Airborne transmission of disease in stratified and non-stratified flow

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ABSTRACT

Airborne transmissions take place as a transport of virus or bacteria via the aerosol flow in rooms. The distribution of aerosols tends to be evenly distributed if the flow in the room is fully mixed. The aerosols distribution 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. 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.

KEYWORDS

Airborne transmission, infectious disease, stratified flow, displacement ventilation, mixing ventilation, human exhalation.

1 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, (Bjørn and Nielsen 2002)(Kosonen et al. 2017). 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.

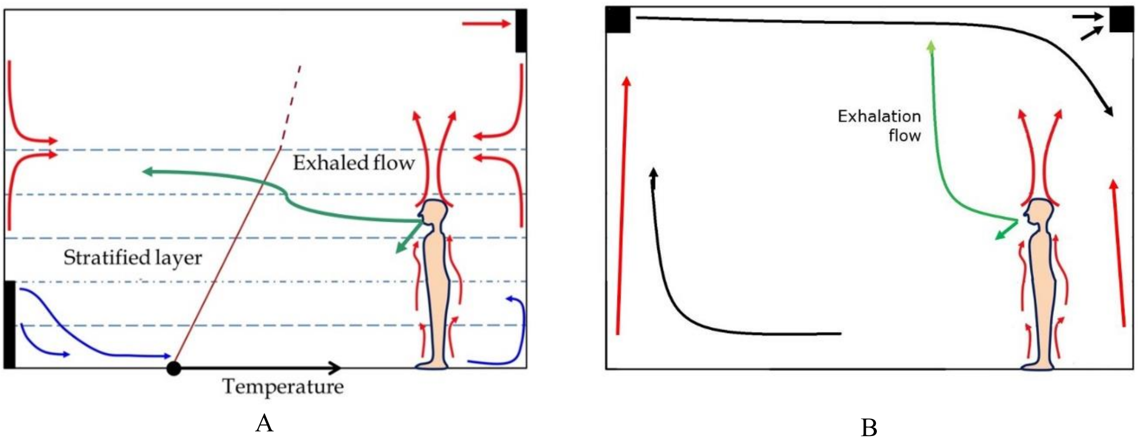


Figure 1. A) Air distribution in a room with displacement ventilation. The figure indicates the stratified flow (Zhou et al. 2017) and B) air distribution in a room with fully mixed flow. Both flows describe a cooling situation.

Figure 1 shows the principle of displacement ventilation. The air movements in the room consist of stratified horizontal flow and vertical movement from boundary layers and plumes. Heat loads, such as person and equipment, create a vertical upward movement; and vertical surfaces, such as windows and walls, create upward or downward movements depending on surface temperature, Figure 1. The flow in the stratified layer is locked into a horizontal temperature band. If we look at the flow from the diffuser, we will see that the height of the layer is rather constant through the whole room, and it is a function of the temperature difference between a reference room temperature and supply temperature (Nielsen 2000). There will only be an insignificant mixing in the horizontal layers because the turbulent mixing will be damped by the temperature gradient. The layer at the floor will have a velocity dependent on the diffuser, temperature difference and flow rate, and layers above may have an insignificant velocity level (Nielsen 2000)(Nielsen 1988). A passive release of tracer gas in any height, or a contaminant of equal density, will spread horizontally in the relevant temperature band in the room (lock-up height) (Bjørn and Nielsen 2002)(Zhou et al. 2017). The distribution of aerosols tends to be evenly distributed if the flow in the room is fully mixed, see Figure 1B. The exhalation will rise to the ceiling if the room temperature is below the exhalation temperature and the room air are entrained into the plume. Virus and bacteria will be fully mixed in the room air by turbulent diffusion. In principle many ventilation systems are based on mixing flow, but some room layouts may generate stratified flow in areas, and a high heat load can also generate stratified flow, as for example in case of direct solar radiation into a room.

2 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, and Figure 2 (Bjørn and Nielsen 2002)(Nielsen et al. 2008)(Liu et al. 2017)(Nielsen and Xu 2022).

Table 1. Definition of nose and mouth.

