Analysis of Spread of Airborne Contaminants And Risk Of Infection

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As businesses are poised to reopen amid the COVID-19 pandemic, people are looking for comprehensive guidance for proper ventilation of indoor spaces. Computational fluid dynamics (CFD) was used to study the impact of the HVAC layout (location and number of supply diffusers and return grilles) on indoor airflow patterns and the resulting risk of infection. The results indicate an HVAC layout with distributed supply and distributed return can form an aerodynamic containment (airflow envelope) that can help reduce the spread of airborne contaminants and reduce the risk of infection without increasing the supply airflow rates. CFD analyses, if performed properly with adequate expertise, can help professionals understand complex airflow patterns and the flow path of airborne contaminants.

Airflow, Ventilation and CFD

Air can carry small droplets and particles containing the SARS-CoV-2 virus that causes COVID-19 over a long distance. Depending on the local airflow patterns, some of these respiratory droplets can travel much farther than 6 ft (1.8 m).[1] Often good ventilation is recommended, along with social distancing and face-covering measures to control the spread of the SARS-CoV-2 virus.[2]

Good ventilation is commonly referred to and understood as an increased supply of clean air or increased air change rates per hour (ach, h^{-1}) for enclosed spaces.[2] However, simply increasing the supply of clean air may not be sufficient to achieve good ventilation.[2,3] Increased supply airflow rates can help in the dilution of airborne contaminants and reduce the overall concentration levels. However, the increased supply airflow rate may not necessarily ensure the acceptable concentration levels everywhere in the occupied zone. High concentration, especially in the breathing zone, can pose a potentially higher risk of infection.[4] Airflow patterns and resulting distribution of clean air in indoor

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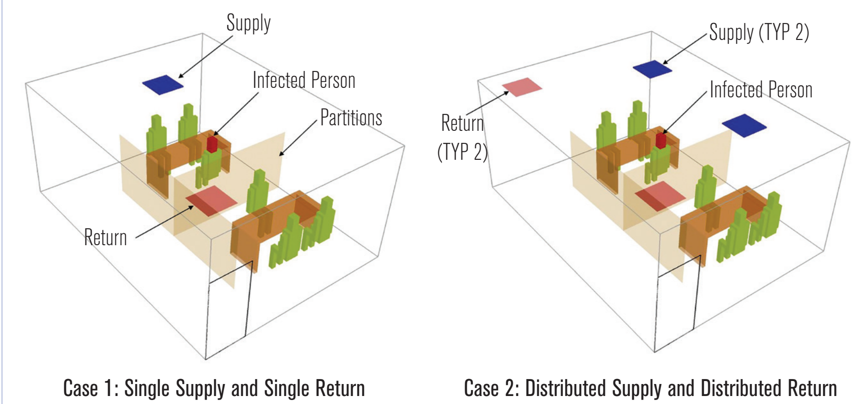
spaces can play a vital role in determining the risk of infection.[2,3]

The effectiveness of ventilation depends on several factors related to the design and operation of HVAC systems, which can impact the airflow patterns in indoor spaces. Ideally, the clean supply air should sweep the contaminants from the breathing zone without significant recirculation and stagnation that usually form pockets of high concentration. Similarly, the clean air should not escape or short-circuit the space without collecting and removing contaminants from the breathing zone.

FIGURE 1 Office CFD models for the two HVAC configurations (location and number of supply diffusers and return grilles) analyzed in this study.



The path of least resistance that the air often follows is generally not intuitive. Airflow patterns, the resulting flow path of airborne contaminants and the risk of infection can depend on several factors including the number, location and type of supply diffusers in the space; supply airflow rates (air change rates) and associated diffuser throws; supply air temperature; number, size and locations of return/exhaust grilles; the location and strengths of various heat sources in a room; an arrangement of furniture and other obstructions to airflow; location, type and capacity of in-room air cleaners; and, importantly, the relative positions of contaminant sources in a space. Strategic layout of supply diffusers and exhaust grilles can form the airflow patterns that can help reduce the risk of contaminant exposure in indoor spaces.[2,3]

Physical testing and real-time measurements of all the parameters that affect the ventilation performance of enclosed spaces are often time- and labor-intensive, if not impossible. In such situations, CFD analyses provide a feasible alternative to gain comprehensive insights into the ventilation performance. Insights into complex airflow patterns and the flow path of airborne contaminants gained during the early stages of a design or retrofit process can help improve the ventilation performance and reduce the risk of infection in indoor spaces.

