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Role of Energy Recovery Ventilators on the Indoor Airborne Disease Transmission

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Highlights

- Impact of energy recovery ventilators (ERV) on the probability of infection in a multi-room office building is studied
- ERV slightly increases the probability of infection only in the connected rooms (rooms without infection source)
- Bypassing ERV increases the probability of infection in both source and connected rooms

Abstract

Energy recovery ventilators (ERVs) are commonly used in HVAC systems to reduce energy consumption. ERVs transfer the energy from the exhaust air and use it to precondition the incoming outdoor ventilation air. According to literature evidence of non-biological contaminant transfer, it is suspected that the bioaerosols (with pathogen) may be transferred from exhaust to ventilation air during energy transfer in ERVs. This may lead to disease transmission indoors. Consequently, without any experimental/field evidence, ERVs are often bypassed in the HVAC systems during pandemic operations. To address this research gap, this study numerically analyzes the effect of ERVs on indoor airborne disease transmission in a multi-room office building. It is identified that the ERV slightly increases the infection risk only in the connected rooms (rooms without the source of infection), whereas bypassing ERV increases the infection risk in both source and connected rooms.

Keywords: Energy recovery ventilator, HVAC system, pandemic ventilation, probability of infection

Introduction

Pandemic is not new to the world. A recent study listed that the world faced at least 17 major pandemics before COVID-19. For example, a human plague outbreak by the flea-borne bacteria Yersinia pestis killed around 100 million people in the Roman Empire between 541 and 543 [1]. Hence, developing the infrastructure to curb disease transmission for future pandemics is essential. When applying the traditional hierarchy of hazard control strategies, the engineering control measures are more effective than the common pandemic control measures (namely using masks, handwashing, and social distancing), which mostly fall in the last two categories of the control hierarchy, as shown in Figure 1 [2]. Hence, engineering measures for controlling airborne transmission have been considered to be a high priority since the last pandemic outbreak. It was found that the airborne transmission of infectious diseases, including COVID-19, mostly occurs indoors rather than in outdoor settings [3]. Hence, it is vital to develop measures to control disease transmission in indoor settings.

Engineering control measures are majorly classified into three types, namely filtration, inactivation, and ventilation. Both filtration and inactivation technologies are somewhat specific to the characteristics of pathogens, such as size, concentration, etc. Moreover, some of the inactivation technologies have safety constraints. For example, ultraviolet germicidal radiation is a widely adopted technology in which irradiation and inactivated contaminants might risk human health. Similarly, the bipolar ionization system may release ozone during disinfection, which concerns the occupant's health. However, increasing ventilation to reduce airborne disease transmission is applicable to all types of infectious diseases and doesn't have safety concerns [4].

In the ventilation technique, the outdoor ventilation rate is increased to dilute the concentration of infectious aerosols indoors, thereby minimizing disease transmission. However, increasing the outdoor air supply is not feasible if outdoor climatic conditions are far from human comfort conditions. For example, the average monthly temperature in Saskatoon, Canada, is -9°C in January [5]. Supply of ventilation air in these extreme outdoor conditions will lead to an uncomfortable indoor environment, which can cause thermal stress to the occupants, may be life-threatening, and can also lower human resistance to infection [6]. Hence, it is essential to first condition the outdoor air before supplying it to an indoor environment. This increases the energy consumption of heating, ventilation, and air conditioning (HVAC) systems. The increase depends on the climatic conditions and operational conditions of the building. A study of the climatic conditions of China predicted that the increase in energy consumption of buildings was likely to be as high as 140% [7].

