Energy-saving and IAQ control in hospital patient room by bed-integrated ventilation

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Abstract. The annual energy-saving potential and IAQ improvement by use of a hospital bed-integrated pollution source control, a ventilated mattress (VM) and local bed ventilation (LBV), was studied. The VM is designed to capture in the bed and exhaust human body bio-effluents. The LBV is supplies clean air close to the breathing zone of the patient in bed and exhausts the polluted (might be infected) exhaled air from the patient before it is mixed with the room air. Exhaled air removal efficiency of the LBV were assumed at 40%, 60% and 80%. Thus, the risk of cross-infection was reduced. Energy use simulations were performed by IDA-ICE software. Intake fraction was used to indirectly assess the risk of cross-infection. Three scenarios were simulated to evaluate the energy-saving potential of the source control methods: 1) a double-patient room (none of patients is infected) using the VM and constant air volume ventilation (CAV), 2) a double-patient room (either one or two patients is infected) using the VM and CAV and 3) a double-patient room (either one or two patients is infected) using the VM, the LBV and CAV. The results reveal that using the VM and the LBV at decreased background ventilation rate can be an effective method for reducing the energy costs needed for hospital wards. Depending on the operation of the VM and the LBV, the energy-saving was between 1880 kWh and 67964 kWh. The annual energy-saving was up to 83.6% when the ward with two infected patients using LBV at 80% exhaled air removal efficiency and CAV at a reduced ventilation rate, compared with the reference cases of only CAV operating at 12 air changes per hour (ACH).

Keywords. Hospital bed ventilation, pollution source control, reduction of airborne cross-infection, indoor air quality, energy-saving
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1. Introduction

Indoor air quality (IAQ) has a direct impact on the health, comfort, and productivity of occupants. It is related to indoor pollutant concentration. As the largest indoor pollution source, occupants emit bio-effluents with the exhaled air and body bio-effluent from the skin [1]. In health care facilities like hospitals, exhaled air of infected patients contains pathogenic particles (many of which are airborne), therefore the medical staff and visitors are at the risk of cross-infection [2].

Total volume ventilation is used as a pollution control solution in hospital patient rooms. During the COVID-19 pandemic, several guidelines recommend increasing ventilation rate in rooms to mitigate the risk of airborne cross-infection [3,4]. A HVAC system operating with high ventilation rate consumes a large amount of energy. Generally, the supplied clean air dilutes room air and reduces the contaminants not only in the occupied zone but also in the non-occupied zone. This process is energy inefficient [5].

Instead of total volume ventilation, source control method can be applied to improve indoor air quality at low energy consumption. With this approach pollutants are removed close to the source, i.e., occupant. Ventilation rate can be reduced because the contaminates are removed locally before they spread in the room. As a result, energy-saving can be achieved. In this study, two localized ventilation systems using the source control method were examined. A ventilated mattress (VM) with local heating and a local bed ventilation (LBV). These bed integrated ventilation systems work independently from the background total volume ventilation system.

The studied ventilated mattress is an advanced air distribution system, which evacuates the bio-effluents generated from the occupant's body and thus reduces the contaminate concentration in the room [6]. The ventilated mattress is placed on the top of the bed mattress. Inside the VM there is a three-dimensional spring. As a result, 96% of its inner volume is an air layer. Local exhaust including a small fan is installed at the end of the mattress (on the head side). There are two exhaust openings on the surface of the mattress under the patient feet (Fig. 1). 1.5-5 L/s of air is extracted from the micro-environment around the lying person through the openings. It has been shown that a filter made of chemically treated carbon fibre installed in the mattress removes efficiently the body-emitted pollution [6]. Thereby, the cleansed air can be released back into the room. The VM enables to capture and remove 98% of the bio-effluents emitted from the patient body [6].

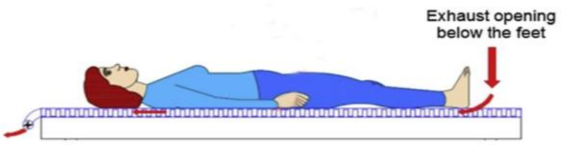

Fig. 1 - Bed-integrated ventilation method: ventilated mattress (Adapted from Bivolarova et al., 2016 [6]).

