figure 2 shows a building for open-air treatment.

Most air-distribution systems create a complete mixing in rooms. Some systems will be more suitable for high flow rates than others. Traditional air-distribution systems distribute the air in the room by adding a high momentum flow from the supply openings. The openings are relatively small, and the jets from the openings have a high velocity in the first part of the flow. The system is designed so the jets

Figure 2. Balcony for 'open-air treatment' of pulmonary diseases in a former TB hospital (Skoerping, Denmark).

decelerate outside the occupied zone. A momentum-controlled system must in many cases have a limited air flow rate because of draught, which is generated by this type of air distribution.

Some systems with a large supply area only generate a low level of draught in rooms. These systems are suitable for high flow rates; however, even with such a system there will be draught if the heat loads in the rooms are high, although this is not a typical situation in hospital wards.

Qian *et al.* (2006*b*) have worked with the dispersion of droplet nuclei in a two-bed hospital ward with three different ventilation systems. The experiments were made in a room of the size 4.2 m (length), 3.6 m (width) and 2.5 m (height). The room was equipped like a hospital ward with two life-size thermal manikins lying in beds as source S and target R as shown in figure 1. Tracer gas was used as the airborne pollutant. The three systems are shown in figure 3. Figure 3*a* shows a traditional mixing ventilation system with a supply opening in the wall; figure 3*b* shows a vertical ventilation system with three diffusers in the ceiling and figure 3*c* shows a vertical ventilation system with a large ceiling-mounted supply opening (textile terminal). All three systems show a personal exposure index $\varepsilon_{\mathrm{exp}}$ for the target manikin which is about 1, so all systems could be considered as systems with a high level of mixing ventilation effect at air flow rates of 6–12 h^{-1}.

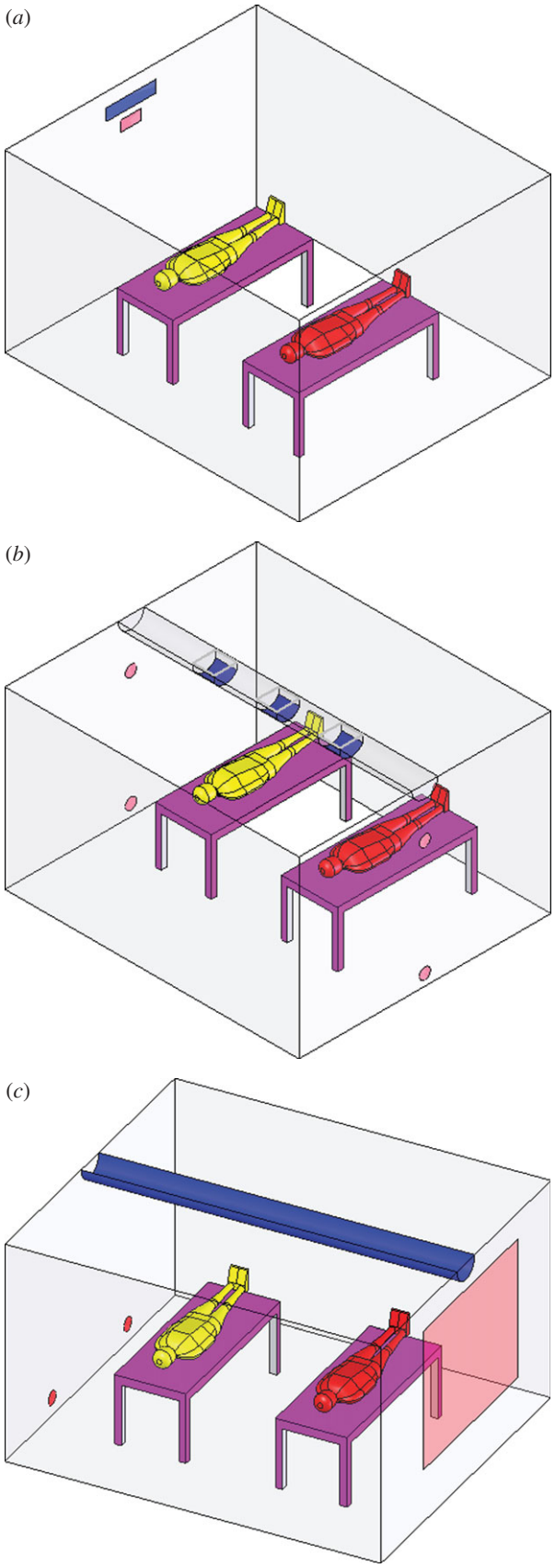

Figure 3. (*a*) Mixing ventilation from a wall-mounted diffuser, (*b*) vertical ventilation from three ceiling-mounted diffusers and (*c*) vertical ventilation from a large textile terminal.

