Local ventilation for general patient rooms

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ABSTRACT

Numerous studies on ventilation of general patient rooms have been performed, while most of the studies have focused on total volume air distribution (mixing or displacement). This study presents results of local ventilation (LV) aimed to efficiently protect a lying person from cross-infection due to airborne respiratory viruses. Experiments performed in a climate chamber (4.7 m × 4.7 m × 2.6 m) included LV when used alone and when coupled with background mixing ventilation (MV). A thermal manikin and a heated standing dummy were used to simulate respectively a patient lying in bed and an infected doctor or nurse standing beside the bed. The LV was able to reduce substantially the exposure of the patient to the infected air exhaled by the doctor. The results show that the efficiency of the LV depended mostly on its supply airflow rate. An increase of the background ventilation's supply flow rate, i.e. increase of the air change rate in the room, was less important. At 15 L/s supplied by LV the concentration of a contaminant at the patient's mouth decreased by 76%. The findings of the paper give insights for researchers and designers in developing a novel ventilation system to be used during a pandemic in general patient rooms.

Keywords: Combined ventilation system, cross-infection, ventilation efficiency, thermal comfort

INTRODUCTION

Control of airborne disease transmission in healthcare facilities is important. A survey involving 138 hospitalized patients with confirmed novel coronavirus infected pneumonia (2019-nCoV) suggests that 41% of these patients were infected in the hospital (Wang et al., 2020). Due to lack of protection, asymptomatic infection was found to be the main cause of hospital transmission. Wang et al (2020) reported that one asymptomatic patient in a surgical department infected over ten healthcare workers and four patients in the same ward. Concentrated outbreakshappened in nursing home as well (Burton et al., 2020). Cross-infection in nursing homes was related to the high fatalities caused by 2019-nCoV among the aged in western countries (Ioannidis et al., 2020). Healthcare workers and visitors might be infection sources in healthcare facilities (Ambrosch et al., 2020).

The main purpose of ventilation of general hospital patient rooms/wards is to remove smell and keep the CO2 level and room temperature at certain standard required levels. Mixing ventilation with a relatively low flow rate is recommended for general patient rooms in the present hospital ventilation standards (ASHRAE, 2008; Huang et al., 2014; Langkilde, 2011).

Increasing the air change rate per hour (ACH) is applied to improve indoor air quality in rooms with mixing ventilation (Zhang et al., 2020). However, full-scale experiments of mixing ventilation studied the risk of cross-infection in an isolation room when a patient is coughing, and reported that elevated ACH might increase the exposure of the person in the room (Bolashikov et al., 2012). A CFD study on the removal of pollutants released from a lying patient indicates that the airflow pattern is more important for control of contaminants than ACH in a healthcare facility (Khankari, 2016). This result is in agreement with the results from an experimental study reported by (Pantelic & Tham, 2013).

There are several problems with mixing ventilation: (a) MV only dilutes the pollution concentration by mixing the clean supplied outdoor air with the polluted room air. In reality, however, the supply air is rarely fully mixed with the room air. Studies have shown that when supplying a high amount of outdoor air in rooms with mixing ventilation, the direction of the airflow pattern may even raise the transport of pollutants to the occupied zone (Bolashikov et al., 2012; Pantelic & Tham, 2013). This leads to an infective hazard for the occupants (Khankari, 2016); (b) In order to dilute the air pollutants, a large volume of outdoor air has to be treated and delivered continually, resulting in unnecessary energy consumptions; (c) It is impossible for existing systems designed economically for normal conditions to respond to epidemics (Melikov, 2020).

Efficient ventilation systems in hospitals are worthy of attention since nearly three-fourth of consumed energy in hospitals is used for HVAC systems (Grosskopf & Mousavi, 2014). Personalized ventilation (PV) is efficient (Melikov, 2004). Local ceiling supply system takes several advantages in patient rooms: (a) A ceiling-mounted local diffuser located above the patient can provide clean air directly to the breathing zone; (b) Unlike common personalized diffusers, the local diffuser is far from the patient's face, which is visually acceptable for the lying patient; and (c) There is no extra equipment installed in the occupied zone, which is important for keeping the space flexibility, especially around the patients' bed.