Nose:
Two symmetrical jets. 30° between the jets
Jets 60° inclined toward the chest
50 mm² each nostril opening (diameter 8 mm)

Mouth:
100 mm² with semi-ellipsoidal shape
Horizontal discharge of exhaled air

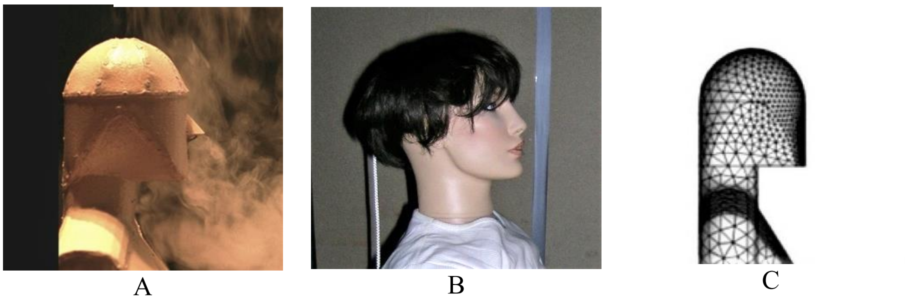


Figure 2. A) Thermal manikin with nose and mouth. B) Manikin with fine details. C) Detailed CFD Manikin.

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 (Abkarian et al. 2020). The number of droplets and aerosols increase (Pan et al. 2022).

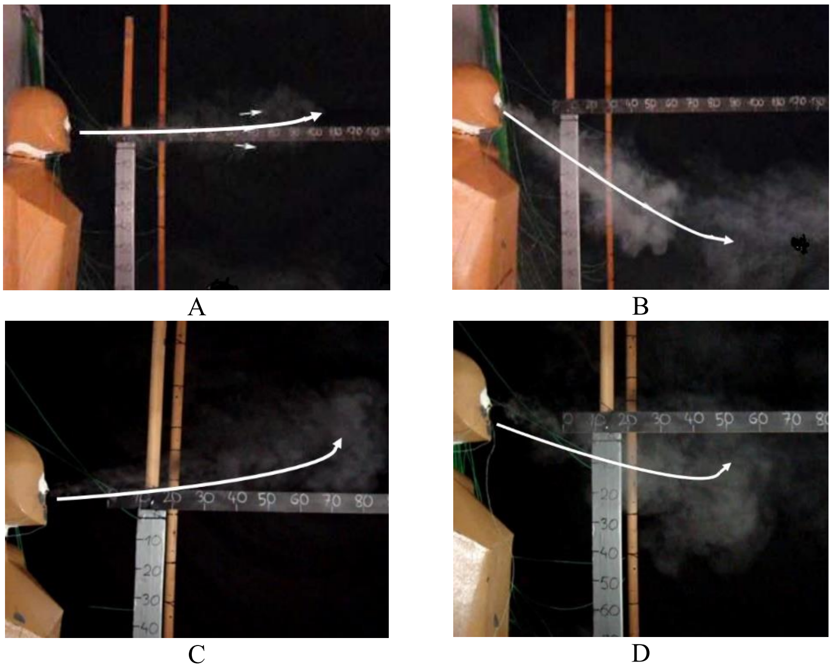


Figure 3. Exhalation 2.5 seconds after start of a sequence. A) DV and Exhalation through mouth. B) DV and Exhalation through nose. C) MV and exhalation through the mouth. D) MV and exhalation through the nose (Nielsen et al. 2009).

Several universities have agreed on both geometries described in Table 1 and Figure 2, and up until now, it is one of the most detailed mouth and face geometries used in experiments and CFD. They include an artificial lung creating the breathing function.
Figure 3A and B shows the flow in the microenvironment around a manikin in surroundings with a vertical temperature gradient of 2.0 K/m. Figure 3A for displacement flow 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 3B. 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° in both cases, but the exhalation jet mixes with the surrounding air and reduces the temperature to a local value in some distance.
Figure 3C shows the exhalation through the mouth in case of mixing flow. The exhalation turns upward due to an initial temperature of 34 °C and a surrounding temperature of 20.8 °C in this case. The upward velocity in the manikin's thermal boundary layer is stronger in this MV case than in the DV case (Figure 3A), and this may explain the more upward directed exhalation. Figure 3D shows the exhalation through the nose. This flow is also influenced by a strong boundary layer around the manikin, and the flow will take an upward direction at some distance from the nose and, in principle, continue to the ceiling, as in Figure 3C.

