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Airborne transmission of disease in stratified flow

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Introduction

Airborne transmissions take place as a transport of virus or bacteria via the aerosol flow in rooms. The transmission can be part of the exhalation flow from the source of infection, it can move in the thermal flow from a warm or a cold source, be transported in the ventilation flow or other air movement in the room, and it can be spread by the turbulent diffusion in the room. The distribution of aerosols tends to be evenly distributed if the flow in the room is fully mixed.

Things will be different if the room air is stratified. A vertical temperature distribution may create stratified layers with either lower or higher concentrations of exhalation from the infected person (source person). Consequently, it could be interesting to use this effect to create a system with a low cross-infection risk between people in the room, [1] [2]. This possibility will be discussed in the following. Another effect in a system with vertically upward increasing temperature is the prospect of obtaining a cooling effect in the room with low location of the supply opening and high location of the return opening. This is the basic principle in displacement ventilation.

Stratified flow can also occur in other air distribution systems if they are highly loaded, as in rooms with a mixing ventilation system. In the following when we write "MV", we assume a fully mixed air distribution and by "DV" we assume stratified air distribution.

Exhalation and inhalation of aerosols

The airborne transmission of diseases in a stratified flow will occur via virus-laden aerosols (droplet nuclei) through human respiratory activities. Therefore, it is necessary to simulate the human exhalation and inhalation process in fine details. "Aerosol dynamic" measurements have hence been performed with breathing thermal manikins, which have the face geometry as described in Table 1, [3] [4] [5] [6].

Table 1. Definition of nose and mouth.

Nose:
Two symmetrical jets. 30° between the jets
Jets 60° inclined toward the chest
50 mm^2 each nostril opening (diameter 8 mm)

Mouth:
100 mm^2 with semi-ellipsoidal shape
Horizontal discharge of exhaled air

The details of the face geometry are important as boundary conditions in experiments and in Computational Fluid Dynamics (CFD) predictions. Other important boundary conditions are the activity level of the person (heat release and thermal boundary layer), breathing frequency and volume flow rate. Movement of the face (direction of exhalation), height of person, movement of the person might also be important for a detailed description in an aerosol dynamic experiment. The airborne transmission of aerosols will increase when we investigate speaking, shouting, singing, and coughing. The parameters in Table 1 change. The mouth area and exhalation direction vary in speaking, singing, and coughing [7]. The number of droplets and aerosols increase [8].

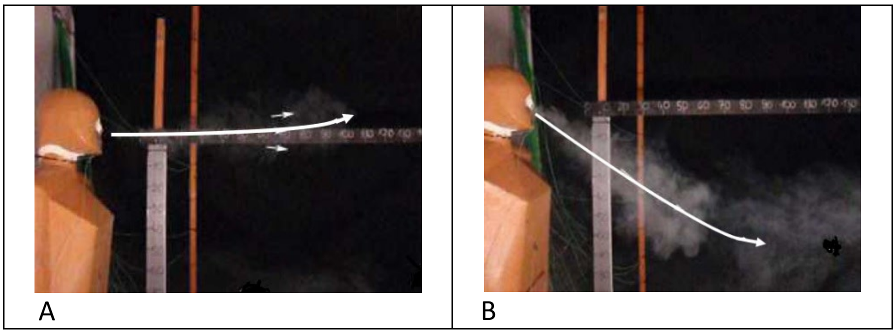

Figure 1. Exhalation 2.5 seconds after start of a sequence in a room with DV. A) Exhalation through mouth. B) Exhalation through nose [9].

Figure 1 shows the flow in the microenvironment around a manikin in surroundings with a vertical temperature gradient of 2.0 K/m. Figure 1A shows that the exhalation from the mouth forms an initial horizontal jet, and the flow is locked up by the temperature gradient just above the mouth in this case. The exhalation through the nose is different from the mouth flow, cf. Figure 1B. It starts with a downward jet and turns into a horizontal flow at some distance because it is also ”locking up” in the vertical temperature gradient. The final flow has very different horizontal locations in the two cases. The initial exhalation temperature is 34^{o} in both cases, but the exhalation jet mixes with the surrounding air and reduces the temperature to a local value in some distance.

