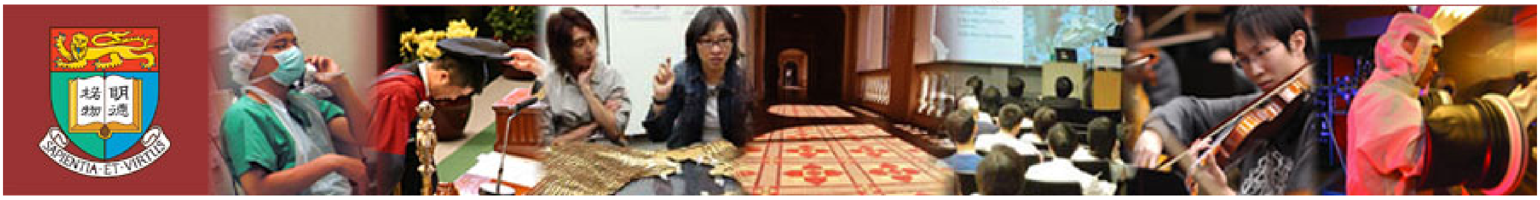


Title	**Cross infection in hospital wards with downward ventilation: different locations of return openings without and with partitions between beds**
Author(s)	**Nielsen, PV; Li, Y; Buus, M; Winther, FV**
Citation	**The 11th International Conference on Air Distribution in Rooms (RoomVent 2009), Busan, South Korea, 24-27 May 2009. In Proceedings of the 11th International Conference on Air Distribution in Rooms, 2009, p. 770-779**
Issued Date	**2009**
URL	**http://hdl.handle.net/10722/126324**
Rights	**Creative Commons: Attribution 3.0 Hong Kong License**

Cross Infection in Hospital Wards with Downward Ventilation - Different Locations of Return Openings without and with Partitions between Beds

Peter V. Nielsen[1], Yuguo Li[2], Morten Buus[3] and Frederik V. Winther[4]

[1] Aalborg University, Denmark
[2] University of Hong Kong, China
[3] COWI A/S, Denmark
[4] Rambøll Danmark A/S, Denmark

Corresponding email: pvn@civil.aau.dk

ABSTRACT

A two-bed hospital ward with one standing healthcare assistant and a ceiling-mounted low-impulse semicircular inlet diffuser is simulated in a full-scale room. Tracer gas is used for simulating gaseous contaminants, and the concentration is measured at different air change rates and different postures of the patients. A textile partition between the beds, which is typical in a hospital ward, is used for protection of the patients in some of the experiments. Three different layouts of return openings are tested. One layout with one opening at the ceiling, another with four openings at the wall opposite to the inlet diffuser, and one with a high location of these four openings. The downward recirculating flow is on average parallel with the partition, and the partition does not decrease cross infection. A high location of the four return openings decreases the risk of cross infection.

INTRODUCTION

Spread of contaminants in hospital wards has been a matter of utmost concern since the severe SARS outbreak in 2003, and a need for an efficient air distribution system is especially pronounced in the hospital environment [1] and [3]. A discussion of the importance of the ventilation system and the possibility to protect people from airborne infection was given in a literature review [4], where it was concluded that there is a 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, TB, chickenpox, anthrax, influenza, smallpox and SARS.

Different air distribution systems such as mixing ventilation, downward ventilation and displacement ventilation offer different possibilities in the protection of people against pollutants. The pollutants are almost fully mixed in the occupied zone in a room ventilated by mixing ventilation and downward ventilation, and they are removed by a diluting process [5], [6] and [7]. If the pollutant source 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 contaminants. It is possible to design a system with low exposure of people, [8], but in certain situations both a very low and a high exposure may also exist in rooms with displacement flow as shown in [9] and [10] as the exhaled air and droplet nuclei may be trapped or "locked up" due to thermal stratification.

Flow with a displacement effect can also be obtained in a room ventilated by a ceiling-mounted low velocity diffuser. The air distribution in the room is mainly controlled by buoyancy forces from the heat sources, but the flow from the diffuser can be characterised 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 [11]. Those possibilities are addressed in this paper, where the air distribution system is used together with different locations of return openings, and without and with partitions between beds.

In this paper downward ventilation is used as an expression for a system with a ceiling-mounted low velocity diffuser giving a downward supply flow. The locations of the return openings are not specified.