In order to develop a promising ventilation system utilized during pandemic in hospital wards or nursing homes where the patients are lying on fixed beds, the performance of three local air supply diffusers were tested (Shu et al., 2021). The novel diffusers included a coaxial rectangular jet and a lobed jet. The clean air was supplied at 23°C at a flow rate of 15 L/s. They found that the normalized contaminant concentration in patient's mouth (Eq.1) in a range of 0.8 to 0.3 was highly related to the designs of the diffuser for local ventilation (LV). Among them, a diffuser with an inner honeycomb plate (24 cm × 24 cm) was the most promising design. However, the heat loss from the thermal manikin's face, which simulated the patient in bed increased by 50% compared to the reference condition with only MV. The study concluded that the local ventilation may cause local thermal discomfort of the users.

A square diffuser with a size of 40 cm × 40 cm named 'honeycomb diffuser' inspired by Shu's design was developed and used in this study. The experimental room setup was the same as in Shu's study. The objective was to investigate the potential of the new diffuser to reduce the local draft caused by LV without undermining the ability to provide clean air to the breathing zone of the patient. The new local ventilation systems were evaluated when used alone and when coupled with background mixing ventilation.

METHOD

Experimental setup

A climate chamber with dimensions of 4.7 m × 4.7 m × 2.6 m (L × W × H) was used to simulate a typical general patient room in a hospital (Figure 1). The experimental room was built at 0.7 m above the floor in a tall hall. For the sake of observation, one of the walls (L × H) was made of single-layer glazing. The rest of the walls were built by chipboard insulated by a layer of styrofoam plates with a thickness of 6 cm. The ceiling was constructed by moveable gypsum plates with a size of 60 cm × 60 cm.

Figure 1. Layout of the experimental room (1. Diffuser for MV; 2. Diffuser for LV; 3. Exhaust vent)

A single bed (2.0 m × 0.9 m) was placed in the room's center. A thermal manikin (discussed later in the report) was used to simulate the patient in the bed. A heated dummy was used to simulate a person (doctor or nurse) standing beside the bed with the patient (25 cm far from the edge of the bed). The detailed locations of the heated dummy and patient bed were marked in the dashed line in Figure 2.

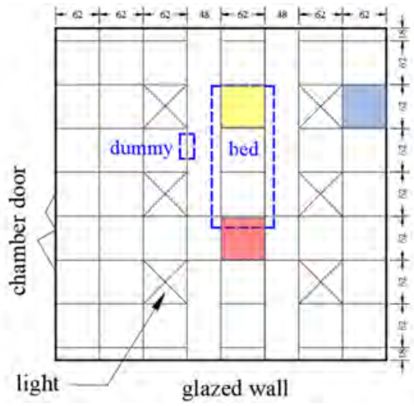

Figure 2. Layout of the climate chamber (top view) (Red: diffuser for MV; Yellow: diffuser for LV; Blue: exhaust vent)

A one-way square diffuser (LKA 125 from Lindab) was attached to the ceiling for the background ventilation. The air was supplied towards the glazing wall so that the supply jet of the MV ceiling diffuser does not disturb the supply jet generated by the LV, shown in Figure 3. A circular exhaust diffuser, type PCA 160 from Lindab, was installed on the ceiling close to the wall, considering a high position beneficial to remove airborne substances (Balaras et al., 2007).

