Effects of Indoor Air Curtain and Fan on Cross-Infection Risk for a Space with Displacement Ventilation

Austin Robinson and Zhiqiang (John) Zhai*
Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, Boulder, CO 80309, US

Abstract. Air curtain is an effective control for separating air spaces and reducing the cross-transfer of air, heat, and contaminant between different zones. Studies show that displacement ventilation is better for indoor air quality than mixed ventilation. However, displacement ventilation may be susceptible to a phenomenon called lock-up, whereby contaminants are held in a lower stratified portion of the space and increase infection potential. This study investigates whether indoor air curtain and circulation fan can reduce the lock-up phenomenon for spaces with displacement ventilation and thus reduce infection risk across the breathing zone. Specially, numerical test is conducted to explore if a side-wall diffuser-integrated vertical slot air curtain would be sufficient for reducing infection risk. Additionally, circulation fans above the occupants are applied to explore if they would reduce the lock-up phenomenon. The conclusions are that neither a side air curtain slot nor circulation fans is/are adequate to reduce infection risk. In fact, all methods tested increased infection risk. This increase in infection risk is contrary to previous research and is due to changing air flow patterns throughout the space that disrupted thermal plumes and created contaminant leakage from one side of the room to the other. Circulation fans provided the promising results while further optimization should be conducted in terms of the ideal quantity, location, flow rate, orientation, and size of fans throughout a given space.

1 Introduction

Respiratory diseases are prevalent throughout the world and are a major cause of concern since a cure does not exist for many. Respiratory diseases are the third leading cause of deaths worldwide, trailing just cardiovascular diseases and cancers [1]. While there may be no cure for many of these diseases, most are avoidable. Alleviation of the disease burden can be as simple as a reduction of exposure to pollutants, both interior and exterior. A novel approach to the separation of spaces to reduce cross-infection risk is offered: demand-controlled air curtains. Air curtains have been widely used to maintain temperature in cold storage and refrigerating rooms [2], to reduce pollutant dispersion and heat loss in industrial furnaces [3], to control smoke and fire spread [4], to provide refuge in an underground tunnel [5], to reduce particle spread in subway tunnels [6], and to maintain air quality in clean rooms [7, 8].

While no studies exist for the particular case of interest presented in this work, there are a few studies that lay a good foundation and suggest that air curtain devices can reduce airborne particle infection risk. The first study of interest looks at the cutting-off performance of air curtains encircling a thermal manikin to confine contaminants [9]. Wang et. al. found that the air curtains reduced exhaled contaminants outside of the region around the thermal manikin by 4.32%-19.6% when compared to mixing ventilation alone. Protected occupied zone ventilation separates a room into two zones, occupied and unoccupied, with two different concentrations of contaminants with a plane jet or air curtain device in the middle of the room, blowing downward [10]. This new air distribution method provides a protection efficiency of 8% to 50% depending on the location of exhausts, supply air velocities, the arrangement of furniture, and the contaminant location [10]. Ye et. al. placed a vertical blowing air curtain on a desk to avoid a doctor’s direct exposure to a patient’s exhalation [11]. It was found that a mass fraction of pollutants could be reduced (70% to 90% reduction) when air curtains were used [11]. It was also found that when the velocity is less than 3 m/s, the angle needed to be larger (0°-40°). When the curtain was set at 40° the pollutant was able to travel over the curtain and contaminate the doctor [11].

This study explored the displacement ventilation as it is becoming more common in new, green, energy efficient buildings [12]. The US Environmental Protection Agency also advocates that designers look into displacement ventilation [13]. Bhagat et. al. stated that displacement ventilation, by design, seems to be more effective than mixing ventilation since it may produce clean zones while mixing ventilation does not [14]. Bhagat does mention an interesting observation in the displacement ventilation case, termed “lock-up layers”. This refers to the possible trapping of exhaled breath below the warm ceiling layer, which causes a

* Corresponding author: john.zhai@colorado.edu

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secondary plume that may settle at an intermediate level and may cause a delay in the exhaust of contaminant/aerosol particles [14]. This lockup height has been noted by others as well, notably Liu et al. [15]. In their study on transmission distances and heights based on thermal stratification, they noted that the lock-up phenomenon could increase infection risk. Particularly, contaminants were trapped in an intermediate layer (the lock-up height) and travelled longer distances than in mixed ventilation cases. Bjørn and Nielsen had previously observed this occurring with exhalation flow settling at breathing height if the gradient of temperature was large enough [16]. This study attempts to explore if indoor air curtain and fan can be used to break up the lock-up height and further improve displacement ventilation with regards to infection risk.