One of the patients is assumed to be the source patient, who releases respiratory pathogens, which are represented by a tracer gas. The exposure of the target patient and the healthcare assistant can be found from Equation 3. The source manikin has a constant exhalation of the level S, and the target manikin inhales a concentration of $c_{exp,}$. The room is supplied with an air flow rate of q_o, and the concentration in the exhaust c_R at steady state is thus

$$c_R = S/q_o \qquad (1)$$

The personal exposure index $\varepsilon_{\exp}$ for the target manikin R is

$$\varepsilon_{\exp} = \frac{c_R}{c_{\exp}} \qquad (2)$$

and the following expression is obtained for the exposure of the target manikin

$$c_{\exp} = \frac{1}{q_o} \cdot \frac{1}{\varepsilon_{\exp}} \cdot S \qquad (3)$$

Equation (3) shows that the inhaled concentration of any airborne infection from the source manikin can be reduced by using a high flow rate q_o to dilute the infected particles to a low level of concentration. Furthermore, Equation (3) shows that systems that generate a large ventilation index ε_{exp} for the target patients or healthcare assistants should be preferred. Those possibilities are addressed in the following sections.

TEST ROOM AND MANIKINS

Figure 1 shows the full-scale room. The dimensions of the room are in accordance with the requirements of the International Energy Agency Annex 20 work with length, width and height equal to 4.2 m, 3.6 m and 2.5 m. The figure shows the layout with a textile terminal located 600 mm from the side wall. In Figure 1A the return opening is located on the back wall close to the ceiling to support the passive displacement flow, which occurs in the room. Figure 1B shows the layout with four return openings which can change positions to address this effect. Two openings are located at each bed and the vertical distance between the openings is 0.96 m. Figure 1C shows the partitions between the beds. The partition is made of textile. It is attached to the wall with the return openings, and there is an opening above the floor of 10 cm, and another one below the ceiling of 40 cm. The opening in the passage is of 1.1 m. The partition is tested in most of the experiments to see if it will change the exposure index of the target manikins.

Figure 1 also shows the furnishings and the heat load of the room. The heat load consists of two desk lamps (92 W) and two manikins (150 W) producing a total heat load of 242 W. A manikin representing a healthcare assistant (120 W) is added to some of the experiments, which gives a total heat load of 362 W.

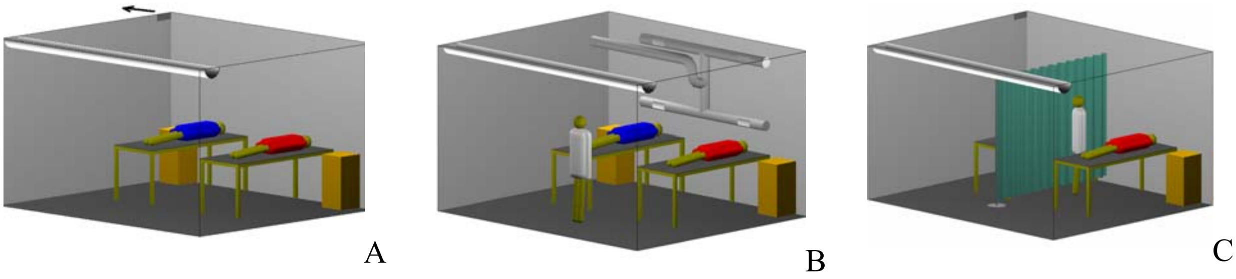


Figure 1. The full-scale room simulating a hospital ward. A: room with one exhaust opening. B: room with four exhaust openings. C: room with movable textile partition.

The source manikin (highlighted in red) is located in the right-hand bed in the room, see Figure 1. The target manikin (blue) is located in the left-hand bed. The manikins can either lie on the back, on the side or sit straight in the bed. A manikin representing a healthcare assistant is also used in the experiments and it can have several positions in the room. The source manikin has a breathing flow rate of 6.22 L/min, and a respiratory rate of 9.76 L/min.

N_2O is used as tracer gas in the experiments. The concentration of the tracer gas is measured by a calibrated multi-gas monitor (Brüel & Kjær, Denmark) and a multipoint sampler and doser (Brüel & Kjær, Denmark). The concentration of N_2O is at a level of 30 ppm in the experiments, and the background concentration of N_2O is about 0.4 ppm.

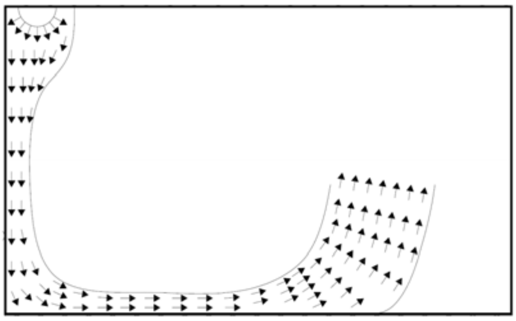


Figure 2. Vertical section of the flow in the room.