Virtual Office Space

A comparative analysis was performed of the ventilation effectiveness of two different HVAC layouts for a typical office space with two cubicles. Three-dimensional, steady-state, isothermal CFD models were developed for this study. The space has an about 300 ft^2 (27.9 m^2) area with 9 ft (2.74 m) height with a total occupancy of six persons. As shown in *Figure 1*, the two cubicles are separated by a 5 ft (1.5 m) tall dividing partition. Each cubicle has an about 100 ft^2 (9.3 m^2) area. A common corridor is adjacent to these cubicles leading to the room's door. Each cubicle has three occupants seated around a table.

Figure 1 shows an infected individual facing two other individuals located in a cubicle farthest from the door. The office space is designed for the supply airflow flow rate of 135 cfm (63.7 L/s) or 3 air changes per hour (ach, h^{-1}), which corresponds to the total cooling load of 3,000 Btu/h (879 W) for a 20°F (11.1°C) difference between the supply and return air temperature.

Two CFD models are developed for two different HVAC configurations. *Figure 1* shows that the Case 1 model has a single four-way ceiling supply diffuser located away from the door with a single return grille placed near the door. In the Case 2 model, an additional four-way ceiling diffuser and return grille are added. To distribute the supply air evenly to all occupants, the diffusers are placed over each cubicle. Similarly, to create sweeping airflow through the occupied zone, the return grilles are placed away from the occupants in the adjacent corridor, and the supply diffusers are moved closer to the opposite wall. Thus, the Case 2 model forms a symmetric layout of distributed supply and distributed return in the space. The total supply airflow rate of 135 cfm (63.7 L/s) is equally divided between the two diffusers.

The k-epsilon turbulence model was used to compute the turbulent viscosity of the air. A computational mesh of about 1.5 million hexahedral cells was created by placing fine mesh near the strategic locations. The ventilation effectiveness of each configuration was evaluated using the spread index as described later. The release of contaminant from an infected individual is simulated as a passive source of a hypothetical gaseous component. The probability of infection is evaluated using the Wells-Riley correlation.

The Eulerian approach, which assumes contaminants as gaseous components, was used to model the transport of contaminants, and the rate of release was computed using the input for the Wells-Riley equation as described later. The probability of infection and its distribution in the space is evaluated at the breathing level of 4.25 ft (1.3 m) from the floor.

These analyses were performed by keeping the supply airflow rate and the contaminant release rate (60 quanta/h) the same for both cases. A steady-state analysis performed in this study represents the worst-case scenario of constant release of contaminants from an infected individual. The supply air is assumed to be clean and free of any infectious aerosols. A commercial software (Ansys Fluent) was used to perform the computations.

Spread Index

Spread index is a CFD-based ventilation effectiveness metric. It is a ratio of the space volume occupied by the contaminated air at or above a certain threshold concentration to the total volume of the space.[3] Ideally, the airflow patterns formed by the HVAC layout should minimize the spread of contaminants and reduce the probability of infection everywhere in a space. Assuming the target concentration (TC) is a safe exposure limit for a certain contaminant, ideally the spread index SI_{TC} should be close to zero everywhere and every time in a space. The safe level of concentration can depend on several risk factors including the type of contaminants or pathogens in a space and their safe exposure limits. Therefore, for each space, SI_{TC} can be evaluated for various levels of target concentrations (TC) and infection levels based on the exposure risk.

The design of an HVAC layout and the resulting flow path of airborne contaminants can play an important role in determining the SI_{TC} levels in a space.[2,3] The spread index thus provides a normalized metric to compare the ventilation effectiveness of various HVAC layouts. In this study, the spread index of the probability of infection is set arbitrarily at 10%; hence, SI_{10} is evaluated.

Probability of Infection

Infection risk assessment is performed using the Wells–Riley model, which has been extensively used for quantitative infection risk assessment of respiratory infectious diseases in indoor spaces.[5,6] This model as stated in *Equation 1* considers the intake dose of airborne pathogens in terms of the number of quanta to evaluate the probability of infection.

$$P_I = \frac{C}{S} = 1 - \exp\left(-\frac{Iqpt}{Q}\right) \qquad (1)$$

where

P_I = Probability of infection, which is a ratio of the number of infection cases (C) to the number of susceptible (S)
I = Number of infectors
p = Pulmonary ventilation rate of a person
q = Quanta generation rate
t = Exposure time interval
Q = Room ventilation rate with clean air.