The airflow through the mattress increases the conductive heat loss from the body of the person in the bed, especially the body part in contact with the mattress. It provides local cooling for the person [7]. With the application of the local heating in the heating season, the ventilated mattress creates a comfortable bed micro-environment.

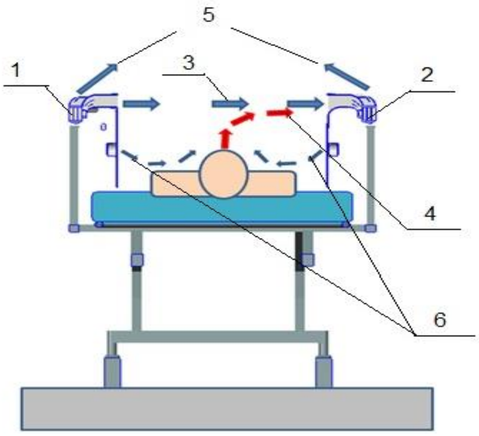

Fig. 2 - HBIVCU working principle: 1 supply ATD; 2 exhaust ATD; 3 horizontal air jet; 4 exhaled air by the patient; 5 vertical upward/inclined air curtains; 6 vertical downward air curtains (Kehayova and Melikov, 2017 [9]).

Hospital Bed Integrated Ventilation Cleansing Unit (HBIVCU), referred in this paper as LBV, is another studied advanced air distribution system that captures and removes human exhaled pollutants [8]. The mobile HBIVCU is installed on the support frame of the hospital bed, and it enables to follow the bed adjustment. Two air terminal devices (ATDs) are mounted on both side of the bed close to the patient head [8]. These devices are connected with air conditioning and distribution box installed at the back of the bed (not shown in Fig.2). HBIVCU working principle is illustrated in Fig. 2.

Room air is extracted in the box (unit 1) by the integrated fan, disinfected from viruses via HEPA filter and UVG light in the unit. The filtered air is then supplied horizontally (3), and gently guides part of the exhaled air toward the box on the opposite side (unit 2). Virus particles are removed in this box (2) and the clean air discharges back to the room. In addition, the clean air is supplied inclined/vertical upward to the ceiling (5) and downward alongside of the patient's head (6). The two upward air curtains are designed to protect a healthy person (medical staff and other occupants) inside the room from exposure to the polluted air coming from the pulmonary activities of the sick person, while it constrains and guides the polluted air upward to an exhaust. The two downward air curtains (6) provide clean air to the breathing zone of the person in bed and also local cooling of his/her head.

The objective of this study was to identify the energy-saving potential of the advanced ventilation system used in hospital room. The energy-saving potential is defined as annual energy-saving property of the hospital room with constant ventilation system (CAV) together with the advanced ventilation system, compared with the hospital room with only CAV.

2. Research Method

2.1 intake fraction

Intake fraction was used to indirectly determine the probability of infection, which was defined as "the proportion of air mass exhaled from the infected person that is then inhaled by the exposed person." [11]. During a certain period, the average intake fraction driven by time was determined with the equation (1):

$$IF = \frac{\int_0^{t_{in}} N_{in(t)} \rho_{in(t)} \dot{V}_{p,in(t)} dt}{\int_0^{t_{ex}} N_{ex(t)} \rho_{ex(t)} \dot{V}_{p,ex(t)} dt} \quad (1)$$

Where:

- $N_{in(t)}\rho_{in(t)}$= concentration of particles in the inhaled air by exposed person, particles/m^3;
- $N_{ex(t)}\rho_{ex(t)}$=concentration of particles in the exhaled air by infected person, particles/m^3;
- $\dot{V}_{p,in(t)}$=the pulmonary ventilation of the exposed person, considered as 1.00×10^{-3}m^3/s;
- $\dot{V}_{p,ex(t)}$=the pulmonary ventilation of the infected person, considered as 1.04×10^{-3}m^3/s;

The concentration of the virus particles was determined based on mass balance. It was related to virus generation rate and air change rate, which is shown in the Appendix of this paper.