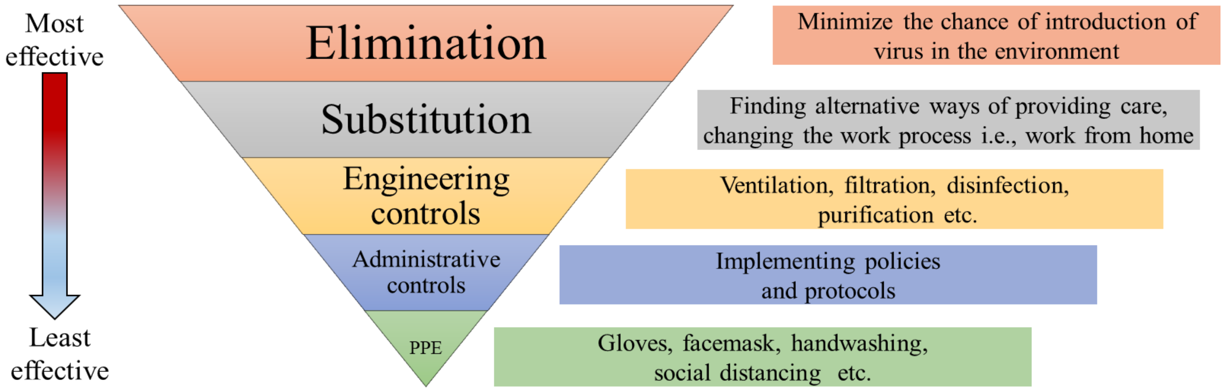


Figure 1: Hierarchy to control the pandemic outbreak (adopted from the hazard control hierarchy in the workplace by the Centers for Disease Control and Prevention, United States)

Energy recovery ventilators (ERVs) are commonly used in HVAC systems to reduce energy consumption and operating costs, especially during pandemic operations when the required ventilation rate is substantially higher than normal operating times. Figure 2 shows the schematic of providing ventilation to a building using the HVAC system with an ERV. As shown, the energy from the exhaust air is used to precondition the incoming outdoor ventilation air. The operation of ERVs may lead to the transfer of bioaerosols (a type of airborne material with microorganisms or biological items that originate from living organisms) from the exhaust to the fresh ventilation air entering the building. Consequently, it may lead to disease transmission in the building. As a result, all the pandemic guidelines [8] are recommended to bypass or operate ERV with constraints to reduce the disease transmission risk. Table 1 lists the recommendations about ERV in pandemic HVAC guidelines [8]. As a result, ERVs are mostly bypassed by HVAC systems during the COVID pandemic operation.

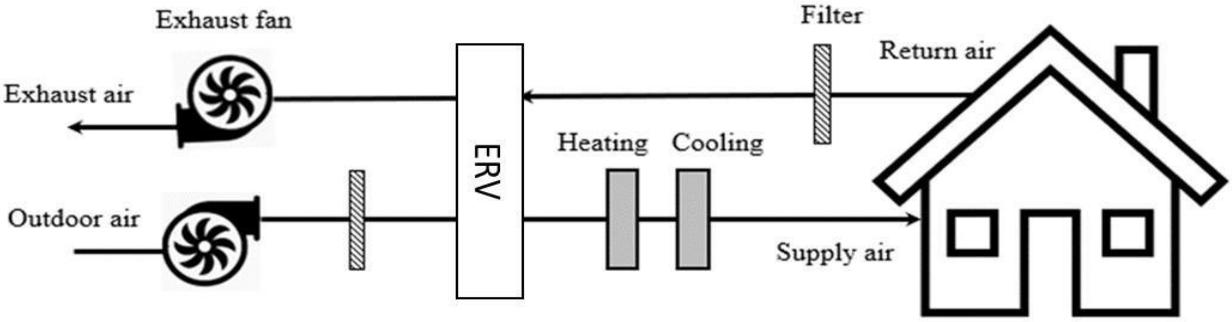


Figure 2: Schematic of the ventilation to a building by the heating, ventilation and air conditioning system with an energy recovery ventilator (ERV)

There is no experimental/field evidence of bio-aerosol transfer in ERV, and thus, the recommendations listed in Table 1 to bypass ERV or operate ERV with constraints are not sustainable. This research gap forms the primary motivation for this research work. When the ERV is bypassed, HVAC systems must operate with a lesser ventilation rate to maintain the designed thermal comfort conditions indoors. Providing a lower ventilation rate indoors may increase the risk of disease transmission. Hence, bypassing ERV has two simultaneous effects: (i) decreases the disease transmission risk by avoiding the bioaerosols transfer across air streams and (ii) increases the disease transmission risk due to the decrease in ventilation rate. The consolidated influence of these effects has not been studied so far. Hence, the present study numerically analyzes the impact of ERV on indoor airborne disease transmission of infectious pathogens.