2 Model Description and Validation

2.1 Overview of space

This experimental case to be studied is that of a simple office with two occupants. Figure 1 shows an isometric view of the room with labels for each object found in Table 1. Table 1 shows each items location, size, and heat gain released into the space. This space was taken from Srebric’s Dissertation at the Massachusetts Institute of Technology [17], which also gives experimental values for velocity, temperature, and contaminant concentration.

![Image of an isometric view of the office model](Fig. 1. Isometric view of the office model: 1) window; 2) diffuser; 3) exhaust; 4) occupant; 5) computer; 6) table; 7) box/cabinet; 8) florescent lighting.)

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2.2 Computational method

Computational Fluid Dynamics (the modelling of Mass, Momentum, and Energy Conservation equations) has been proven through a variety of studies to be a valid and trustworthy way to study airflows in the built environment. For this study, a two-equation Re- Normalization Group (RNG) Reynolds Averaged Navier-Stokes (RANS) model was used to model indoor air flow and heat transfer. The Boussinesq approximation was applied to simulate buoyancy effect. The contaminant was modelled as an air particle (gas), without additional mass being considered.

2.3 Model validation

The CFD simulation results were first compared to the experimental results from the Srebric’s dissertation. The general velocity vectors and temperature contours through the central y-plane (y=1.825m), are shown below in Figure 2. As anticipated, the cool air enters at the lower level of the space and displaces the heat to the upper level. A large air circulation is observed at the occupied zone, as seen in the experiment. The velocity and temperature values were nondimensionalized to confirm the qualitative results and compare them to the values provided in the experimental data. With the velocity and temperature validated for the CFD model, the SF6 contaminate was added. Source 1 was located at (x, y, z) = (2.18, 0.84, 1.1) and Source 2 was located at (x, y, z) = (3.33, 3.16, 1.1). Both sources released SF6 at a rate of 40 ml/h. The non-dimensional vertical profiles were plotted to compare against the measured concentration (as seen in Figure 3). The contaminant contour across the center of the room is shown in Figure 4. The lock-up height is visible in the center region of the room where the contaminant has spread to the right in higher concentrations in the height range of about 1.75m to 2m. Further analysis shows that below the diffuser height the concentration of contaminant is low enough for the probability of infection to be <1%.
The root-mean-square error (RMSE) values between the experiment and the simulation results on each pole were calculated for both velocity and temperature and were found to be within an acceptable range, with the predicted values being within the uncertainty range of measurement error 75% of the time. To further ensure the validation of the model, a grid independence study was conducted. Poles one, three, and five were used to validate the grid independence for velocity and temperature using one hundred values across the pole. All the models were sufficient for temperature grid independence, but the 1.98 million cell grid produced velocity results that were below the 30% RMSE threshold. Therefore, the 1.98 million cell model was used going forward.

### 3 Air Curtain Tests

Air curtain was proposed to integrate with the side-wall supply diffuser so that they can share the same inflow ducts and the air-conditioning and fan systems. The simulation tested various positions for the vertical diffuser-height air curtain 'slots' (a single side slot, dual side slots, and a central slot on the supply diffuser) with different amounts of supply air volume (1, 2, and 3 ACH) at different slot widths (0.0025, 0.0125, 0.025m). The room was supplied from the side diffuser with 4 ACH total in the experiment. To avoid increasing the system cost, the room in the test cases was also supplied with a total 4 ACH (from both the diffuser and the slot) (i.e., 1-3, 2-2, and 3-1 ACH through the diffuser and the slot, respectively). All combinations were numerically tested in a simpler model to determine the optimal to pursue further in the full model. The simpler model had the same dimensions as the full model, just without the items in the room. However, none of the tested cases seemed to adequately divide the space and in fact had worse performance than the base case, as partly showed in Figure 5 for some prediction results. Apparently, the slot air curtain causes unstable airflows to the indoor environment.