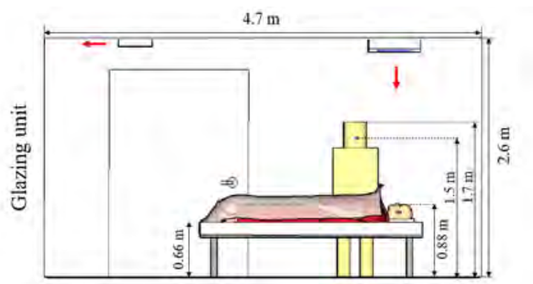

Figure 3. Layout of the climate chamber (side view) (Shu et al., 2021)

The honeycomb diffuser of the local ventilation was installed above the patient, a cool downward flow was supplied from it. The honeycomb structure was made of straws with Ø 0.8 cm and 15 cm long, fixed by a net at 8 cm above the box edge, shown in Figure 4. The diffuser was hanging from the ceiling with its opening being 118 cm above the patient's mouth. A 40 cm long flexible duct with Ø 0.8 cm was connecting the plastic box of the local diffuser from the top to the main supply duct of the ventilation system. Separate HVAC systems were used for the LV and MV.

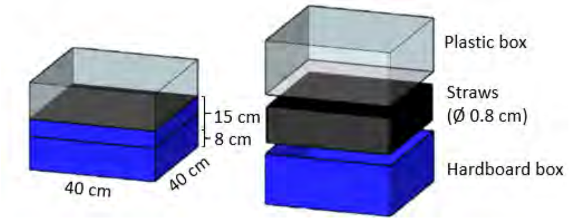

Figure 4. The construction of honeycomb diffuser

There were three internal heat sources in the experiments. A dummy made by galvanized ducts was used to present a standing person as an infected doctor, while a lying manikin was considered as an exposed patient. There were six lightings with a total power rate of 36 W attached to the ceiling. But most of their heat dissipated above the ceiling, since the backside of the lightings was directly exposed to the tall hall.

Both the dummy and the thermal manikin had a height of 1.7 m based on the average figure of Scandinavian women. The torso of the dummy was composed of a rectangular duct with dimensions of 0.35 m × 0.2 m × 0.6 m. In order to simulate the free convection flow around the human body, three bulbs with a total power rate of 109 W were installed inside the doctor's head, torso and legs, respectively. A small fan was placed in the torso to obtain a uniform temperature distribution on the surface of the dummy. The moisture released from occupants were disregarded in the study.

The heat loss from the human body depends on the thermal insulation of the clothing the body is covered. The non-breathing thermal manikin (TM) was wearing a set of short-sleeve pajamas and covered by a light-weight quilt. For measurement of the heat loss from different body parts, the manikin was divided into 17 segments and heated by electric resistance wires independently. In order to produce heat as a real person, the manikin was set to work in a "comfort mode". For this regulation method, the surface of the manikin's body has a temperature distribution, similar to the skin temperature of an average human under thermal comfort. The surface temperature of the manikin's whole body was about 35.5°C at steady-state.

The tracer-gas technique was applied to study how efficient is the local diffuser to protect the lying patient from airborne pollution. It is reliable to use tracer gas in investigating the dispersion of both fine and coarse aerosol particles in an indoor environment (Bivolarova et al., 2017). N_2O at a flow rate of 0.15 L/min was continuously released through a tube connected to a porous ceramic cylinder with a diameter of 0.012 m and a height of 0.02 attached to the doctor's mouth. The tube was connected to a gas cylinder located outside of the patient room. The initial momentum of the tracer gas flow released from the cylinder was neglected.

INNOVA 1303 is a multi-channel sampler, which was connected to an INNOVA photoacoustic gas monitor 1312 to monitor the concentration of the tracer gas at different points in the room. The precision of this system is 3%. There were six measurement points for each case. The concentration of the tracer gas in the inlet duct and exhaust duct were monitored in all conditions. The remaining four sampling points were arranged below the local ventilation diffuser, shown in Figure 5. The point at the left side of the diffuser at 108 cm above the patient was to study if there is entrainment of the pollutants coming from the doctor to the supply jet of the local diffuser. The rest of the points were located at the mouth of the patient, 40 cm and 108 cm above the mouth.