2.2 parameters

The energy-saving potential of using the advanced ventilation systems was measured in three types of hospital rooms, namely a general ward, a patient room and an infection isolation room. These three rooms had same layouts (Fig. 3) with dimensions 8.4 m×4.7 m×2.8 m (W×L×H), i.e., 39.48 m^2 [12]. The window with area of 2.27 m^2 (1.2 m×2.27 m, W×L) was located 1 m above the floor. It was assumed that there were two patients reclined on the beds during the whole day. Their metabolic rate was 0.8 met (corresponding to approximately 73.6 W heat generated by each person with average body surface area at 1.6 m^2 in this position) [13]. Because medical staff spent little time in the room, their influence on the indoor environment was ignored.

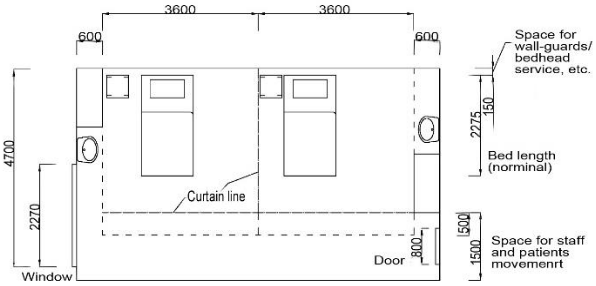

Fig. 3 - Hospital room layout.

It was assumed that the hospital building was located in Copenhagen, Denmark. Its building materials and U-value complied with the Danish Building Regulation [14]. The thermal resistance of the external wall with the window was 0.5372 W/m^2·K. The U-value of the internal walls and the floor were 0.37 W/m^2·K and 2.385 W/m^2·K, respectively. The glazing U-value of the chosen glass was 0.6 W/m^2·K, its solar and visible transmission coefficients were respectively 0.32 and 0.63. The window was oriented to south, its external blind would automatically draw when sunlight exceeded 100 W.

There were nine light-emitted diode lamps installed on the ceiling, each with a power of 5 W. Average heat gain of the medical equipment for each patient was assumed to be 114 W. Thus, the internal heat gain was 402.2 W. The medical equipment operated during the whole day while the lights only turned on from 7:00 to 21:00.

The local bed ventilation consumed 28.5 W during operation. The power of the VM consisted of driving the exhaust air through the mattress at 20W and the local heating. Energy consumption of the local heating depended on the room air temperature, its power was 36 W within the room temperature range of 18-20 ℃ and 18 W in the range of 20-23 ℃. The local heating was only provided when the indoor temperature was lower than 23℃.

2.3 simulated cases

The two hospital beds equipped with VM were used in the ward to enhance indoor air quality (Scenario 1). Neither of the two accommodated patients was infected in this scenario.

The two-bed ward without using the VM was considered as the reference case in Scenario 1. The ward was designed as a common public building room. Due to patients' high requirement of indoor environment quality, the ward was defined as Category Ⅰ, a very-low polluting building. Thus, the required ventilation rate for occupants was 10 L/(s·person) and 0.5 L/(s·m^2) for diluting the generated pollution, i.e., 39.74 L/s (corresponding to 1.30 ACH) for the whole room [13]. It was assumed that half (5 L/s) of the required ventilation rate for occupants is used to dilute body emitted bio-effluents and the other half (5 L/s) to dilute exhaled bio-effluents. The indoor temperature was kept in the range of 21-23 ℃ in the heating season, 23.5-25.5 ℃ in the cooling season. When VM is in operation, 98% of the body-emitted bio-effluents is removed [6]. Therefore, half of the required ventilation rate for occupants, i.e., 5 L/(s·person), was reduced to 2% (corresponding to 0.1 L/(s·person)). As a result, the ventilation rate in the ward with hospital bed equipped with the VM was reduced from 39.74 L/s to 29.94 L/s. Preliminary simulations in IDA ICE showed that this supply air flow rate was sufficient to keep the CO_2 concentration in the ward less than 950 ppm. This CO_2 level complies with the standard requirement for Category I [13]. The ventilation rate and supply temperature set-points of both cases are shown in Tab. 1. The return air temperature was set to 23 ℃.

Tab. 1 -Ventilation system parameters of the simulated cases in Scenario 1 (reference case with only CAV at 1.30 ACH and case with the VM and CAV at reduced ventilation rate in the ward).