Figure 2 shows the flow from the ceiling-mounted textile terminal. The flow can be characterised as passive displacement ventilation with an area outside the occupied zone with vertically downward flow and stratified flow in the rest of the room. The velocity in the occupied zone is restricted, and it is mainly dependent on the heat load [6]. This is very important because it is possible to have a high flow rate q_o, see Equation (3), and thereby obtain a low level of exposure for the target manikins. Figure 3 shows the velocity profiles at the floor at three different flow rates, and it is seen that the velocity is only a restricted function of the flow rate. The horizontal flow, generally directed upwards, in the occupied zone indicates a possibility for an exposure index larger than the one in this area.

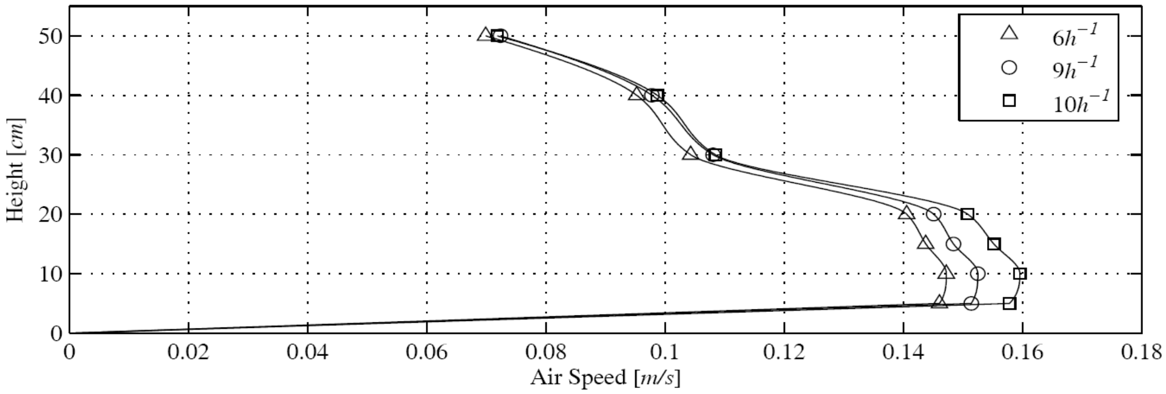


Figure 3. Velocity profile measured at the floor 1.5 m from the wall close to the diffuser.

MEASUREMENTS AND DISCUSSION

The experiments with a single exhaust opening located in the end wall are performed for two manikins in the beds, two manikins in the beds and a healthcare assistant at two different positions in the room, and all the sets of measurements are combined without and with a textile partition.

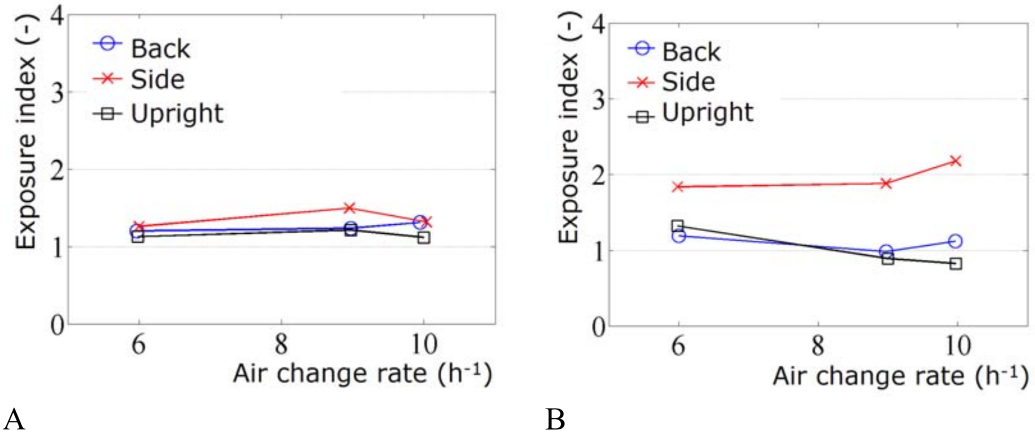


Figure 4. Personal exposure index for the target manikin when the source manikin is lying on the back, on the side, and sitting straight in the bed. A: The target manikin is lying or sitting in the bed opposite to the source manikin. B: The target manikin is standing simulating a healthcare assistant close to the downward flow below the ceiling-mounted diffuser. The room has one return opening.