Using the same air-distribution systems for examining thermal comfort, Nielsen (2007) shows that the mixing ventilation system in figure 3*a* creates draught at the floor level of $0.15\ \mathrm{m\,s^{-1}}$ at a flow rate of $q_o = 0.075\ \mathrm{m^3\,s^{-1}}$ ($7\ \mathrm{h^{-1}}$). However, if the heat load is small, which is often the case in a hospital ward, the system in figure 3*c* can handle very large flow rates, q_o approximately $0.20\ \mathrm{m^3\,s^{-1}}$ (approx. $19\ \mathrm{h^{-1}}$), without creating draught. This is a very important difference. If, for example, the source patient continuously emits 3000 droplet nuclei per second, then the concentration in the room is 40 000 droplet nuclei $\mathrm{m^{-3}}$ in the first case (figure 3*a*) and <15 000 droplet nuclei $\mathrm{m^{-3}}$ in the last case (figure 3*c*). This emphasizes that it is important to consider the draught generated in different systems in the dimensioning of the maximum air flow rate to a room.

Although the flow in the room is a fully mixed flow with an exposure index of approximately 1 in the occupied zone, a low value of $\varepsilon_{\mathrm{exp}}$ is obtained if there is a short distance between the source manikin and the target manikin. Nielsen *et al.* (2008*b*) have shown that a pollutant takes a short cut in the microenvironment around persons if the distance between two standing persons is smaller than 1.20 m, and the exposure index decreases to 0.25–0.5 at a distance of 0.4 m between the manikins, at normal breathing. The probability of cross-infection increases if the source manikin (person) has an increased breathing frequency, is speaking, or especially if the source manikin (person) is coughing (Badeau *et al.* 2002).

Figure 4 shows a visualization of the flow from a thermal manikin that simulates breathing and coughing. Figure 4*a* depicts the flow 2 s after start of the exhalation cycle through the mouth. The direction is influenced by the thermal boundary layer around the manikin and the temperature of the exhalation. The surroundings have a constant temperature and an insignificant air velocity. Figure 4*b* shows the flow 2 s after exhalation through the nose has started. The peak velocity in the exhalation from the mouth will be about $0.5\ \mathrm{m\,s^{-1}}$ at a horizontal distance of 0.5 m, while it will be much smaller when the exhalation is through the nose. The flow from the nose consists of two jets, which will decrease the velocity level compared with the flow from the mouth. Entrainment into the jets will decrease the level of virus in both cases if the breathing manikin in figure 4 is the source.

A person's outbreak of a disease is often combined with coughing. Figure 4*c* shows the flow when the manikin is coughing. In this case the velocity level is much higher, up to several metres per second at a distance of 0.5 m from the face. Coughing might in many cases be the right way to describe the boundary conditions in experiments and computer simulation of airborne cross-infection.

Downward-directed ventilation systems are recommended by several guidelines for isolation rooms (CDC 1994; ASHRAE 2003). The guidelines for preventing the transmission of *Mycobacterium tuberculosis* in healthcare facilities (CDC 1994) gave the following recommendations.

(i) The general ventilation systems should be designed to provide optimal patterns of airflow within rooms and prevent air stagnation or short-circuiting of air from supply to exhaust.