Table 1: Recommendations about ERV in the pandemic HVAC guidelines [8]

Agency	Recommendation related to ERV
• American Society of Heating, Refrigerating and Air-Conditioning Engineers	Heat recovery devices can be utilized if the leakage percentage is acceptable
• Federation of European Heating, Ventilation and Air Conditioning Associations • European Centre for Disease Prevention and Control • Society of Heating, Air-Conditioning and Sanitary Engineers of Japan	Heat recovery devices can be utilized when leakage is below 5%
• Canadian Committee on Indoor Air Quality	Cross-contamination between outdoor air and exhaust air should be avoided with the application of heat recovery devices
• ASHRAE Singapore Chapter • Indian Society of Heating, Refrigerating and Air Conditioning Engineers	Rotary heat exchangers should not be applied

Method

The study is performed for a building with three medium-sized enclosed office rooms and an HVAC system, as shown in Figure 3. Each room contains two adults, and only one adult in the source room got infected with COVID-19. Each room is considered a standard enclosed office of approximately 42.3 m^2 and a height of 2.7 m. The office schedule is assumed to be 8 hours, and the work is regarded as sedentary. The study assumes that the room air is well mixed due to its circulation, i.e., the concentration of any pollutants or pathogens in the room is the same. In addition, the concentration of pathogens in the rooms and ducts is assumed to be uniform in space. The concentration of pathogen is measured in terms of "quanta". A quantum is defined as the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons. The estimated infection risk of the pathogen is generally presented as "probability of infection", which depends on the number of quanta inhaled by the susceptible person. The conservation of pathogen concentration in a room can be expressed as [9, 10]:

$$V\frac{dC}{dt} = A_sN_s - A_rN_r - A_dN_d + \oiiint R_{generation}dV + \oiiint R_{decay}dV \tag{1}$$

Where C is the volume-averaged concentration (m^{-3}), V is the volume of the room (m^3), A_jN_j is the flux of the pathogen to or from the room (s, r, d and f denotes the supply air duct, return air duct, door leakage area and floor settling), $R_{generation}$ is considered as a constant generation term that accounts for coughing, sneezing etc. Various environmental factors such as humidity, temperature, and sunlight can inactivate the virus and are represented by the first-order term R_{decay}.

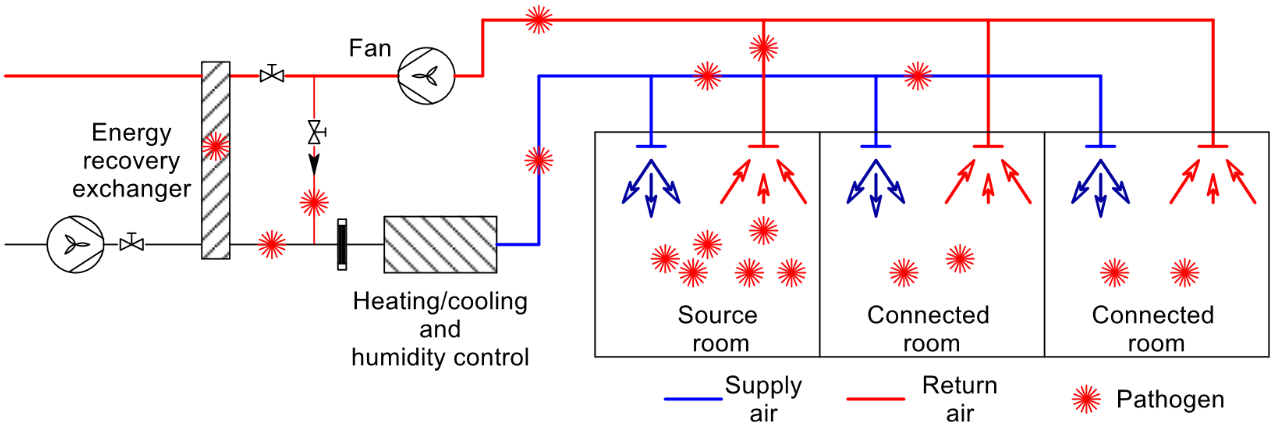


Figure 3: Disease transmission due to the pathogen transfer in ERV in an office building with one source and two connected rooms