Case	Ventilation rate	Min/Max supply temperature
RF-1.30 ACH	1.30 ACH (39.74 L/s)	19/19℃
VM-0.98 ACH	0.98 ACH (29.94 L/s)	19/19℃

In addition, the VM provided local heating and cooling, which created a comfortable bed micro-environment. Therefore, the indoor environment temperature range was set to be from 18 to 28℃. This range still fulfilled the requirement of occupants' thermal satisfaction and medical equipment operation [16]. The design relative humidity was kept between 30%-60% [15].

The local bed ventilation system was used to reduce the risk of airborne cross-infection in the hospital room (Scenario 2). The design temperature range was 21-24℃, return temperature was set to be 23℃ in IDA ICE model. The relative humidity was kept less than 60% and the CO_2 concentration was under 950 ppm as recommended [17].

A patient room without using the LBV was designed as a reference case. One of the two patients present in the room was assumed to be infected and exhaling infectious particles (Scenario 2.1). The design ventilation rate was 6 ACH, i.e., the recommended minimum total ventilation rate in patient rooms to reduce the risk of airborne transmission and protect uninfected person [4]. This is considered as sub scenario 2.1.1. By using the local bed ventilation, the recommended ventilation rate for airborne transmission control was reduced to achieve energy-saving. Three different exhaled air removal efficiencies (EARE) of the LBV were studied: 80%, 60% and 40%. When using the LBV, the background ventilation rate was reduced to a level which will not result in a higher than 0.0016% intake fraction. IF of 0.016% was obtained at the reference case with only background ventilation (referred in the following as IF=0.0016%). On the other hand, there is a minimum standard requirement of supplying 2 ACH outdoor air to a patient room for maintaining indoor air quality [17]. Therefore, background ventilation rate of 2 ACH was kept in the cases when it could be lower than this. The EARE of the LBV was implemented in equation (1) in order to calculate the intake fraction when the LBV was in operation (see equation 2, 3 and 4 in the Appendix). The corresponding calculated intake fraction for each case is shown in Tab. 2.

Tab. 2 – Intake fraction and ventilation system parameters of the simulated cases in Scenario 2.1.1 (reference case with only CAV at 6 ACH and cases with LBV at 80%, 60% and 40% in conjunction with reduced ventilation rate in the patient room).

Case	Ventilation rate	Intake fraction	Max/Min supply temperature
RF-6 ACH	6 ACH (184.24L/s)	0.016%	20/20°C
LBV - EARE80%	2ACH (61.41L/s)	0.006%	18/19°C
LBV - EARE60%	2ACH (61.41 L/s)	0.012%	18/19°C
LBV - EARE40%	2.8ACH (85.98 L/s)	0.016%	19/19°C

In another sub scenario 2.1.2, the ventilation rate of the reference patient room was designed as 60 L/(s·person), i.e., 3.91 ACH, according to the recommendations in the WHO roadmap [4]. The calculated intake fraction of the uninfected exposed patient was 0.022% under this condition (designated as IF=0.022%). Thus, the background ventilation rate was reduced to levels, which would keep the same or lower IF when the LBV was in operation. The intake fraction and the ventilation system parameters of the cases are shown in Tab. 3.

Tab. 3 - Intake fraction and ventilation system parameters of the simulated cases in Scenario 2.1.2 (reference case with only CAV at 3.91 ACH and cases with LBV at 80%, 60% and 40% in conjunction with reduced ventilation rate in the patient room).

Case	Ventilation rate	Intake fraction	Max/Min supply temperature
RF-120 L/s	3.91 ACH (120 L/s)	0.022%	20/20°C
LBV - EARE80%	2 ACH (61.41L/s)	0.006%	19/19°C
LBV - EARE60%	2 ACH (61.41L/s)	0.012%	19/19°C
LBV - EARE40%	2 ACH (61.41L/s)	0.019%	19/19°C

Scenario 2.2 was a situation of two infected patients present in an airborne infection isolation room. The infection isolation room only with CAV system at 12 ACH (368.48 L/s) was considered as the reference case [17]. In this scenario, only visitors like doctors were under the risk of cross-infection, their intake fraction was 0.009% in the reference case, which was designated as IF=0.009%. Intake fraction and ventilation system parameters of the cases are shown in Tab. 4.