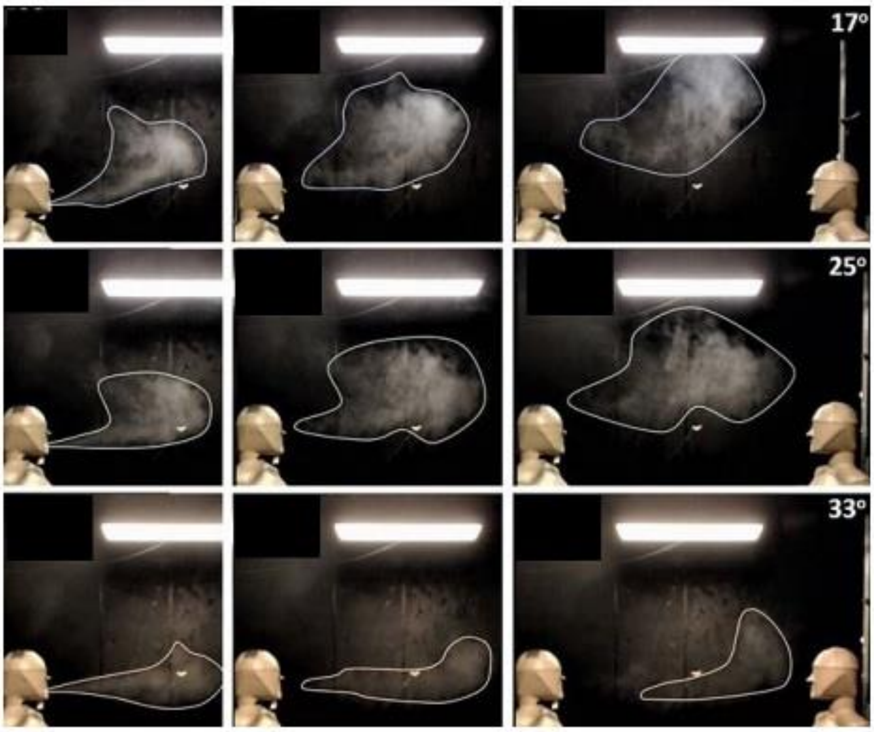


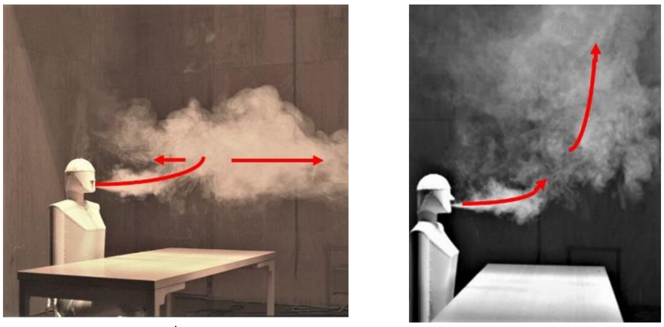
Figure 4 shows the movement of the pulsating exhalation flow based on the location of the tracer (smoke) at different time steps. Mixing ventilation. The smoke pattern is measured at three different room temperatures: 17 °C, 25 °C, and 33 °C (Nielsen et al. 2022).

The room temperature is an important parameter for the trajectory of the exhalation flow in a room with mixing ventilation as shown in Figure 4. The figure shows the pulsating exhalation as a time dependent flow. The position of exhaled tracer (smoke) is given at three different time steps, and the last time step is 1.66 sec of a total breathing cycle of 3.7 sec. It is clearly a more informative depiction of the instantaneous flow than the earlier Figure 3. It shows that the exhaled jet will have an upward movement in the beginning of an exhalation due to a combination of momentum and buoyancy. Later, when the velocity from the