Equation (1) can be normalized for the source room (C_{SR}) with respect to the volume of the rooms and considering the order of various terms above gives:

$$\frac{dC_{SR}}{dt} = \left(\left[\frac{\lambda.A \cdot m_{RA}}{m_{SA}}\right] \cdot [C_{SR} + (N \cdot C_{CR})]\right) + \dot{C}_g - \Lambda C_{SR} \tag{2}$$

Where λ is the air change per hour of the room (h^{-1}), which includes the effect of door leakage, m_{RA} and m_{SA} are the recirculation and supply air flow rates normalized to the volume of the room (h^{-1}), N is the number of connected rooms, C_{CR} is the volume averaged virus concentration in the connected rooms, $\dot{C}_g$ is the virus generation rate, which could be evaluated as per equation (3):

$$\dot{C}_g = \frac{q}{V} \tag{3}$$

Where q represents the quantum generation rate (h^{-1}), which is a function of the pathogen species, hazard control effectiveness, etc. q is estimated using a Monte Carlo approach to solve the piecewise volume integral of the virus concentration and is taken as 58 h^{-1} in this study for sedentary office work. A is a constant expressed as:

$$A = \frac{1-\eta_f}{(N+1)} \tag{4}$$

Where η_f is the efficiency of the filter used in the HVAC system. Λ is the effective ventilation rate (h^{-1}), which takes into account the effect of virus inactivation and settling and is written as:

$$\Lambda = \lambda + \frac{v_f}{H} + k_{decay} \tag{5}$$

Where H is the height of the room (m) and k_{decay} is the virus decay rate (0.63 h^{-1}), v_f is the floor settling velocity (ms^{-1}), which is calculated as per Stokes' terminal velocity approximation:

$$v_f = \frac{\rho_d - \rho_f}{18\mu_f} g d^2 \tag{6}$$

ρ_d and ρ_f are the densities of the droplet (1000 kgm^{-3}) and air (1 kgm^{-3}), μ_f is the viscosity of air ($1.8 \cdot 10^5$ Pa s), g is 9.81 ms^{-2} and d is the geometric mean diameter of the virus in size ranges at 0.55 µm (0.3-1 µm), 1.7 µm (1-3 µm) and 5.5 µm (3-10 µm). The distribution of the virus generated in these ranges was observed to be 15%, 25%, and 60%, respectively. The virus distribution in these size ranges was also considered in the settling velocity term.

If ERV is included in the HVAC system, then the rate of change of concentration of pathogen in the source room is given as

$$\frac{dC_{SR}}{dt} = \lambda\left(\frac{(A \cdot [C_{SR} + (N \cdot C_{SR})]).(m_{RA} \cdot EATR)}{m_{SA}}\right) + \dot{C}_g - \Lambda C_{SR} \tag{7}$$

Where EATR is the exhaust air transfer ratio of ERV. Similarly, the concentration of the pathogens in the connected room (C_{CR}) without ERV is given as

$$\frac{dC_{CR}}{dt} = (A \cdot m_{RA} \cdot [C_{SR} + (N \cdot C_{CR})] - C_{SR} \tag{8}$$

With ERV,

$$\frac{dC_{CR}}{dt} = \lambda\left(\frac{(A \cdot [C_{SR} + (N \cdot C_{CR})]).(m_{RA} \cdot EATR)}{m_{SA}}\right) - \Lambda C_{SR} \tag{9}$$

Equations 2, 7, 8 and 9 are solved using the Runge Kutta 4th order method to obtain the concentration of pathogen in the source and connected rooms at different time steps. The probability of infection to an uninfected individual (P) at a particular time step is evaluated based on the equations:

$$P_{SR}(t) = 1 - e^{-C_{SR} \cdot b \cdot t} \tag{10}$$

$$P_{CR}(t) = 1 - e^{-C_{CR} \cdot b \cdot t} \tag{11}$$

Where t is the time step, and b is the breathing rate for an adult executing sedentary office work (0.3 m^{-3}/h).