Tab. 4 - Ventilation system parameters of the simulated cases in Scenario 2.2 (reference case with only CAV at 12 ACH and cases with LBV at 80%, 60% and 40% in conjunction with reduced ventilation rate in the infection isolation room).

Case	Ventilation rate	Intake fraction	Max/Min supply temperature
RF-12 ACH	12 ACH (368.48L/s)	0.009%	20/20℃
LBV - EARE80%	2 ACH (61.41L/s)	0.006%	20/20℃
LBV - EARE60%	3.8 ACH (116.69L/s)	0.009%	20/20℃
LBV - EARE40%	6.6 ACH (202.66L/s)	0.009%	20/20℃

In order to improve indoor environment meanwhile reduce the risk of airborne cross-infection, both LBV and VM were used in the patient room (Sub scenario 3.1) and the infection isolation room (Sub scenario 3.2). The air quality level was not evaluated in these scenarios, because the airflow requirement of bio-effluent dilution was undefined. Therefore, the ventilation methods of cases in Scenarios 3.1 and 3.2 were equipped VM on the basis of cases in Scenarios 2.1 and 2.2. All cases in Scenario 3 were shown in Tab.5, 6, and 7. Energy-saving was achieved by extending design temperature range to 18-28 ℃ in simulation cases with the use of VM.

Tab. 5 - Ventilation system parameters of simulation cases in Scenario 3.1.1 (cases with VM and LBV at 80%, 60% and 40% in conjunction with reduced ventilation rate in the patient room).

Case	Ventilation rate	Intake fraction	Max/Min supply temperature
LBVVM - EARE80%	2ACH (61.41L/s)	0.006%	19/21℃
LBVVM - EARE60%	2ACH (61.41L/s)	0.012%	19/21℃

LBVVM - EARE40%	2.8ACH (85.98L/s)	0.016%	20/20℃

Tab. 6 - Ventilation system parameters of simulation cases in Scenario 3.1.2 (cases with VM and LBV at 80%, 60% and 40% in conjunction with reduced ventilation rate in the patient room).

Case	Ventilation rate	Intake fraction	Max/Min supply temperature
LBVVM - EARE80%	2 ACH (61.41L/s)	0.006%	19/21℃
LBVVM - EARE60%	2 ACH (61.41L/s)	0.012%	19/21℃
LBVVM - EARE40%	2 ACH (61.41L/s)	0.019%	19/21℃

Tab. 7 - Ventilation system parameters of simulation cases in Scenario 3.2 (cases with LBV at 80%, 60% and 40% in conjunction with reduced ventilation rate in the infection isolation room).

Case	Ventilation rate	Intake fraction	Max/Min supply temperature
LBVVM-EARE80%	2 ACH (61.41L/s)	0.006%	20/20℃
LBVVM - EARE60%	3.8 ACH (116.69L/s)	0.009%	20/20℃
LBVVM - EARE40%	6.6 ACH (202.66L/s)	0.009%	20/20℃

2.4 HVAC system

Thermal comfort environment in the simulated hospital patient rooms was provided by constant air volume (CAV) system with steam humidifier. A specially controlled steam humidifier and a relative humidity sensor installed to fulfil the standard requirement of 30%- 60% RH [15]. A second heating coil in the AHU installed after the cooling coil was used to dehumidify the supply air in the cooling season. It turned off when there was no need to dehumidify (the case with combination of VM and CAV at reduced ventilation rate in this study). The max and minimum supply air humidity were set at 30% and 90% separately, and the return air humidity set-point was 50%.

The studied room was designed as a typical hospital room. Typical thermal bridge was created in the model as a source of heat loss. Typical infiltration of 0.5 ACH at 50 Pa was chosen based on the wind driven outdoor air. Temperature set-point of the chiller in the default plant was 5℃, its coefficient of performance was 3.8; water set-point of the boiler was 35℃ while its coefficient was set to 90%.

3. Result

3.1 potential energy-saving with the ventilated mattress

Fig. 4 presents results of the annual energy need of the cases with only CAV system (reference case) and the ventilated mattresses with local heating combined with CAV system at reduced background ventilation rate. Compared with the reference case, the annual energy consumption was reduced by 22.5% when using hospital beds equipped with the VM in the ward.