Unlike contaminant dilution theory, this equation evaluates the statistical probability of infection; hence, the exponential term is not a dimensionless number. This equation assumes the supply air is evenly distributed in the entire space, and, thus, predicts a single number for the infection probability for each space.

In a real situation, the spatial and temporal variations of airflow patterns in a space can result in a nonuniform airflow distribution, which in turn can yield a nonuniform distribution of infection probability. This study demonstrates that the risk of infection depends on the location of each individual and the HVAC configuration of the space.

In the present study, the number of infectors (I) is assumed to be a single person, and the exposure time (t) is assumed to be one hour. The quanta generation rate for influenza varies from 2 to 128 quanta/h. The q value of 60 quanta/h is assumed, which is frequently used in the ventilation analysis.[5,6]

Results and Discussion

Case 1: Single Supply and Single Return

Figure 2 shows the airflow patterns at two vertical planes in the space passing through the center of a supply diffuser. In Case 1, the entire volume of the supply air (135 cfm [63.7 L/s]) enters through a single four-way ceiling diffuser. The air exiting from the diffuser travels along the ceiling, descends along the walls and moves inward along the floor. Such airflow patterns create large recirculation loops along and across the room. These large recirculation zones are formed inside the cubicles between the room walls and the dividing partitions in the occupied zone. Three-dimensional airflow patterns (not shown here) are quite complex. They promote mixing in the entire space, as is expected from such diffusers.

Figures 3 shows the resulting risk of infection computed per *Equation 1* at a breathing level. *Figure 4* shows the extent of infection spread in a space above 10% probability—a spread index of SI_{10}. For Case 1, the airflow patterns described earlier create a nonuniform distribution of contaminants with a zone of high concentration in the vicinity of the infected person. The stagnation of air in the recirculation zones form pockets of high concentration. The lowest concentration occurs outside the cubicle away from the return grille. In spite of mixing airflow patterns, the contaminant distribution is not uniform and does not create well-mixed conditions.

For Case 1, as shown in *Figure 3,* the risk of infection is above 15% in the vicinity of the infected individual, whereas the average and the minimum probability of infection at the breathing plane is 11.3% and 7.1%, respectively. The spread index SI_{10} of 49.4% indicates that about half of the space is at or above 10% probability of infection (*Figure 4*). It should be noted that all occupants in this space are covered under the cloud of the high risk of infection. The zones of high and low risk of infection divide the space along the length of the room. The probability of infection as predicted in this case indicates that it is not a "single number" for the entire space as assumed in *Equation 1*.

With a single point of supply and a single point of extract, the contaminated air travels farther from the

FIGURE 2 Airflow patterns in an office space. Case 1 shows large air recirculation zones. Case 2 shows that an HVAC configuration with a symmetric layout of distributed supply and distributed return can form an aerodynamic containment with identical airflow patterns in both zones.