Figure 4A shows the personal exposure of the target manikin in the bed opposite to the source manikin. The exposure index ε_{exp} is only about 1.1 to 1.4, and this is independent of the individual positions, which is: both manikins lying on the back, both manikins lying on the side face to face, and both manikins sitting on the beds face to face. The distance between the faces is 1.8 m in all three cases.

It is very important to realise that the exposure index is rather independent of the variation in the air change rate from 6 h^{-1} to 10 h^{-1}. A minimisation of the cross infection effect can therefore be achieved by using a high flow rate without having the risk of a decreasing exposure index or having decreasing thermal comfort as shown in the last section.

Experiments with a textile partition do not change the personal exposure index for the target manikin. The dominant flow in the room seems to be quasi-two-dimensional and parallel to this partition surface, although the breathing action of the source manikin is perpendicular to the main flow direction in two of the cases. Those results indicate that the level of the exposure index close to one (full mixing) is due to entrainment into the downward flow from the diffuser. The air distribution system does not have a high exposure index. In this connection it should also be realised that the contaminant (tracer gas) has to cross half the room to reach the singe exhaust in the end wall, which probably also increases the mixing process between exhalation from the source into the room air movement.

Figure 4B shows the personal exposure index for a healthcare assistant simulated by a manikin standing in the symmetry plane of the room below the diffuser. The results for the case with the source manikin lying on the back or sitting straight in the bed are close to full mixing with ε_{exp} close to 1.0. Improved results with ε_{exp} about 2.0 are obtained when the source manikin is lying on the side. The exposure index for the healthcare assistant is close to 1.0 when the manikin has a position between the two beds facing the source manikin.

The exposure of the target manikin, lying in a bed opposite to the source manikin, is not influenced by the presence of the extra standing manikin, and the results are similar to the results found in Figure 4A.

Experiments with textile partitions are also carried out with the manikin (healthcare assistant) standing by the source manikin with the back to the partition. The exposure index is about 1.0, the same as for the target manikin on the other side of the partition, except in the situation where the source is sitting straight in the bed. The index is in this situation very low for the standing manikin, $\varepsilon_{exp} \sim 0.2$, which means that in this case the partition has worsened the situation.

Downward-directed ventilation systems are recommended by several guidelines for isolation rooms, see [12] and [13]. The basic idea of these systems is to supply cool air at the ceiling from large supply openings, and then let it flow down in the room and displace particles to the return openings at the floor with a high flow rate. This layout is tested by the use of four return openings located at the side wall close the breathing zone of the manikins. The openings are located below and above the mean plane of the beds at a distance of 960 mm. The openings have a size of 100 mm × 250 mm.

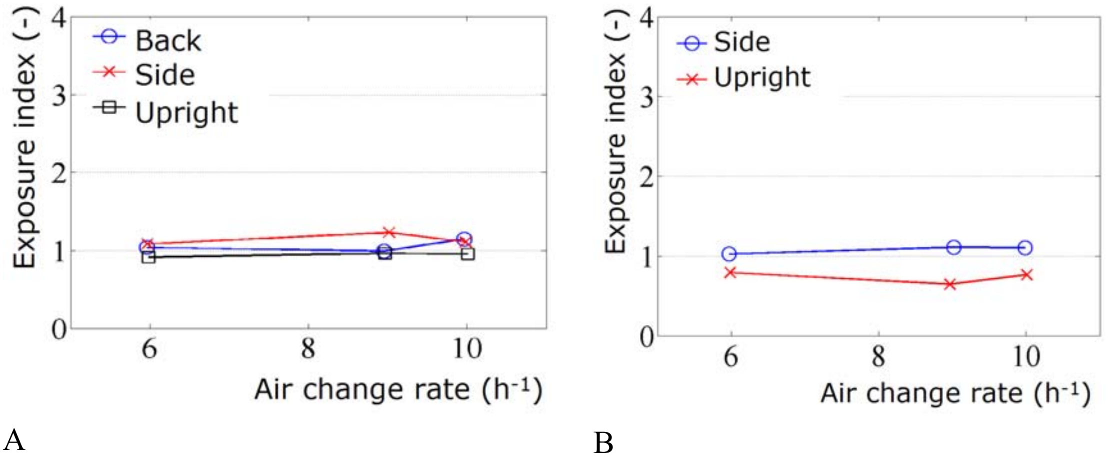


Figure 5. Personal exposure index for the target manikin when the source manikin is lying on the back, on the side, and sitting straight in the bed. A: The target manikin is lying or sitting in the bed opposite to the source manikin. B: The target manikin is standing and simulates a healthcare assistant close to the downward flow below the ceiling-mounted diffuser. Four return openings at low level.