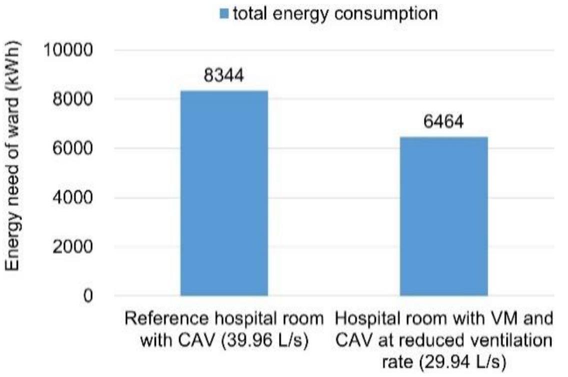

Fig. 4 – Annual energy need of the ward with background ventilation only (reference case) and with the ventilated mattress in conjunction with reduced background ventilation.

3.2 potential energy-saving with the local bed ventilation

Fig.5 presents the results of the annual energy need of the cases focusing on cross-infection reduction. In Scenario 2, the reference cases for the patient room included CAV at recommended 3.91 ACH (60 L/(s·person)) and 6 ACH (184.24 L/s). For the infection isolation room, the reference case included CAV at 12 ACH (368.48 L/s).

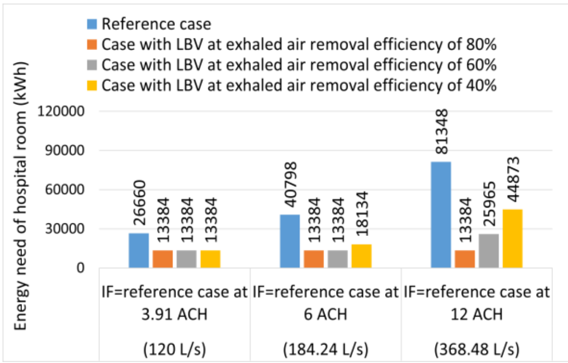

Fig. 5 – Annual energy need of the ward with background ventilation only (reference case) and with the local bed ventilation in conjunction with reduced background ventilation.

Compared with the reference case at 3.91 ACH (120 L/s), 49.8% energy-saving was achieved by the use of the local bed ventilation operated at 40%, 60% or 80% exhaled air removal efficiency (in Fig. 5). Under this condition, the CAV system with reduced background ventilation was maintained at 2 ACH.

The reduction of background ventilation by the use of the LBV at 80%, 60% and 40% exhaled air removal efficiency led to respectively 67.2 % (2 ACH), 67.2% (2 ACH) and 55.6% (2.8 ACH) energy-saving, compared to the reference case at 6 ACH (184.24 L/s).

With the comparison of the reference case with CAV at 12 ACH (368.48 L/s), the energy-saving of 83.6%, 68.1% and 44.8% was achieved when the LBV operated at respectively 40%, 60% and 80% with reduced background ventilation (2 ACH, 3.8 ACH and 6.6 ACH, respectively) in the infection insolation room.

3.3 potential energy-saving with combination of ventilated mattress and local bed ventilation

Fig. 6 presents the result of the annual energy need of the cases focusing on both cross-infection reduction and indoor air quality improvement.

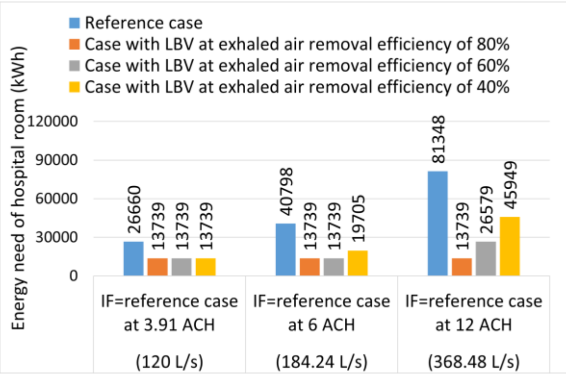

Fig. 6 – Annual energy need of the ward with background ventilation only (reference case) and with the ventilated mattress and the local bed ventilation in conjunction with reduced background ventilation.

48.5% energy-saving was achieved by the use of the VM and LBV operated at 40%, 60% or 80% exhaled air removal efficiency with reduced background ventilation at 2 ACH, compared with the reference case at 3.91 ACH (120 L/s).