The inhalation of a person also depends on several parameters. The air is inhaled from the thermal boundary layer around the body if the person does not move or turn around. Inhaling from the boundary layer means that a person will get his/her inhaled air from a lower level in the room than from the head height [1]. This is a positive effect if there is a concentration gradient in the room since the concentration at the bottom of the occupied zone can be low in displacement ventilation. The effect of the body boundary layer will disappear when the person is moving forward with more than 0.2 m/s [3].

Microenvironment, x < 1.5 m

The microenvironment around a person is the area where the air movement and the contaminant distribution processes are both influenced by the person and by the surrounding air conditioning system. The microenvironment can include two persons if they are standing in short distance x < 1.5 m.

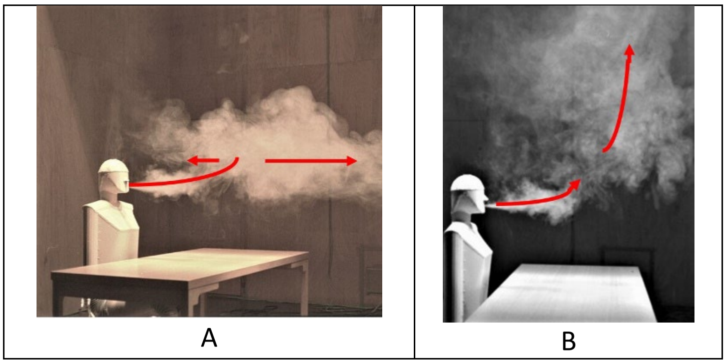

Figure 2. Exhalation flow from the mouth inside and outside the microenvironment. A) Stratified flow with a temperature gradient at head height of 0.5 K/m. B) Exhalation flow in a similar case with fully mixed flow without any temperature gradient, 0.0 K/m.

The vertical temperature distribution does influence the flow in the microenvironment. Figure 2A shows the exhalation flow from the mouth in the case of DV with a gradient of 0.5 K/m. The flow is an instantaneous jet close to the mouth, and it moves upward, at some distance, and spreads horizontally at head height due to the lock-up effect in the case of Figure 2A. The situation is typical for DV, because a gradient of 0.5 to 1.0 is within the comfortable conditions and a certain gradient is required to obtain an efficient energy solution.

Figure 2B shows the situation in the case of fully mixed flow, MV, in the room. The exhalation from the mouth is first an instantaneous jet mixed with the surrounding air, but in principle it will move continuously up to the ceiling area due to the temperature difference. Although the exhalation flow will rise in both cases, it will be possible to stand closer to a person in the MV case without being influenced by the exhalation flow of the opposite person. This effect is documented in many measurements of cross- infection risks between two persons at short distance inside the common microenvironment, (< 1.5 m) [3] [4] [5] [6].

Let us look at a situation where the cross-infection risk between two persons is expressed as the inhalation of tracer gas (aerosols) from one person to the other. Figure 3 shows the exposure of a target person expressed as normalized exposure c_{exp}/c_R (= ε), where c_{exp} is the exposure of inhaled tracer gas standing opposite to a source manikin and c_R is the concentration in return opening (fully mixed value). Although traces gas cannot be directly used as a measure for the health risk assessment, it can give an indication of this risk.