Results and Discussion

The pathogen transfer possibility through any ERV can be related to its performance characteristics,

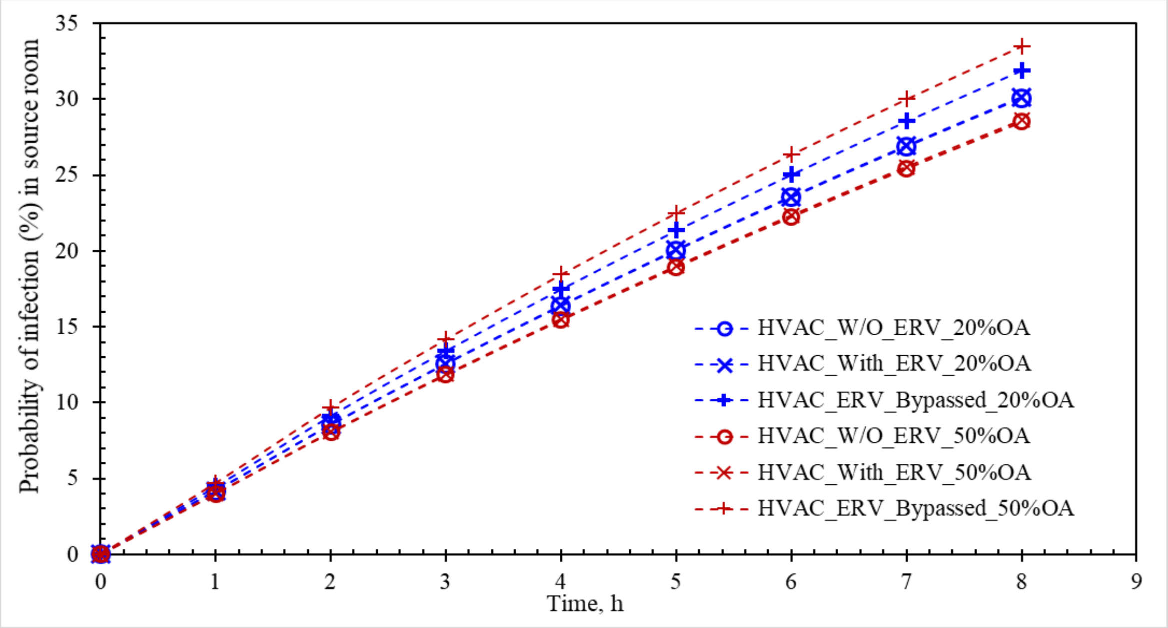
"Effectiveness (ε)" and "Exhaust Air Transfer Ratio (EATR)". According to ASHRAE [11], effectiveness is defined as the ratio of the actual energy transfer to the maximum possible energy transfer across air streams in ERV. Similarly, EATR is the ratio of the concentration increase (of any contaminant) in supply air (including ventilation air) relative to the maximum concentration difference between supply and exhaust air streams. The effectiveness and EATR of ERVs generally vary between 40 to 90% and 0 to 10%, respectively. Hence, an effectiveness of 70% and EATR of 5% is considered for the present study. The thumb rule for the outdoor air (OA) fraction in the supply air to meet the ventilation requirements (prescribed in the standards, e.g., ASHRAE Standard 62.1) generally varies from 20 to 50% (i.e., the total supply air constitutes 20 to 50% outdoor air). Thus, the study also analyses the effect of ERV with the OA fractions of 20 and 50%.