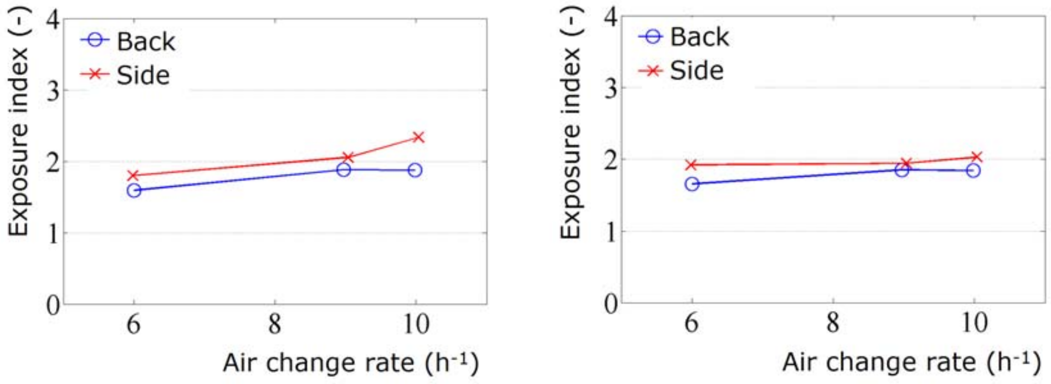
The four return openings are not improving the results comparing to a single return opening as seen in Figure 4A. The target manikin in the bed opposite to the source manikin has a personal exposure index of ε_{exp} ~ 1.0. The low-set return opening does not remove any tracer gas directly from the breathing of the source manikin, and the upper openings catch only a small fraction of direct exhalation. The removal of tracer gas from the room is done as a diluting process of fully mixed tracer gas and air. The low location of an exhaust opening is only interesting when large particles have to be removed, but even in this case a low-set return opening seems to be less efficient [14].

Figure 5B shows the personal exposure index for a healthcare assistant simulated by a manikin standing in the symmetry plane of the room close to the diffuser. The results for the case with the source manikin lying on the side are close to full mixing with ε_{exp} ~1.0. An exposure index around 0.7 is obtained when the source manikin is sitting straight. The exposure index for the healthcare assistant is below 0.5 when the manikin has a position between the two beds facing the source manikin.

Experiments with textile partitions are made with the manikin (healthcare assistant) standing by the source manikin with the back to the partition. The exposure index is slightly above 1.0 for the target manikin on the other side of the partition. The index for the standing manikin is slightly below 1.0.

The results in Figure 5 show that the CDC recommendation of a high flow rate [13], is a possibility because the exposure index is uninfluenced by the flow rate.

A final set of experiments is made with a high location of the four return openings. Two openings are 260 mm above the exhalation points of the manikins when the manikins are lying on the back, and the two other openings have a position of 1220 mm above this level.



A B

Figure 6. Personal exposure index for the target manikin when the source manikin is lying on the back and on the side. A: The target manikin is lying in the bed opposite to the source manikin. B: The target manikin is standing and simulates a healthcare assistant close to the downward flow below the ceiling-mounted diffuser. Four return openings located at a high level in the room.

A high location of the return openings improves the level of the exposure index for both the target manikin and for the manikin standing close to the inlet flow in the corridor area, figures 6A and 6B. The exposure index is around 2.0 for all air change rates, and the index for the target manikin is even increasing with the air change rate.

The layout of the air distribution system with a high location of both the supply opening and the return openings opposite to the supply opening has improved and optimised the flow pattern in the room with respect to a minimisation of cross infection. The system is a passive displacement ventilation system where the heat and the contaminant release from the manikins in the room, and the connected plumes from the heat sources are part of the main flow in the room. This air distribution system has been addressed earlier with respect to the possibility of obtaining a high personal exposure index, [11], but the high and distributed location of the exhaust openings has improved the results compared to earlier measurements.

A minimisation of cross infection can be further improved by the use of personalised ventilation, either in the form of a separate diffuser [11], or by diffusers integrated into the hospital beds [15, 16].

CONCLUSIONS

The risk of airborne infection can be minimised in hospital wards by using a high air change rate, and by obtaining a high personal exposure index with respect to exhalation from other patients.