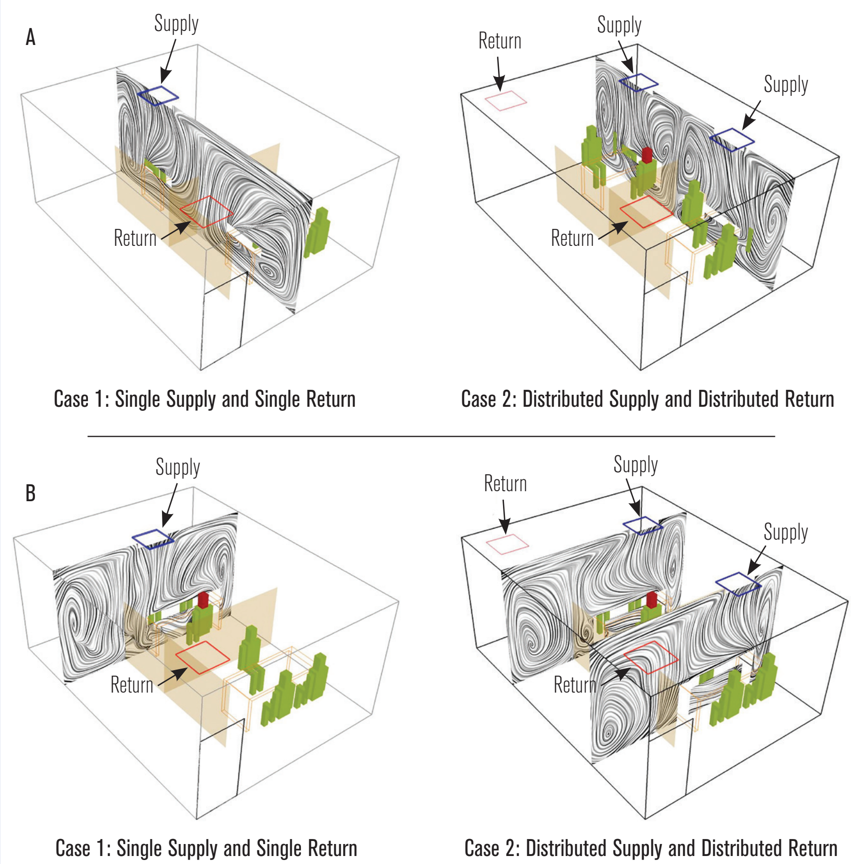
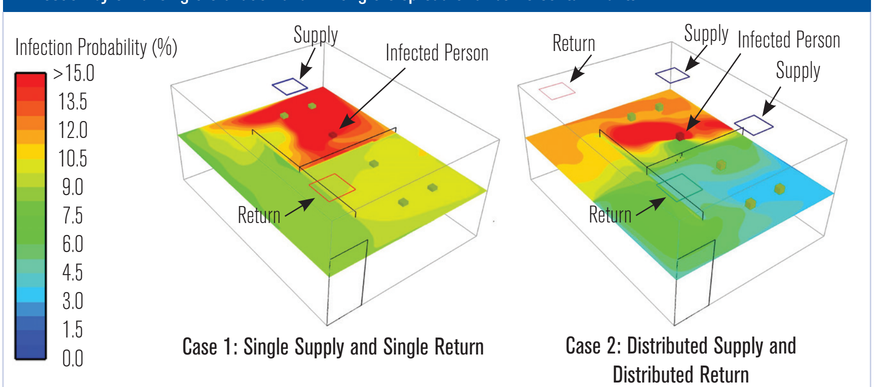


FIGURE 3 Distribution of infection probability at the breathing plane at 4.25 ft (1.30 m) from the floor. Case 1 shows large zones of high risk of infection. Case 2 shows that aerodynamic containment can reduce the risk of infection by enhancing the dilution and limiting the spread of airborne contaminants.



source, and the physical barrier formed by the cubicle walls promote formation of air recirculation zones, which in turn promote the accumulation of contaminants. Cubicle partitions offer little barrier to the transport of airborne contaminants.

Case 2: Distributed Supply and Distributed Return—A Concept of Aerodynamic Containment

As mentioned before, in the Case 2 configuration each pair of supply diffusers and return grilles forms independent zones of airflow. The airflow distribution shown in *Figure 2* indicates two identical airflow patterns within each zone of supply and return. Unlike in Case 1, in Case 2 the air recirculation zones are formed locally within each zone. Similarly, the travel of contaminated air is mostly limited within each zone.

As shown in *Figure 3* for Case 2, the risk of infection is reduced in the second cubicle, and the zone of high infection above 15% remains in the vicinity of the infected individual. The average and minimum values of probability of infection are reduced from 11.3% to 9.1% and from 7.1% to 2.7%, respectively. The spread index SI_{10} as shown in *Figure 4* for Case 2 is reduced from 49.4% to 39.3%. Unlike the previous cases, only about one-third of the room space is at or above 10% probability of infection.

In this case, dividing the total supply of air through two diffusers created two distinct aerodynamic containment zones. The airflow patterns from each diffuser create their own zone of containment, which minimizes bidirectional air movement between the zones. Providing returns for each zone reduced the long travel of contaminated air through the occupants. Additionally, moving the supply diffusers away from the returns helps sweep the clean air through occupied zones. Such aerodynamic containment with a symmetric layout of distributed supply and distributed return alters the flow path of contaminated air and moves it away from the occupants.