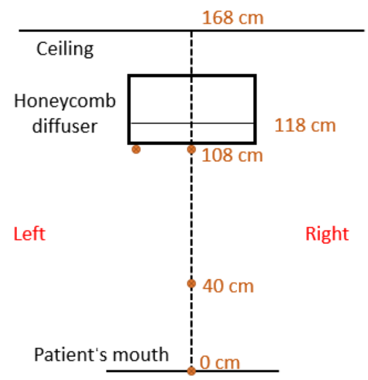

Figure 5. Measurement points for the concentration of N_2O

Experimental conditions

Table 1 summarizes the experimental conditions regarding the supply flow rate of the LV from 5 to 15 L/s. The background mixing ventilation at 5 L/s or 10 L/s was operated with LV to study the combined ventilation systems' performance.

Table 1. Experimental conditions

Case	Supply Air	
	Local Ventilation	Mixing Ventilation
1	0 L/s (Reference case)	15 L/s at 23°C
2	5 L/s at 23°C	0 L/s
3	5 L/s at 23°C	10 L/s at 23°C
4	10 L/s at 23°C	0 L/s
5	10 L/s at 23°C	5 L/s at 23°C
6	10 L/s at 23°C	10 L/s at 23°C
7	15 L/s at 23°C	0 L/s
8	15 L/s at 23°C	10 L/s at 23°C

The performance of the ventilation systems with the total volume of supply air in the range of 5 L/s to 25

L/s was tested. Slightly lower flow rate of exhaust air was adapted in all conditions to avoid unwanted infiltration of tracer gas to the chamber. 25.3±0.2°C was designed as room air temperature. The supply air temperature was set at 2°C lower than the room air temperature for a preferable downward movement of cold fresh air. The improvement of the patient's inhaled air quality and the local thermal discomfort caused by the local ventilation were compared with the results of the reference case of mixing ventilation at 15 L/s (No.1 listed in Table 1).

Experimental procedure

One experimental condition lasted approximately from 5 h to 8 h, depending on the total volume of supply fresh air. It took 3 h to 4 h to get a stable air temperature distribution in the room and to reach a steady-state of the tracer gas concentration. The room air temperature was adjusted prior to the measurements kept constant. The air temperature in the tall hall was kept at 23.8±0.2°C. At least 30 values of N_2O concentration were collected under steady-state for each measuring point. More values were collected for reliable results when concentration fluctuated largely.

Evaluation indicators

Average N_2O concentration, heat loss from the manikin and room air temperature were key indicators, obtained by calculating the mean values of the measurements after steady state for at least two-hour measuring period. Since the total amounts of clean air were different from case to case, normalized concentrations of N_2O tracer gas were calculated for all points to make cases comparable by the following equation. The results were corrected to the presence of tracer gas (due to leakages in the system) in the supply air c_{supply}. The ability to supply clean air to the manikin's breathing zone was evaluated by the normalized concentration of the measurement point placed at the centre of the upper lip of the thermal manikin (that is the patient). If it was less than 1, the measured concentration "c_i" at the point was lower than the concentration in the exhaust duct $c_{exhaust}$, the air at the breathing zone of the person simulated by the manikin was cleaner than that at the exhaust.

$$Normalized\ concentration = \frac{c_i - c_{supply}}{c_{exhaust} - c_{supply}} \quad (1)$$

Absolute concentration was used to evaluate the air quality directly, which is calculated by c_i - c_{supply}.

Local convective cooling of the body is one of the thermal comfort problems with the local ventilation that generates relatively high velocity at the head region of the person in the bed. Considering that in our study the body of the lying patient was covered with duvet, the average heat loss obtained under steady state condition from the manikin's head and top of the head, was the main concern. Heat loss from the head and the top of the head of the manikin measured under different conditions was compared with the heat loss measured under the reference case (clean air supply by the background ventilation of 15 L/s at 23°C), 34 W/m^2 and 35 W/m^2, respectively.

RESULTS

The following graphs summarize results of the tracer gas concentration obtained during the experiments with the honeycomb diffuser when it was operated alone and when it was combined with background ventilation at 5-10 L/s at 23°C. Figure 6 and Figure 7 show the concentration of N_2O at the patient's mouth in absolute and normalized values, where the x-axis is the sum of the supplied clean air by LV and MV from 5 to 25 L/s.