exhalation is low, the exhaled volume of air will rise mainly due to buoyancy. The combined flow describes the true time dependent movement of the exhalation, and it expresses the flow as a combination of an instantaneous buoyant jet and a vortex flow (Nielsen et al. 2009).
The middle row in figure 4 shows the exhalation flow in a room with a room temperature of 25 ºC. This is close to the comfort temperature in a room, and it corresponds to most measurement in literature and to the situation in Figure 3. The upper row shows the situation in a cold room or outside. It is obvious that the horizontal distance in the exhalation is reduced in cold rooms or cold outdoor surroundings (Nielsen et al. 2022). The lower row shows the results for a room with a room temperature close to the exhalation temperature (34 ºC) of a person. The exhalation moves horizontally through the room, but it do not reach the opposite manikin because this manikin's boundary layer and breathing are protecting the face regions.
The inhalation of a person also dependent 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 (Bjørn and Nielsen 2002)(Murakami 2004). 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 (Bjørn and Nielsen 2002).

3 MICROENVIRONMENT

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.



A B

Figure 5. Exhalation flow from the mouth inside and outside the microenvironment. A) Surrounding stratified flow with a temperature gradient at head height of 0.5 K/m. B) Exhalation flow in a similar case with fully mixed surrounding flow without any temperature gradient, 0.0 K/m.

The vertical temperature distribution does influence the flow in the microenvironment. Figure 5A show 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 5A. The situation is typical for DV, because a gradient of 0.5 to 1.0 K/m is within the comfortable conditions and a certain gradient is required to obtain an efficient energy solution.
Figure 5B 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 as a plume 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) (Bjørn and Nielsen 2002)(Nielsen et al. 2008)(Liu et al. 2017)(Nielsen and Xu 2022).
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 6 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 from an opposite 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.

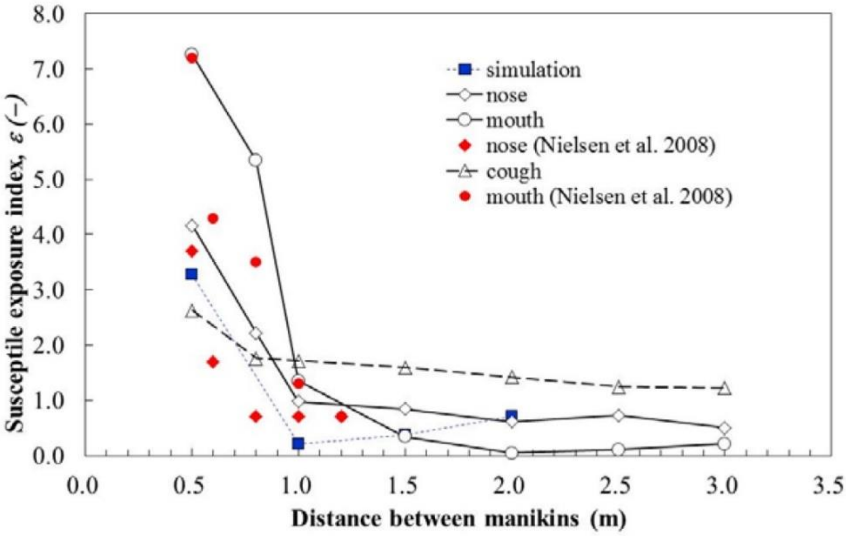


Figure 6. Exposure of target manikin versus distance between the two manikins of same height in a room with displacement ventilation. Results are shown for both breathing through the mouth, through the nose, for coughing and for CFD predictions (Liu et al. 2017).

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 (Nielsen et al. 2008) 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 5. 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 for breathing through the mouth 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 (Nielsen and Xu 2022). Thermal stratification gives a high exposure in the microenvironment, and fully mixed (MV) conditions with a normalized exposure up to 1.5 (at 1.35 m) for breathing through the mouth 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.

4 MACRO-ENVIRONMENT

Figure 6 also shows the conditions in the macro-environment of a displacement ventilated room (x > 1.5 m). The normalized 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 very essential in the measurements and simulation of 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 6 are for people of same height and without moving. Walking and movement of persons could increase infection risk (Bjørn and Nielsen 2002). 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 (Abkarian et al. 2020) 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 (Bjørn and Nielsen 1997).
Fully mixed flow will be an alternative safe solution, but it requires a higher flow rate of outdoor air (Li, Nielsen, and Sandberg 2011). The system should be well-designed without creating any stratification at high heat load.