![Fig. 3. Non-dimensional profile comparison for contaminant concentration at pole 1, 3, and 5.](image)

![Fig. 4. Contaminant contour across the center of the room.](image)

![Fig. 5. Velocity vectors at the breathing zone (z=1.1m) with 3ACH air curtain slot.](image)
attributed to the complex airflow and entrainment caused by the strong jet from the side air curtain, which also degrades the thermal plume effect in the original displacement ventilation. It is concluded that air curtain is ineffective at protecting the susceptible occupant from the source. The study also tested different source locations and increased the air curtain height to 1.7m (vs 1.1m), as well as supplied the air curtain from the ceiling and floor. Unfortunately, none of these improved the situation over the base case.

The probability of infection equation from Zhai and Li [18] was used to predict the infection risk at z=1.1 m, 1.3 m, 1.5 m, and 1.7 m.

\[
P_I = 1 - e^{-\frac{1}{\text{Dr}}} \times q_{\text{location}} \times q_{\text{source}} \times T
\]

(1)

\[
\text{Dr} = \frac{q_{\text{source}}}{q_{\text{location}}}
\]

(2)

where Dr is the dilution ratio of contaminant, \(q_{\text{location}}\) is the inhalation rate of the susceptible person at any given location, \(q\) is the exhaled airflow rate of the infected person, \(q_{\text{source}}\) is the exhaled quanta from the infected person, and T is the time of exposure.

The results for both infected and susceptible persons talking for one hour for both the base and 2CH single side slot case are shown in Figure 7. The limit for infection was set at 1%, therefore every calculated value less than 1% was forced to zero for plotting purposes. The results reveal that the base case is actually better than the case with the air curtain. This is mostly

4 Circulation Fan Tests

It was theorized that indoor upward fan would force the contaminant up and away at an adequate rate to reduce the lock-up effect and thereby the infection risk. ASHRAE Standard 62.1-2019, Table 6.1 was used as the basis for determining the fan flow rate. For office spaces, the recommended minimum ventilation rate is 2.5 L/s per person, or 0.0025m3/s [19]. Two fans, one over the contaminant and one over the second occupant’s mouth, both at a height of 2m with a 0.4405m diameter, were tested. The fan locations are shown in Figure 8. Figure 9 shows the predicted contaminant contour across the center of the room.
5 Conclusions and Future Research

This study investigated the use of indoor air curtain and circulation fan to reduce cross-infection risk for spaces with displacement ventilation. The evidence indicates that neither case is sufficient in reducing the infection risk across the entire breathing zone. Rather than concluding in an optimal reduction, each of these cases showed an unfavorable increase in infection risk to a susceptible person, when compared to the base case. This increase is a result of changing airflow dynamics throughout the room and the resultant interruption to the displacement ventilation thermal plumes. The base case’s thermal plumes carried the contaminant to higher levels of the breathing zone, but the air curtain case showed reduced plumes and thereby increased contaminants at lower levels.

The circulation fan case provided the promising results and was able to shift the lock-up height to a side of the room with no occupant, albeit in higher concentrations of contaminant. The fan case also began to show signs of a renewed safe zone for < 1%. The 10% infection risk at the lower end of the breathing zone (1.1 m) for the two-fan case also showed a large safe zone. At higher levels it was beginning to show a resurgence of risk due to the eddies located around the two fans.
Each of the cases tested appeared to fail due to the changing physics in the space with regards to the interactive effects around velocity. These changing velocity patterns increased the number of recirculating eddies throughout the space, which led to the increased infection risk and leakage that was shown throughout. These results are contrary to those found for the mixed ventilation cases discussed in the introduction and further investigations should be done to better understand the intricacies of displacement airflow with air curtains or fans. In general, the air curtain jet gives rise to large air flow instability and entrainment air flows. Similarly, the ceiling fans also introduce strong circulation and impingement along the surfaces.

Future research will determine if infection risk can be reduced further when using indoor circulation with displacement ventilation. Such research may include a parametric study investigating the ideal quantity, location, flow rate, orientation, and size of fans throughout a given space. This prescribed study holds promise for a result in reduced infection risk. Further, air curtains may still be a viable option for localized protected zones for displacement ventilation when not attached directly to the diffuser face and should be further investigated.

References