Infection risk due to ERV

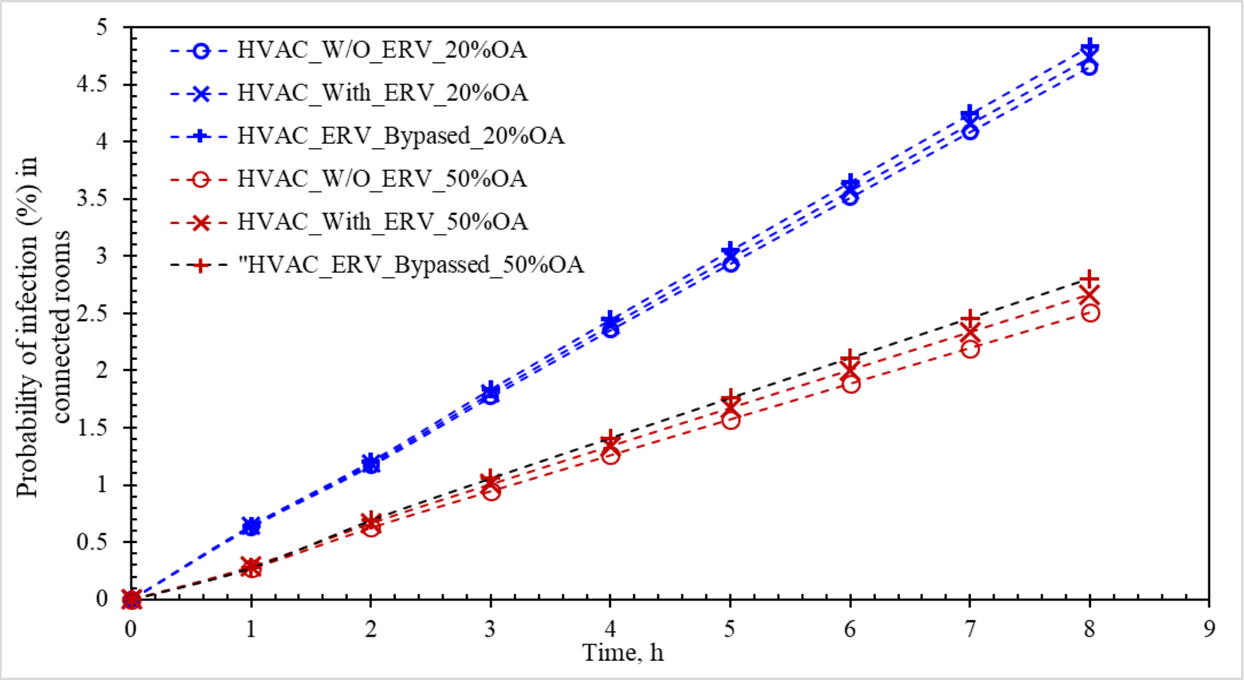
Figure 4 shows the effect of ERV in the HVAC systems on the probability of infection in the source and connected rooms. When the susceptible person is exposed to the infected person for a longer duration, the likelihood of getting infection increases. Hence, the probability of infection increases linearly with the time in the source room, as shown in Figure 4(a). Similar observations are found in the connected rooms (Figure 4(b)), except the probability of infection in the connected rooms is significantly lower than in the source room since there is no infected occupant, i.e., no source of the pathogen. When the HVAC system is operating with ERV, the pathogens from the exhaust air can be recirculated to the rooms through return air and also through ventilation air due to ERV, as shown in Figure 3. Consequently, the pathogen transfer in ERV increases the concentration of the pathogen in the source and connected rooms. However, due to the significantly higher emissions of pathogens from the infected person, the increase is negligible in the source room for both OA conditions. Hence, there is no noticeable effect on the probability of infection due to ERV in the source room, as shown in Figure 4(a). However, since there is no source of infection, ERV slightly increases the probability of infection in the connected rooms. The increase is high when the HVAC system operates with a higher OA fraction. This is because, at the same EATR, the amount of pathogen transferred from the exhaust air to the supply air through ERV is higher for the higher OA fraction. The increase in the probability of infection is 6% in the connected rooms at 50% OA fraction, as shown in Figure 4(b).

Infection risk due to bypassing ERV

When the ERV is bypassed, HVAC systems must operate with a lesser ventilation rate to maintain the designed thermal comfort conditions indoors. The lower the ventilation rate, the higher the probability of infection due to insufficient dilution of pathogens by the fresh outdoor air. Hence, the probability of infection increases in both source and connected rooms. The increase in the probability of infection is higher for 50% OA conditions. This is because bypassing ERV at a higher OA fraction leads to a significant increase in the load of the HVAC system. Consequently, the ventilation rate to the source and connected rooms decreases substantially to achieve the required indoor thermal comfort conditions. Hence, the increase in the probability of infection is significant for a 50% OA fraction when compared to a 20% OA fraction when the ERV is bypassed. As shown in Figure 4(a), the increase in the probability of infection in the source room is 6 and 17% for the OA fraction of 20 and 50%, respectively. Similarly, as shown in Figure 4(b), the corresponding increase in the connected rooms is 4 and 12%. Hence, bypassing ERV is a highly inefficient practice that promotes indoor airborne disease transmission.