The reduction of background ventilation by the use of combination of the VM and the LBV at 80%, 60% and 40% exhaled air removal efficiency led to 66.3 % (2 ACH), 66.3% (2 ACH) and 51.7% (2.8 ACH) energy-saving, compared to the reference case at 6 ACH (184.24 L/s).

Compared with the reference case at 12 ACH (368.48 L/s), the energy-saving of 83.1%, 67.3% and 43.5% was achieved when the LBV operated at respectively 40%, 60% and 80% with reduced background ventilation (2 ACH, 3.8 ACH and 6.6 ACH respectively) in the infection insolation room.

4. Discussion

An important challenge of creating an acceptable indoor air environment while saving energy could be achieved by ventilation based on the source control method. The simulation results of the present study showed that both the ventilated mattress and the local bed ventilation efficiently reduced the annual energy need in the studied hospital room scenarios. The energy-saving potential of the local bed ventilation increased when its exhaled air removal efficiency increased. However, the application of the VM lessened the energy-saving of the room with the combination of the LBV and CAV. More researches are needed to assess the ability of the VM to improve air quality under the risk of cross-infection, which was not considered in the current study.

Because the ventilated mattress removes 98% of the bio-effluents generated from the body, the same indoor air quality level as in the reference case only with mixing ventilation can be obtained but at a reduced ventilation rate. Therefore, less energy is needed for the AHU operation to air-condition the outdoor supply air.

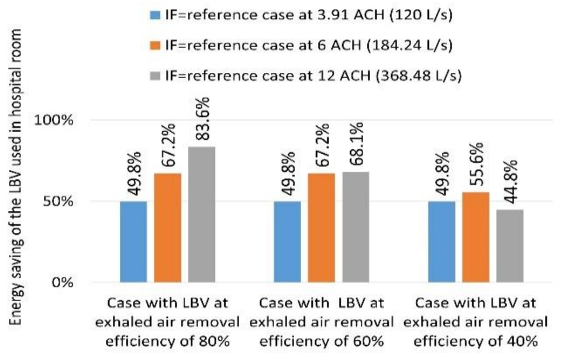

Fig. 7 – Energy-saving of the hospital rooms with the local bed ventilation (LBV) at 80%, 60% and 40% removal efficiency in conjunction with reduced background ventilation.

The energy-saving efficiency of the LBV system (as shown in Fig. 7) was related to the reduction rate of the background ventilation. The local bed ventilation at 60% and 80% EARE had the largest energy-saving capacity and led to highest background ventilation reduction rate in the infection isolation room. In contrast, the energy-saving potential of the LBV at 40% EARE in the isolation room was lower than that of the LBV at same EARE operating the patient room (reference case at 6 ACH, i.e., 184.24 L/s). This is because the background ventilation rate was reduced by 45% (from 12 ACH (reference) to 6.6 ACH) and 52.3% (from 6 ACH to 2.8 ACH) in the case of isolation room and patient room with the LBV with 40% EARE, respectively.

The energy-saving potential of the combination of VM and LBV was slightly lower than in the case when only the LBV was used. This was due to the energy need for local heating in the case with both VM and LBV.

The use of the local bed ventilation might also save initial cost and space for the construction of the HVAC system. Due to noise generation and pressure control, the acceptable air velocity in ventilation ducts connecting the air terminal devices is recommended to be in a range of 1.2 m/s and 2.3 m/s.

The duct diameter of the cases in Scenario 2.1.2 were calculated as an example how building space can be saved when using advanced ventilation systems (as shown in Table 8).

Tab. 8 – Air velocity in a duct and duct diameter (connecting with ATD) of the cases in Scenario 2.1.2.

Case	Ventilation rate	Duct [mm]	Velocity [m/s]
RF-120L/s	3.91 ACH (120 L/s)	315	1.54
Case with LBV	2 ACH (61.41 L/s)	200	1.95

As of November 2021, over 2 billion cases of confirmed Sars-COV-2 have been reported worldwide. Ohsfeldt et al. reported that the median hospitalization day of an infected person was 6 days, and the median cost per day for one patient was $1772 in the USA (intensive care unit required patients were not included) [18]. A healthy and clean indoor environment provided by ventilation systems promotes rehabilitation, reduces the infection risk of exposed person and cross-infection risk. Shorter hospital stays and fewer inpatients mitigate the significant burden on the healthcare system and finances.