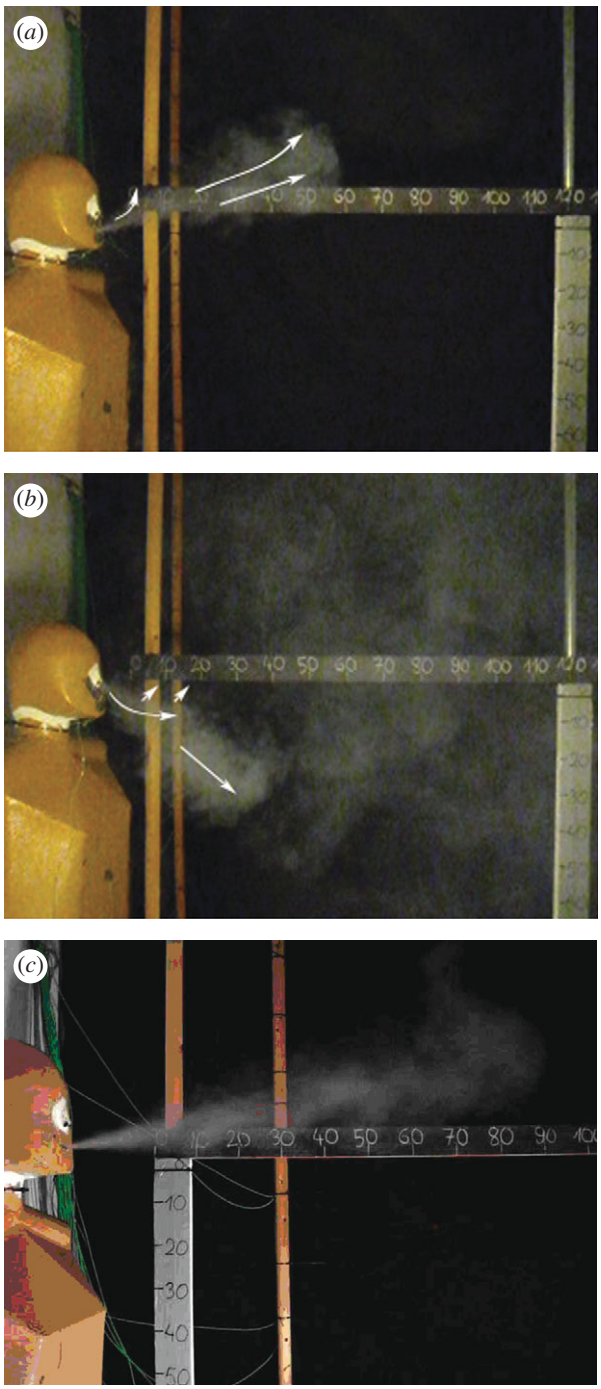

Figure 4. (*a*) Exhalation through the mouth; (*b*) exhalation through the nose; (*c*) coughing.

(ii) Adequate air mixing requires adequate number of air change rates.
(iii) To provide optimal airflow patterns, the air supply and exhaust should be located such that clean air first flows to parts of the room where the healthcare workers are likely to work.
(iv) Such an airflow pattern is achieved when the air is supplied at the side of the room opposite the patient and exhaust is from the location where the patient is located. Another method is to supply cool air near the ceiling and locate the exhaust near the floor.

The basic idea is thus to generate a flow from large supply openings, and then let it flow down in the room and displace particles to the return openings at the floor. This type of flow should, in principle, give a high personal exposure index, but measurements show that it is difficult to be established (Qian *et al.* 2006*a*).

A high personal exposure index requires a downward-directed displacement flow without mixing movement. This should especially be the case for the flow around standing or lying persons. The thermal plume above a person has an upward velocity of approx. 0.25 m s^{-1}. Figure 5 shows the thermal boundary layer around a person illustrated by smoke release from the surface of the manikin for different downward flow velocities. The thermal plume is preserved up to a downward velocity of 0.25 m s^{-1}. A large flow rate (approx. 50 h^{-1}) is required to obtain a downward displacement flow around a person, and this is used in operating theatres and 'laminar' clean rooms, but not in hospital wards.

The downward-directed flow indicated in the CDC recommendations will not be obtained in practice with a flow rate of 12 h^{-1}, and it will not be possible to have a displacement flow from the source patient to the exhaust because the flow is fully mixed. On the other hand, it is possible to have a high flow rate in a room without draught, because of large supply areas in the ceiling or in the wall, as discussed earlier, and this gives the possibility of working with a high dilution and thus a low level of contaminant concentration (see equations (2.1) and (2.3)). Also the thermal flow from the heat sources will help in preventing any stagnant areas in the ward.

4. HIGH VENTILATION INDEX

A high ventilation index is obtained when the contaminant moves from the emission source to the outlet with a limited mixing with the surrounding air. A unidirectional (piston) movement or a thermally generated movement may generate such a flow. Pressure differences in large rooms generated by the ventilation system can create a unidirectional flow within the room, but the pressure difference is especially used to control the flow between rooms. Operating theatres and clean rooms are protected from the surroundings by a high internal pressure, while the surroundings are protected from infected patients by a low pressure in an isolation room. Literature review by Li *et al.* (2007) has proved the importance of unidirectional flow for the reduction of cross-infection.