5 CONCLUSIONS

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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7 REFERENCES

Abkarian, Manouk, Simon Mendez, Nan Xue, Fan Yang, and Howard A. Stone. 2020. "Speech Can Produce Jet-like Transport Relevant to Asymptomatic Spreading of Virus." *Proceedings of the National Academy of Sciences of the United States of America* 117(41):25237–45. doi: 10.1073/pnas.2012156117.

Bjørn, E., and P. V. Nielsen. 2002. "Dispersal of Exhaled Air and Personal Exposure in Displacement Ventilated Rooms." *Indoor Air* 12(3):147–64. doi: 10.1034/j.1600-0668.2002.08126.x.

Bjørn, Erik, and Peter V. Nielsen. 1997. *Passive Smoking in a Displacement Ventilated Room*. Dept. of Building Technology and Structural Engineering. Indoor Environmental Technology.

Kosonen, Risto, Arsen Melikov, Elisabeth Mundt, Panu Mustakallio, and Peter V. Nielsen. 2017. *REHVA Guidebook No.23: Displacement Ventilation*. Federation of European

Heating, Ventilation and Air Conditioning Associations.
Li, Yuguo, Peter V. Nielsen, and Mats Sandberg. 2011. "Displacement Ventilation In Hospital Environments." *ASHRAE Journal* 53(6):86–88.
Liu, L., Y. Li, P. V. Nielsen, J. Wei, and R. L. Jensen. 2017. "Short-Range Airborne Transmission of Expiratory Droplets between Two People." *Indoor Air* 27(2):452–62. doi: 10.1111/ina.12314.
Murakami, S. 2004. "Analysis and Design of Micro-Climate around the Human Body with Respiration by CFD." *Indoor Air, Supplement* 14(SUPPL. 7):144–56. doi: 10.1111/j.1600-0668.2004.00283.x.
Nielsen, Peter V., Rasmus L. Jensen, Michal Litewnicki, and Jan Zajas. 2009. "Experiments on the Microenvironment and Breathing of a Person in Isothermal and Stratified Surroundings." *9th International Conference and Exhibition - Healthy Buildings 2009, HB 2009*.
Nielsen, Peter V., and Chunwen Xu. 2022. "Multiple Airflow Patterns in Human Microenvironment and the Influence on Short-Distance Airborne Cross-Infection – A Review." *Indoor and Built Environment* 31(5):1161–75. doi: 10.1177/1420326X211048539.
Nielsen, Peter V. 2000. "Velocity Distribution in a Room Ventilated by Displacement Ventilation and Wall-Mounted Air Terminal Devices." *Energy and Buildings* 31(3):179–87. doi: https://doi.org/10.1016/S0378-7788(99)00012-2.
Nielsen, Peter V, F. V Winther, M. Buus, and M. Thilageswaran. 2008. "Contaminant Flow in the Microenvironment Between People Under Different Ventilation Conditions." *ASHRAE Transactions* (Part 2):632–40.
Nielsen, Peter V, Chen Zhang, Kirstine M. Frandsen, Rasmus L. Jensen, Patrick Hundevad, Simon Madsen, Tonje Luckenwald, Najim Popalzai, Yuguo Li, Hua Qian, and Chunwen Xu. 2022. "Cross-Infection Risk between Two People in Different Temperature Surroundings Studied by Aerosol Dynamics." in *COBEE 2022*.
Nielsen, Peter Vilhelm. 1988. *Displacement Ventilation in a Room with Low-Level Diffusers*. Vol. R8836. Aalborg.
Pan, Shihai, Chunwen Xu, Chuck Wah Francis Yu, and Li Liu. 2022. "Characterization and Size Distribution of Initial Droplet Concentration Discharged from Human Breathing and Speaking." *Indoor and Built Environment* 0(66):1–14. doi: 10.1177/1420326X221110975.
Zhou, Qi, Hua Qian, Haigang Ren, Yuguo Li, and Peter V. Nielsen. 2017. "The Lock-up Phenomenon of Exhaled Flow in a Stable Thermally-Stratified Indoor Environment." *Building and Environment* 116:246–56. doi: 10.1016/j.buildenv.2017.02.010.