Both graphs demonstrate that increasing the supply volume of clean air through the LV improved the air quality in the patient's breathing zone. This can be observed when the supply flow rate of the LV increased from 5 L/s up to 15 L/s and the MV was switched off (cases 2, 4 and 7). But its efficiency (the ability to provide clean air to the manikin's mouth) decreased when the MV was turned on supplying 5 L/s and 10 L/s together with the LV at 10 L/s, resulting in total volume of supply air of 15 and 20 L/s (cases 4, 5 and 6).

When LV was supplying only 5 L/s, elevating the clean air supplied by the mixing ventilation was efficient to dilute some of the pollutants in the room (cases 2 and 3). This can be seen in Figure 6, case with total volume of supply air of 15 L/s compared with total volume of 5 L/s of air supplied only from the LV (green markers). The absolute concentration in the patient's mouth decreased due to the cleaner air entrained into the supply jet of the LV.

At the same total volume of supply air, the local ventilation was more efficient than the mixing background ventilation to protect the patient from infection. Compared with the background ventilation (reference case), 76% of the contaminant in the patient's mouth were reduced by the local ventilation with a supply flow rate of 15 L/s at 23°C (case 7) in Figure 7. These results show the importance of room air distribution and the volume of supply air is insufficient as criterion for ventilation design. This observation is also confirmed by comparing the absolute contaminant concentration at the patient's mouth, which doubled when the volume of supply air was 20 L/s (case 6), comparing to the concentration at 15 L/s supplied by the LV alone (case 7).

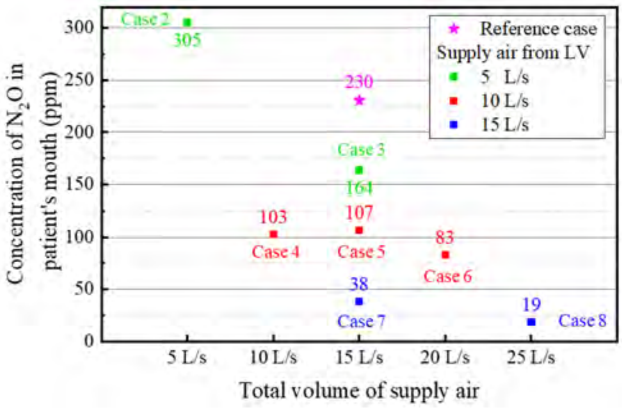

Figure 6. Absolute concentration of N2O in the patient's mouth

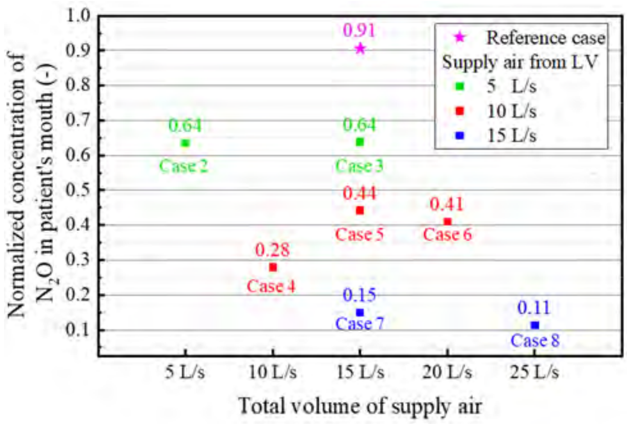

Figure 7. Normalized concentration of N2O in patient's mouth

Figure 8 and Figure 9 present the concentration measured along the centreline of the honeycomb diffuser at 40 and 108 cm above the patient's mouth. The measured tracer gas concentration at the mouth is located at a distance of zero in the figures.