The ventilation index is used to express details about the air distribution in a room, while flow between rooms is estimated with other parameters.

Displacement ventilation can in some situations create high ventilation indices in the occupied zone because of the thermal plumes created in such a system. Figure 6 shows the layout of experiments with this type of air distribution made in the same room as used for tests of mixing ventilation and vertical ventilation in a hospital ward.

The figure shows the diffuser mounted on the left side wall close to the floor. The air from the diffuser

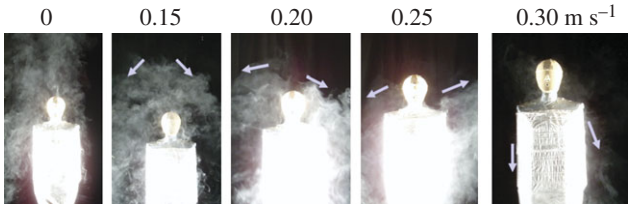

Figure 5. The figure shows a manikin located in a downward air flow. The boundary layer around the manikin is shown by smoke, and it is preserved at head height up to a downward velocity of 0.25 m s^{-1}.

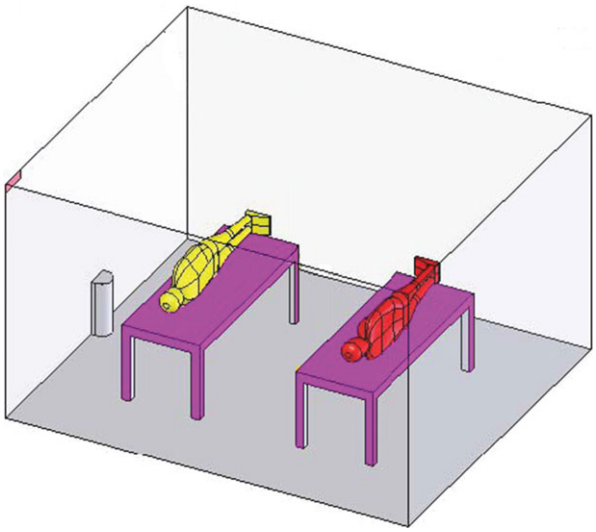

Figure 6. Full-scale room with displacement ventilation. The diffuser is side wall-mounted and the exhaust opening is located below the ceiling.

flows along the floor as a stratified layer, and heat release from the manikins (patients) moves it to the upper part of the room where it is exhausted. A vertical temperature gradient is generated in the room, and two zones are established in the room. The lower zone contains clean supply air, which may cover the lower part of the occupied zone (1–1.5 m) while the upper zone below the ceiling contains the emission from the source manikin S, and this air is extracted from the room. The ventilation index or the personal exposure index for the target manikin R is high if the target manikin inhales relatively clean supply air compared with the concentration in the exhaust air (equation (2.2)).

Qian *et al.* (2006*b*) show, among other things, that the displacement ventilation system offers a very good protection of the target manikin from cross-infection when the source manikin is lying on the back (figure 7*a*). A personal exposure index of 70 is typically obtained in this case. A problem arises when the manikin is lying on the side, facing the target manikin (figure 7*b*). The temperature gradient in the room will stratify the exhalation from the source manikin, and the high concentration of tracer gas (exhalation) flows to the target manikin's breathing zone, giving a low personal exposure index of 0.7. A similar effect on the exhalation flow between two persons has also been

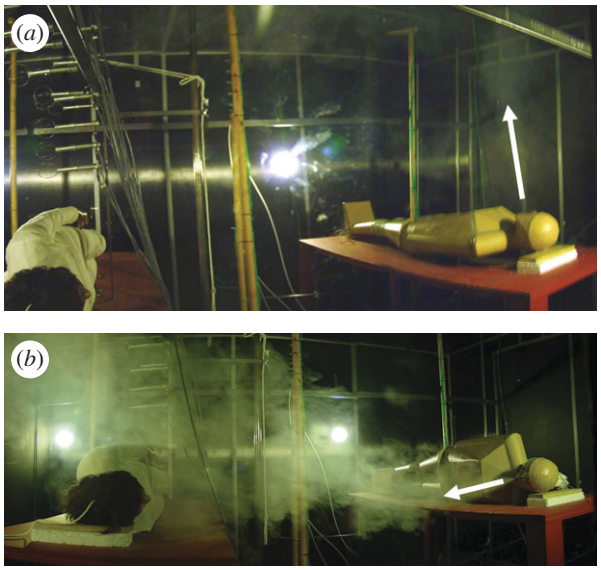

Figure 7. Two persons (manikins) in a full-scale room. The source manikin is lying on the back in (*a*), and on the side in (*b*). The room is ventilated by displacement ventilation (Qian *et al.* 2006*b*).