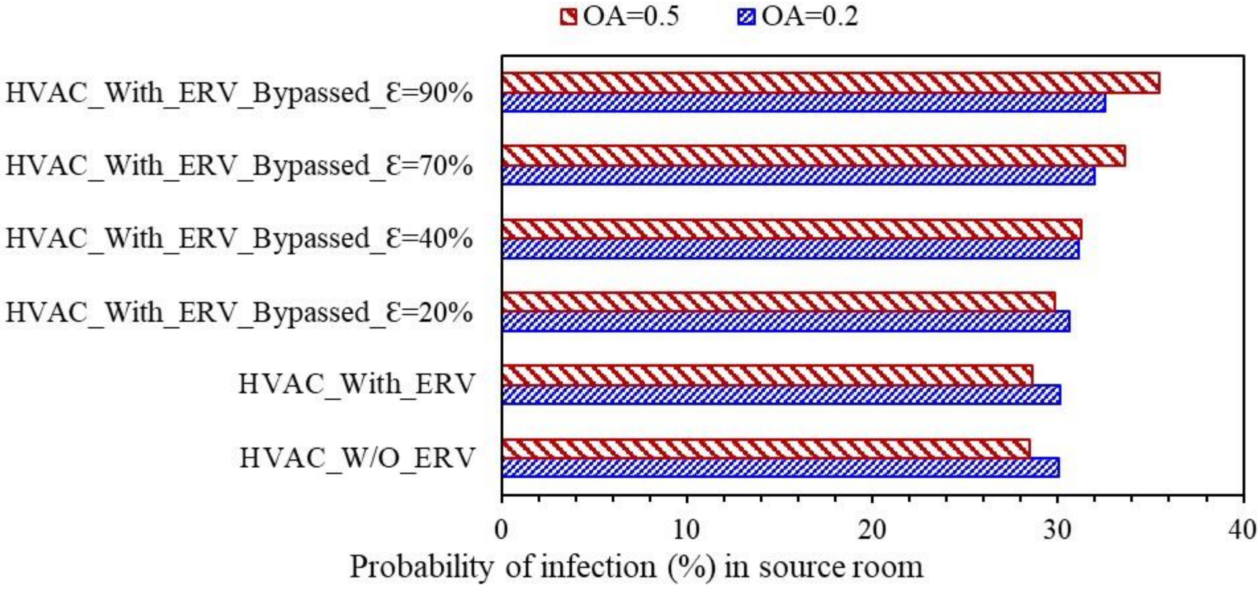
(a)