Figure 8 summarizes the absolute concentration of N_2O along the centerline when the total volume of clean air at 15 L/s was delivered by the local diffuser and background mixing ventilation. Reference case (black line) shows that the mixing ventilation system worked as expected because a uniform pollutant concentration above the patient's mouth of 230 ppm was achieved. The absolute concentration in the patient's mouth falls from 164 ppm to 38 ppm when the flow rate of LV increases from 5 L/s to 15 L/s. Less room air was entrained by the airflow generated by the local ventilation when the flow rate of LV was higher.

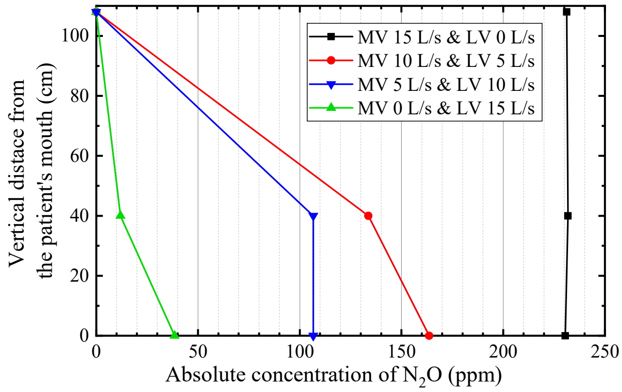

Figure 8.Concentration profile along the honeycomb diffuser's centreline at the total supply air volume of 15 L/s

Figure 9 shows the normalized concentration profile along the centreline below the honeycomb diffuser during experimental conditions with LV alone and combined with MV. MV was not the main factor of providing clean air when the LV supplied 5 L/s or 15 L/s. This can be seen when comparing the concentration profiles obtained with LV at 5 L/s alone and LV at 5 L/s combined with MV at 10 L/s (green curves in Figure 9), as well as when comparing the concentrations at LV at 15 L/s alone and combined with MV at 10 L/s (blue curves). Nevertheless, the local microenvironment below the local diffuser was influenced by the MV when 10 L/s was supplied by the LV. Less contaminant concentration was measured at both the patient's mouth and at 40 cm above the patient's head with LV at 10 L/s alone than with LV at 10 L/s combined with MV at 5 L/s or 10 L/s. An unexpected result was that with LV at 10 L/s alone, the tracer gas concentration at 40 cm above the manikin's head was slightly higher than at the mouth. The mechanism for the phenomenon is undefined.

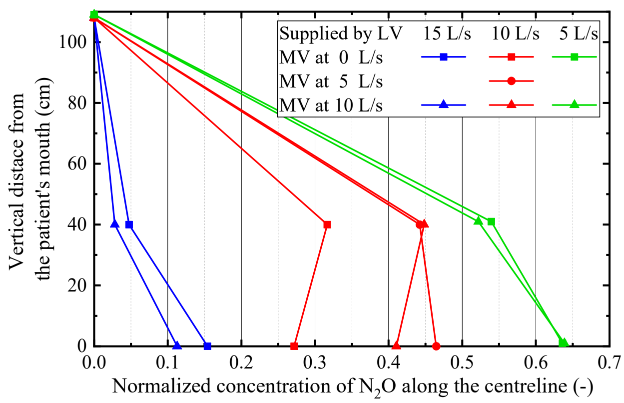

Figure 9. Normalized concentration profile

Heat losses from the TM's head and top of the head were different in all cases, excluding only the reference case. In almost all cases with LV the heat loss from the head was higher than the heat loss from the top of the head. Higher heat loss from the TM's head means that the supply jet of the LV penetrated the free convection flow from the TM's head. However, heat losses from the top of TM's head were slightly higher than from the head segment of the manikin in cases 5 and 6 when the LV supplied 10 L/s in combination with MV at 5 L/s and 10 L/s, respectively. These results could be due to complex flow interactions between the free convection flows of the heated dummy and the thermal manikin with the background room air distribution and supply jet of the LV. As a result, the local supply jet was deflected towards the top of the head of the manikin. This can be confirmed to some extent with the higher tracer gas concentration at the mouth in these conditions compared with LV at 10 L/s alone (Figure 9, red concentration profiles).