shown by Bjoern & Nielsen (2002). This is a typical problem for displacement ventilation. It is possible to obtain a very high ventilation index, but it cannot be guaranteed that the value is preserved in all situations.

It is also necessary to analyse the thermal comfort in a displacement ventilation system. The vertical temperature gradient and the draught in the stratified flow along the floor are limiting factors. Nielsen (2007) shows that the system can handle a flow rate q_o of approximately 0.05 $m^3 s^{-1}$ without creating draught. If, for example, the source patient continuously emits 3000 droplet nuclei s^{-1}, as in the earlier example with mixing ventilation, then the concentration around the second manikin is 860 droplet nuclei m^{-3} (equation (2.3)) in the case with the source manikin lying on the back. The concentration around the target manikin is 86 000 droplet nuclei m^{-3} when the source manikin is lying on the side facing the target manikin. This is a high concentration, even compared with the values obtained by a traditional mixing ventilation system with restricted flow rate.

It is a general conclusion that the displacement ventilation system is difficult to use for cross-infection protection, firstly, because it is difficult to obtain a high ventilation index in all situations and, secondly, because thermal comfort considerations restrict the flow rate to the room.

A vertical ventilation system can have a ventilation index which is higher than 1 when the heat loads are located at some distance from the diffusers in the ceiling (Nielsen *et al.* 2007*a*). An index larger than 1 is obtained because cold flows from the diffusers are separated from the warm plumes above the heat sources. The system requires a high location of the return openings as shown by Nielsen *et al.* (2009). It is typical that a high flow rate will reduce the ventilation index because the flow is partly driven by a thermal effect which will be reduced by the increased flow rate.

5. PERSONALIZED VENTILATION

The use of a PV system installed in beds is a new idea, which in the future may be a solution for minimizing cross-infection in isolation rooms. The PV system should be supplemented with a general ventilation system in the room. PV is especially efficient if the patients are bed-bound, and the effectiveness will be reduced when they are more mobile. A system with PV will therefore be more efficient at night when patients are sleeping.

The principle of PV is usually based on jets of air with a high momentum directed to a person's face (Melikov *et al.* 2002, 2003; Melikov 2004; Nielsen *et al.* 2007*a*). A large supply opening is normally used in the PV system to minimize the entrainment of contaminated air from the surroundings, but a large individual opening is not a practical solution in hospital wards with the demand for adjustment of position and direction.

A system suitable for a bed is a PV system which uses pillows, mattresses, etc. as supply openings of fresh air by using fabric as a diffuser (Nielsen *et al.* 2007*b*).

An air supply pillow is shown in figure 8. A personal exposure index $\varepsilon_{\mathrm{exp,PV}}$ higher than 10 is obtained for flow rates above $10\,\mathrm{l\,s^{-1}}$, and the exposure index is up to 35 for a flow rate of $14\,\mathrm{l\,s^{-1}}$. The exposure index is also relatively high at low flow rates. The specially good results reflect the fact that the patient's breathing zone is localized directly into the supply opening when the patient is lying on the side. A system based on this principle can retain a high effectiveness, even when the patient is mobile but lying in the bed.

The consequence of the high exposure index of the PV system means that particles in the target manikin's inhaled air can be reduced from a level of 15 000 droplet nuclei $\mathrm{m^{-3}}$ in the room, found in the earlier example with vertical ventilation, to a level of 1500 droplet nuclei $\mathrm{m^{-3}}$ ($\varepsilon_{\mathrm{exp,PV}}$ approx. 10) with a combined system. The system does to some extent protect the healthcare personnel in the hospital ward when it is used in combination with other air-distributions systems (see §6).

The use of PV in a hospital ward is focused on minimizing cross-infection, but the PV system has of course all the features known from conventional PV systems, as, for example, the possibility to have individual control of the thermal environment.