The location of the return openings plays an important role for the distribution of the exhaled contaminant (tracer gas) in the room. A low location of return openings does not raise the exposure index for the patients above 1.0 when the viruses or bacteria are airborne (< 5 µm).

A ceiling-mounted low velocity diffuser generates vertical ventilation and passive displacement flow in a room when it is used together with a high location of distributed return openings. This type of flow can produce a personal exposure index larger than one (~ 1.5 - 2.0). The system can handle a high flow rate without causing discomfort, and it is therefore appropriate for the ventilation of a hospital ward.

Textile partitions, which are often used in hospital wards, do not decrease the risk of cross infection. It could even increase the risk for the healthcare assistants.

REFERENCES

1. Li, Y, Huang, X, Yu, I T S, Wong, T W, and Qian, H. 2004. Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. Indoor Air, Vol 15, pp 83-95.
2. Li, Y, Yu, I T S, Xu, P, Lee, J H W, Wong, T W, Ooi, P P, and Sleigh, A. 2004. Predicting super spreading events during the 2003 SARS epidemics in Hong Kong and Singapore. American Journal of Epidemiology, 160, pp 719–728.
3. Qian, H, Li, Y, Nielsen, P V, and Huang, X. 2007. Predicting spatial distribution of infection risk of airborne transmission diseases in a hospital ward. Proceedings of Healthy Buildings, Lisboa, Portugal, ISBN 9789899506718.
4. Li, Y, Leung, G M, Tang, J W, Yang, X, Chao, C Y H, Lin, J Z, Lu, J W, Nielsen, P V, Niu, J, Qian, H, Sleigh, A C, Su, H-J J, Sundell, J, Wong, T W, Yuen, P L. 2007. Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review. Indoor Air, 17, pp 2-18.
5. Nielsen, P V, Larsen, T S, and Topp, C. 2003. Design methods for air distribution systems and comparison between mixing ventilation and displacement ventilation. Proceedings of Healthy Buildings 2003, Singapore.
6. Nielsen, P V, Topp, C, Soennichsen, M, and Andersen, H. 2005. Air distribution in rooms generated by a textile terminal – comparison with mixing and displacement ventilation. ASHRAE Transactions, 111, Part 1, pp 733-739.
7. Nielsen, P V, Heby, T, and Moeller-Jensen, B. 2006. Air distribution in a room with ceiling-mounted diffusers – comparison with wall-mounted diffuser, vertical ventilation and displacement ventilation. ASHRAE Transactions.
8. Skistad, H, Mundt, E, Nielsen, P V, Hagstroem, K, and Railio, J. 2002. Displacement ventilation in non-industrial premises. REHVA Guidebook No 1.
9. Bjoern, E and Nielsen, P V. 2002. Dispersal of exhaled air and personal exposure in displacement ventilated rooms. Indoor Air, Vol 12, No 3, pp 147-164.
10. Qian, H, Nielsen, P V, Li, Y, and Hyldgaard, C E. 2004. Airflow and contaminant distribution in hospital wards with a displacement ventilalation system. The 2nd International Conference on Build Environment and Public Health, BEPH 2004, Shenzhen, China.
11. Nielsen, P V, Hyldgaard, C E, Melikov, A, Andersen, H, and Soennichsen, M. 2007. Personal exposure between people in a room ventilated by textile terminals – with and without personalized ventilation. HVAC&R Research, Vol 13, No 4.
12. ASHRAE. 2003. Health care facilities. ASHRAE Handbook, HVAC Applications, SI Edition, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, Ga.
13. Centers for Disease Control and Prevention. 1994. Guidelines for preventing the transmission of mycobacterium tuberculosis in health-care facilities. MMWR 1994;43 (No. RR-13). US Department of Health and Human Services, Atlanta, Ga.
14. Nielsen, P V, Li, Y, Buus, M, Winther, F V, and Qian, H. 2009. Cross infection in a hospital ward and deposition of particles exhaled from a source manikin. The Third International Conference on Built Environment and Public Health, Guilin.
15. Nielsen, P V, Jiang, H, and Polak, M. 2007. Bed with integrated personalized ventilation for minimizing cross infection. Roomvent 2007, 10th International Conference on Air Distribution in Rooms, Helsinki 2007.
16. Nielsen, P V, Polak, M, Jiang, H, Li, Y, and Qian, H. 2008. Protection against cross infection in hospital beds with integrated personalized ventilation. Indoor Air, 2008, Copenhagen.