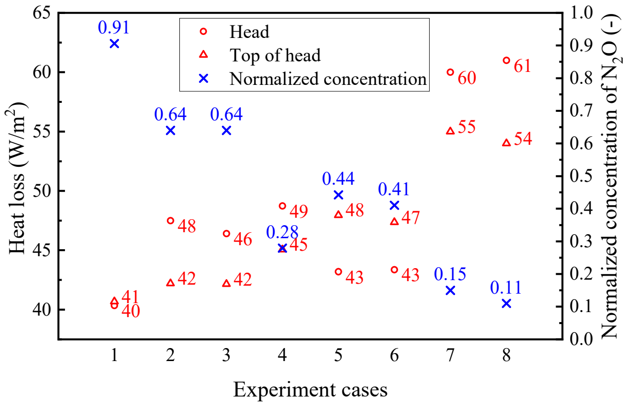

Figure 10. Heat loss and normalized concentration

DISCUSSION

Downward ventilation is suggested in hospitals for reducing the risk of cross-infection (ASHRAE, 2003). Shu et al. (2021) pointed out that contaminant concentration in the patient's mouth relies on the downward airspeed. Compared to the most efficient local diffuser design (diffuser with an inner plate of a honeycomb structure in a size of 24 cm × 24 cm), the presented in this study honeycomb diffuser with size of 40 cm x 40 cm provides 15% cleaner air to the patient's mouth, which resulted in about 80% reduction of pollutants. It was reported in Shu et al. (2021) that the airspeed measured at 20 cm above the manikin's face was 0.62 m/s with the local diffuser with honeycomb plate. Measurements of the airspeed (not shown in this paper) also at 20 cm above the manikin's face showed that the airspeed decreases to 0.35 m/s. Thus, the ventilation efficiency of the current LV diffuser is not merely dependent on the supply air velocity. It is also influenced by the size of laminar airflow generated by the diffuser. Laminar flow is beneficial for contaminant removal. Further improvement of the current design of honeycomb diffuser can be achieved by extending the length of the honeycomb assembly or reducing the size of the holes of the honeycomb, so that even more laminar flow is produced.

Although the new diffuser for the LV with a lower airspeed is also efficient to remove the contaminant from the patient's breathing zone, the heat loss from the patient's head is still high. Further studies with regards to reducing heat loss, including higher supply air temperature of LV, higher room air temperature, local heating and a supply jet which is not towards the patient's face might be considered. The potential of the honeycomb diffuser's practical use should be further studied with human subjects.

CONCLUSIONS

In this study, experiments in a climate chamber of 57.2 m³ were carried out to study the local ventilation performance in a single-bed general patient room when local ventilation is operating with/without the background mixing ventilation. The results show that the local ventilation (LV) is more efficient than the background mixing ventilation with a supply flow rate of 15 L/s at 23°C based on the concentration of a contaminant at the patient's mouth, with a significant decrease by 76%. The LV at 15 L/s combined with MV at 10 L/s only decreases normalized concentration in the breathing zone by 4%. Increasing total volume of clean air by MV might disturb the local supply airflow, and thus the clean air supply to the breathing zone of the patient, if the mixing ventilation induces an improper air pattern. Normalized concentration increases with the distance from the local diffuser's opening when there is only a local ventilation system operating.

REFERENCE

Ambrosch, A., Rockmann, F., Klawonn, F., & Lampl, B. (2020). Effect of a strict hygiene bundle for the prevention of nosocomial transmission of SARS-CoV-2 in the hospital: a practical approach from the field. *Journal of Infection and Public Health*, *13*(12), 1862–1867. https://doi.org/10.1016/j.jiph.2020.10.005

ASHRAE. (2003). *HVAC Design Manual for Hospitals and Clinics (Second Edition)*. W. Stephen Comstock.

ASHRAE. (2008). *ANSI/ASHRAEIASHE Standard 170-2008 Ventilation of Health Care Facilities*.