6. REDUCTION OF CONTAMINANT EMISSION TO THE ROOM

An efficient way to reduce the cross-infection risk is to reduce the emission from the source patient. The emission can be reduced by avoiding disturbing activities around the patient, as, for example, the use of nebulizers, and it could also be reduced by using local exhaust around the infected patient. Figure 9 shows such a device, which can be expanded above a patient (see Li *et al.* 2003). The problems with such a device are that it is difficult to keep clean, it cannot be expanded the whole time and it is uncomfortable for the patient.

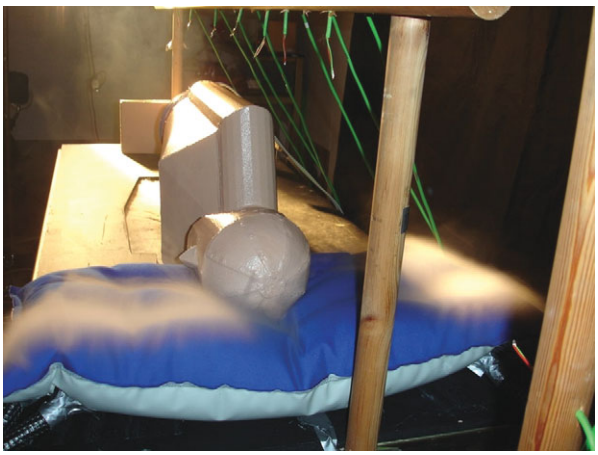

Figure 8. Air supply pillow intended for a hospital bed. Smoke visualization of the flow through the textile surface shows the flow immediately after the smoke penetrates the textile surface.

Figure 9. Retractable hood design. Idea of Victor Cheung, JRP, Hong Kong.

New experiments have shown that the PV with supply through the pillow can work as an aerodynamic hood when it is used together with a general ventilation system, which has the exhaust in the ceiling area (Nielsen *et al.* 2007*b*, 2008*a*). The experiments were made in a six bed SARS ward at the University of Hong Kong. The room has a vertical downward ventilation system and exhaust openings in the ceiling. The concentration level in the breathing zone at the neighbouring bed close to the source manikin is reduced by a factor of 0.6 when only the source manikin uses a pillow as PV. This is a reduction that probably can be larger in other areas of the room for the benefit of the healthcare personnel.

If the downward ventilation system in the SARS ward has a flow rate of $q_o = 0.23\,\mathrm{m^3\,s^{-1}}$, and the source patient emits 3000 droplet nuclei $\mathrm{s^{-1}}$, then the concentration at the neighbouring bed is 13 000 droplet nuclei $\mathrm{m^{-3}}$ when the source patient is without a PV system (ventilated pillow). With a PV system, the concentration can be reduced to 8000 droplet nuclei $\mathrm{m^{-3}}$.

Experiments with PV at all beds show that a very high protection can be achieved when the flow rate to the PV system is high (10–20 l s^{-1}), and the supply temperature is close to the room temperature.

7. CONCLUSIONS

Full-scale experiments with tracer gas can be used to simulate the movement of droplet nuclei in the air in ventilated rooms. The concentration distribution of tracer gas gives an estimate of the airborne cross-infection risk in the room outside the closed area around the source patient where droplet infection is prevailing.

Analyses of the transport process of particles and tracer gas show that a high flow rate to the ventilated space reduces the level of viruses and bacteria in this space.

A high flow rate to a room is possible by the use of mixing ventilation and vertical ventilation. The highest flow rates can be achieved without causing draught in the room when the supply system has a large supply area, as for example a large number of ceiling-mounted diffusers.

A high flow rate is especially possible by natural ventilation when the surrounding outdoor temperatures are sufficient for thermal comfort.

The air-distribution system suggested by CDC for isolation rooms fulfils the requirement for a high flow rate, but the flow will be fully mixed without the reduced cross-infection effect of unidirectional flow.

A high ventilation index can reduce the cross-infection effect, but it is difficult to obtain in practice if it is based on a thermal force, because this may gradually disappear at high flow rates.

Displacement ventilation has a high ventilation index, but it is also possible to have stratified exhalations in the occupied zone because of the vertical temperature gradient. This effect may increase cross-infection, and the system cannot be recommended.

PV built into hospital beds is a new interesting possibility that can be used to reduce the cross-infection problem without having separate rooms for each patient.

A PV can also be used as a device that reduces the emission from the source patient and therefore protects the healthcare personnel.

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