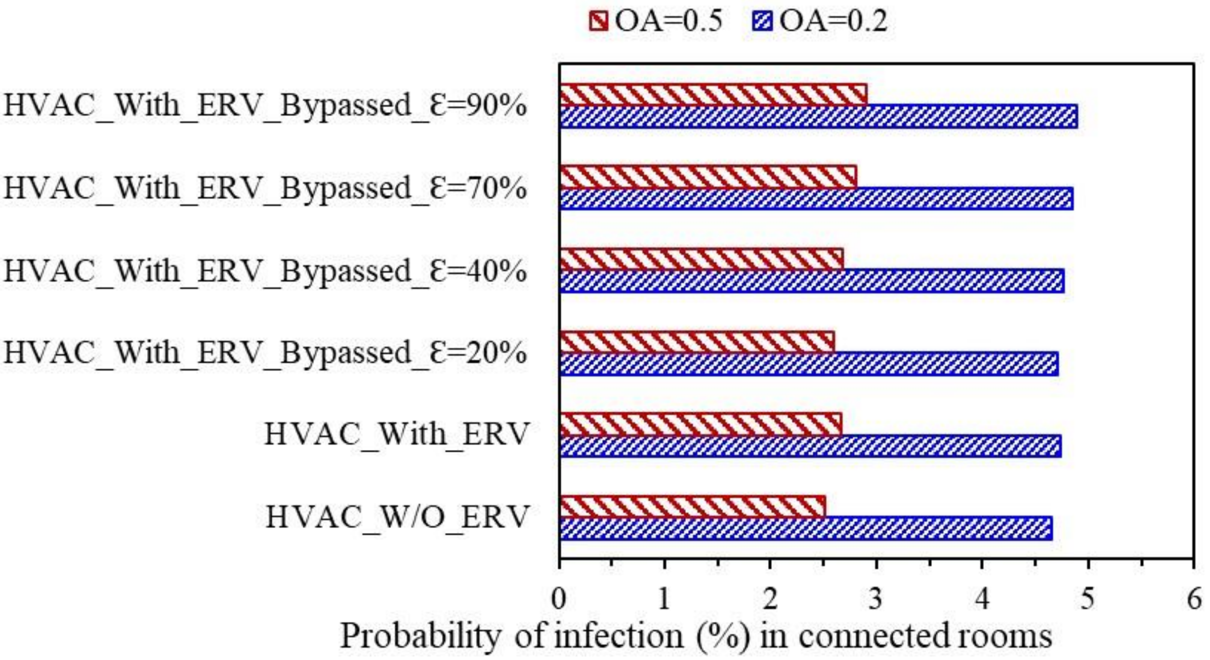
(b)

Figure 4: Effect of ERV of HVAC systems on the probability of infection in (a) source and (b) connected rooms of an office building. An HVAC system is considered with 20% and 50% outdoor air (OA) conditions

The effect of the increase in the probability of infection when bypassing ERV is highly dependent on the reduction in the ventilation rate, as discussed earlier. The reduction, in turn, depends on the effectiveness of ERV. Hence, the present study analyzed the effect of effectiveness on the probability of infection while bypassing ERV, and Figure 5 depicts the corresponding results. As expected, an increase in the effectiveness increases the probability of infection in both source and connected rooms. As shown in Figure 5(a), the increase in the probability of infection in the source room is 8 and 24% for the OA fraction of 20 and 50%, respectively. Similarly, as shown in Figure 5(b), the corresponding increase in the connected rooms is 3 and 9%. It is also inferred from the figure that bypassing ERV with an inferior effectiveness of 20% (which is the least possible condition) increases the probability of infection. Hence, bypassing ERV is a highly inefficient practice in any operating condition.



(a)



(b)

Figure 5: Effect of the effectiveness of ERV on the probability of infection in (a) source and (b) connected rooms of an office building. An HVAC system is considered with 20% and 50% outdoor air (OA) conditions

Conclusion

The effect of ERV on indoor airborne disease transmission is analyzed for a medium-sized office building with one source and two connected rooms. The transmission risk is quantified using the probability of infection. The study considers an ERV with an effectiveness of 70% and EATR of 5% and includes the influence of OA fraction (20 and 50%). It is identified that the ERV slightly increases the probability of infection only in the connected rooms and at a higher OA fraction. The increase in the probability of infection is only 6% at 50% OA fraction. Hence, bypassing or operating ERV with constraints as per the pandemic HVAC guidelines is not necessary for single enclosed space applications like common hospital wards, church prayer halls, etc. Moreover, it cannot be concluded that the slight increase in the probability of infection in connected rooms leads to disease transmission. This is because the metal and/ or chemical coating of ERVs may deactivate the viability of the pathogen. The study also shows that bypassing ERV increases the probability of infection in both source and connected rooms at any operating condition. The increase in the probability of infection in the source room is 6 and 17% for the OA fraction of 20 and 50%, respectively. Similarly, the corresponding increase in the connected rooms is 4 and 12%. Therefore, bypassing ERV, even with inferior effectiveness as per the pandemic HVAC guidelines, is a highly unsustainable practice.

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Nomenclature

EATR	Exhaust Air Transfer Ratio
ERVs	Energy recovery ventilators
HVAC	Heating, ventilation and air conditioning
OA	Outdoor air
Ɛ	Effectiveness

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