Balaras, C. A., Dascalaki, E., & Gaglia, A. (2007). HVAC and indoor thermal conditions in hospital operating rooms. *Energy and Buildings*, *39*(4), 454–470. https://doi.org/10.1016/j.enbuild.2006.09.004

Bivolarova, M., Ondráček, J., Melikov, A., & Ždímal, V. (2017). A comparison between tracer gas and aerosol particles distribution indoors: The impact of ventilation rate, interaction of airflows, and presence of objects. *Indoor Air*, *27*(6), 1201–1212. https://doi.org/10.1111/ina.12388

Bolashikov, Z. D., Melikov, A. K., Kierat, W., Popioek, Z., & Brand, M. (2012). Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation. *HVAC and R Research*, *18*(4), 602–615. https://doi.org/10.1080/10789669.2012.682692

Burton, J. K., Bayne, G., Evans, C., Garbe, F., Gorman, D., Honhold, N., McCormick, D., Othieno, R., Stevenson, J. E., Swietlik, S., Templeton, K. E., Tranter, M., Willocks, L., & Guthrie, B. (2020). Evolution and effects of COVID-19 outbreaks in care homes: a population analysis in 189 care homes in one geographical region of the UK. *The Lancet Healthy Longevity*, *1*(1), e21–e31. https://doi.org/10.1016/s2666-7568(20)30012-x

Grosskopf, K., & Mousavi, E. (2014). Bioaerosols in Health-care Environments. *ASHRAE Journal*, *56*(8), 22–31.

Huang, X., Xin, C., & Ling, X. (2014). *Code for design of infectious diseases hospital (GB 50849-2014)*. China planning press.

Ioannidis, J. P. A., Axfors, C., & Contopoulos-Ioannidis, D. G. (2020). Second versus first wave of COVID-19 deaths: Shifts in age distribution and in nursing home fatalities. *MedRxiv*, *195*(January). https://doi.org/10.1101/2020.11.28.20240366

Khankari, K. (2016). Airflow path matters patient room HVAC. *ASHRAE Journal*, *58*(6), 16–26.

Langkilde, P. (2011). *Ventilation for hospitals FprCEN/TR 16244*. Danish Standards Foundation (DS).

Melikov, A. K. (2004). Personalized ventilation. *Indoor Air*, *14*(s7), 157–167. https://doi.org/10.1111/j.1600-0668.2004.00284.x

Melikov, A. K. (2020). COVID-19: Reduction of airborne transmission needs paradigm shift in ventilation. *Building and Environment*, *186*, 19–21. https://doi.org/10.1016/j.buildenv.2020.107336

Pantelic, J., & Tham, K. W. (2013). Adequacy of air change rate as the sole indicator of an air distribution system's effectiveness to mitigate airborne infectious disease transmission caused by a cough release in the room with overhead mixing ventilation: A case study. *HVAC and R Research*, *19*(8), 947–961. https://doi.org/10.1080/10789669.2013.842447

Shu, L., Bivolarova1, M. P., & Melikov1, A. K. (2021). *Localized Ventilation Method for Providing Clean Air to Hospitalized Patients*.

Wang, D., Hu, B., Hu, C., Zhu, F., Liu, X., Zhang, J., Wang, B., Xiang, H., Cheng, Z., Xiong, Y., Zhao, Y., Li, Y., Wang, X., & Peng, Z. (2020). Clinical Characteristics of 138 Hospitalized Patients With 2019 Novel Coronavirus–Infected Pneumonia in Wuhan, China. *JAMA*, *323*(11), 1061. https://doi.org/10.1001/jama.2020.1585

Zhang, Y., Cao, G., Feng, G., Xue, K., Pedersen, C., Mathisen, H. M., Stenstad, L. I., & Skogås, J. G. (2020). The impact of air change rate on the air quality of surgical microenvironment in an operating room with mixing ventilation. *Journal of Building Engineering*, *32*(May), 101770. https://doi.org/10.1016/j.jobe.2020.101770