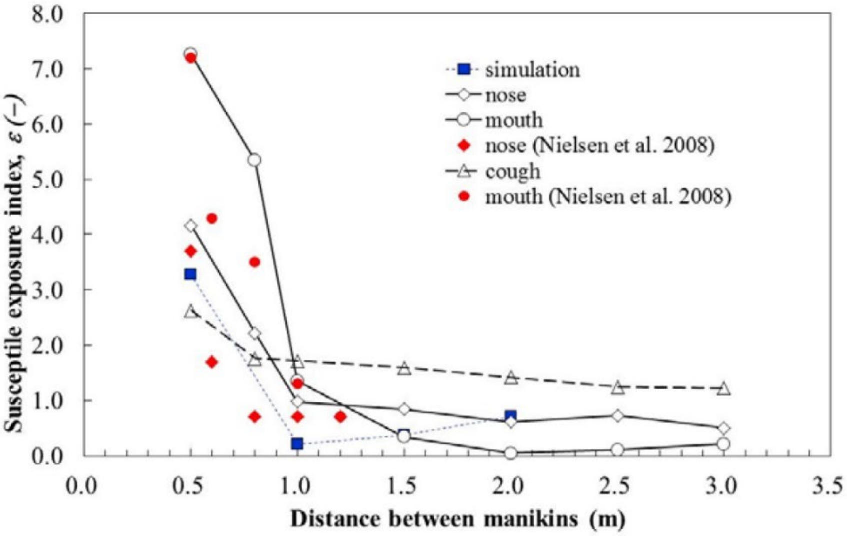

Figure 3. Exposure of target manikin versus distance between the two manikins of same height in a room with displacement ventilation. Results are shown for both breathing through the mouth, through the nose, for coughing, and for CFD predictions [5].

It is obvious that there is a large increase in the cross-infection risk when the two persons are standing close to each other (in a common microenvironment, x < 1.5 m). This is both the case for breathing through the mouth and through the nose. It is also seen from [10] that the increase in this exposure is expected to be low in the case of MV, in agreement with the two situations shown in Figure 2. The effect is due to the influence of the temperature gradient on the exhalation flow, which is different for different ventilation systems. The normalized exposure, c_{exp}/c_R, at the distance 0.35 m is, for example, around 7.0 for displacement ventilation, 4.3 for vertical ventilation, 1.8 for diffuse ceiling ventilation, and only 1.5 for mixing ventilation, [6]. Thermal stratification has an unfortunate effect on exposure in the microenvironment, and fully mixed (MV) conditions with a normalized exposure up to 1.5 (at 1.35 m) are to be preferred. It should be noted that it can be difficult to obtain MV conditions at certain load conditions and at some certain geometries in the system.

Macro-environment, x > 1.5 m

Figure 3 also shows the conditions in the macro-environment of a displacement ventilated room (x > 1.5 m). The exposure is below the fully mixed value, and it is different for breathing through the nose (0.7) than for breathing through the mouth (0.2). The values are preferable values in a ventilated room, and they are achieved because people's inhalation is from the lower part of the room via the personal thermal boundary layer. The concentration of exhaled aerosols is often low in this lower part of a room with displacement ventilation. The results show that detailed boundary conditions for the breathing function of the source manikin must be essential in stratified flow.

What will challenge this overall low cross-infection risk between people in the room in case of DV? Let us look at the parameters discussed earlier. Results in Figure 3 are for people of same height and without moving. Walking and movement of the face could increase infection risk [3]. Blocking the target manikin's boundary layer by a table may increase infection risk. Breathing through the nose instead of the mouth could increase infection risk. The activity level of the person (heat release and thermal boundary layer), breathing frequency, and volume flow rate will have an influence. Mouth area and exhalation direction vary in speaking, singing, and coughing [7] and could modify the lock-up height.

The position of the human exhalation layer depends on several variables as the size and location of the vertical temperature gradient in the room. In addition, this gradient is dependent on the heat load and temperature level in the room, on vertical and horizontal location of heat loads etc. Different situations obtained with a seated and a standing person (distance 4 m) in a room with different heat loads and flow rates, have normalized exposures from 0.6 to 1.75, [11].

Fully mixed flow will be an alternative safe solution, but it requires a higher flow rate of outdoor air [12]. The system should be well-designed without creating any stratification at high heat load.

Conclusion

The use of the stratification effect made it possible to create a reduced cross-infection risk for long range airborne transmission in some situations, but we need research in system layout to find solutions which will give a safe environment in all practical situations. A solution must be followed up with some necessary restrictions/information of use, if necessary. Another possibility is to use mixing ventilation and accept a higher flow rate of outdoor air.

It is also a question whether or not it is acceptable to select a solution with the stratified flow, which shows high exposure at the close distance between people (< 1.5 m); if it can be solved with mixing ventilation where the cross-infection risk is lower at close distance, although a higher flow rate to the room is required to obtain an overall acceptable infection risk.

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