This study has several limitations. To simplify the simulation, the models were assumed as a steady indoor environment with constant airflow, air pressure, indoor temperature, internal heat gain, etc. In reality, these factors vary with time and accommodated person movement. Meanwhile, the present energy-saving potential of the advanced ventilation systems were determined in hospitals built in a cold and dry environment (Copenhagen, Denmark). Outdoor climate might somewhat impact the energy-saving capability of these devices. Further studies which consider these variables are required.

The results of the present study were limited by the simulation software. The ventilated mattress and the local bed ventilation were not simulated as advanced ventilation systems. They were built as normal equipment which only generated heat and consumed energy, cooling effect due to air movement was not took into account. In addition, local heating of the ventilated mattress was unable to be incorporated as a heating unit. Instead, it was also simulated as an equipment with certain power.

5. Conclusion

In this study, annual energy consumption of a two-patient hospital room was simulated to determine the energy-saving potential of the ventilated mattress and the local bed ventilation.

The results showed that the use of the ventilated mattresses with local heating achieves 22.5% energy-saving in the hospital room with two uninfected patients. The local bed ventilation performed the greatest energy-saving potential of 83.6% in the infection isolation room with two infected patients, the exhale air removal efficiency of the LBV was 80%. The hospital room with beds equipped with a combination of the local bed ventilation and the ventilated mattress consumed slightly higher energy than equipped with only LBV under the same condition.

The implementation of local bed ventilation will lead to use of smaller HVAC and duct systems and thus space in hospital buildings will be saved.

Further studies might explore the influence of the occupancy schedule, activities of people and outdoor climate. The simulation method should be improved to model the LBV and VM as ventilation units and take local heating into account.

6. Acknowledgement

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8. Appendix

According to the mass balance, the average virus particle concentration was determined by equation (2).

$$\frac{X_r - X_0}{X_\infty - X_0} = 1 - \mathrm{e}^{-b(t-t_0)} \tag{2}$$

Where:

- X_0=concentration of pollutant at the beginning, considered as 0, particles/m^3;
- $X_\infty=\frac{\dot{G}}{V_r}$, equilibrium particle concentration of the investigated space, particles/m^3;
- $b=\frac{\dot{V_r}}{V_r}$, air change rate, L/s;
- t=time, s;
- t_0= beginning time, considered as 0, s.

Sars-Cov-2 was considered as the main studied airborne virus, its generation rate was 426 particles/s, corresponding to 2554 particles/exhalation when the patient's exhalation rate is assumed as 10 exhalation/min.

When $(t-t_0) = 5\cdot\frac{1}{b}$, $\frac{X_r - X_0}{X_\infty - X_0} = 0.997$ and the virus concentration in the investigation space keeps approximately constant. Then the average particle concentration for an interval of $[t_0, 5\cdot\frac{1}{\mathrm{b}}]$ could be determined by equation (3):

$$\overline{X_b} = X_\infty + \frac{(X_0 - X_\infty)(\mathrm{e}^{-bt_1} - \mathrm{e}^{-bt_2})}{b(t_2 - t_1)} \tag{3}$$

$\overline{X_b}$ is the determined average Sar-COV-2 virus concentration. t_1, t_2 is the stating time and ending time of the determined interval.

The studied LBV removes exhaled virus particles at 40%, 60% and 80% close to patient's breathing zone, thus calculated exhaled particles in the investigate space reduce to 60%, 40% and 20%.

Then the virus particle concentration in the hospital room with LBV was determined by equation (4).

$$\overline{X_b{}'} = X_\infty{}' + \frac{(X_0 - X_\infty{}')(e^{-bt_1} - e^{-bt_2})}{b(t_2 - t_1)} \tag{4}$$

Where:

- $\overline{X_b{}'}$=concentration of pollutant of the investigated space using LBV, particles/m^3;
- $X_\infty{}'=X_\infty(1-\eta_{LC})$, equilibrium particle concentration of the investigated space using LBV, particles/m^3.

Data Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.