FIGURE 4 Spread Index SI_{10} indicating the extent of the space volume at or above the 10% infection probability. Case 1 shows that almost half of the space is at high risk of infection with all the occupants under the cloud of high infection. Case 2 shows that aerodynamic containment can reduce the zone of high risk infection by limiting the spread of airborne contaminants.

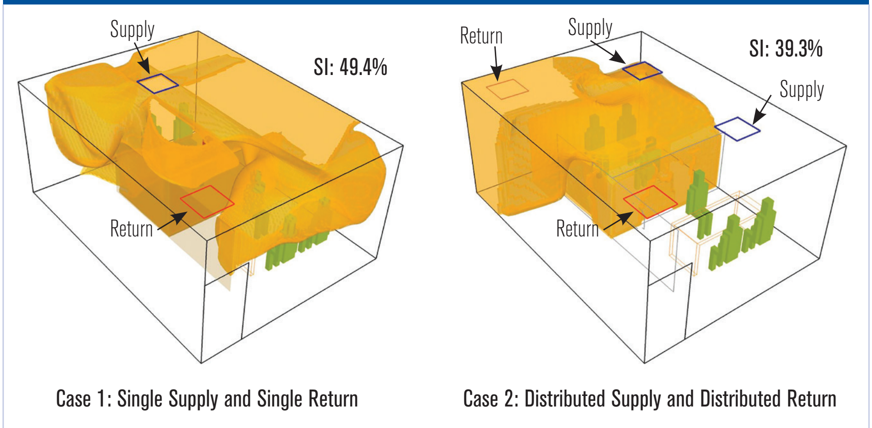
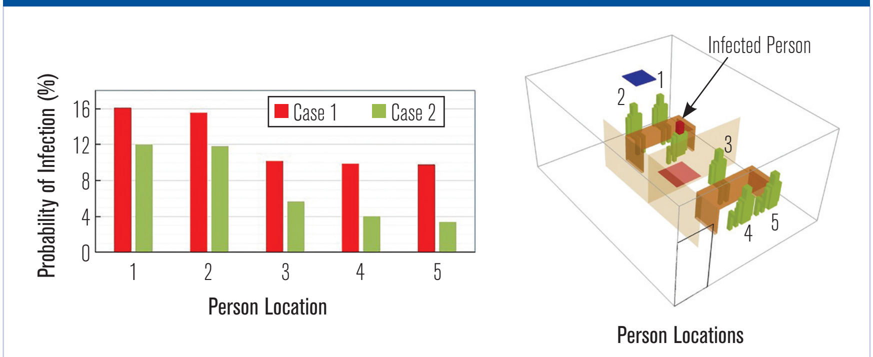


FIGURE 5 Impact of HVAC configuration on the probability of infection (%) for various locations of the individuals. It indicates that poor airflow distribution can make the measure of social distancing less effective. Aerodynamic containment with distributed supply and return locations can significantly reduce this risk.



This analysis indicates that creating sweeping airflow patterns, increasing the number of returns and placing returns away from the occupied zone can reduce the spread of contaminants and minimize the risk of infection. However, infection risk cannot be entirely eliminated without removing the source.

Location of Occupants

The impact of the HVAC configuration on the probability of infection varies with the location of a person in the space. *Figure 5* shows the probability of infection for various individuals for two cases. The location of each individual is numbered from 1 to 5, and the infected person's location is noted.

The infected person, Person 2 and Person 3 are located in the same cubicle. Persons 3, 4 and 5 are located in the other cubicle. The distance from the infected person to Persons 1, 2 and 3 is about 4.6 ft (1.4 m); the distance from the infected person to Persons 4 and 5 is 9.5 ft (2.9 m). Virtual sensors were placed in front of the occupants' faces to record the contaminant concentration to determine the level of infection risk.

These analyses indicate that the HVAC configuration (layout of the supply and return locations) has a significant impact on the risk of infection even for individuals who are located away from the source. The aerodynamic containment with distributed supply and distributed return can reduce the infection risk for all individuals, even for those who are in the vicinity of the source.

These analyses further indicate that the poor airflow distribution caused by discrete locations of supply and return can make the social distancing measure less effective even with a physical barrier. Such a layout promotes the spread of contaminants, making occupants vulnerable to a high risk of infection; the proper distribution of the supply air and creating a path of least resistance for the contaminated air can reduce the risk of infection.

Summary and Conclusions

The primary goal of HVAC systems for indoor spaces is maintaining a healthy, comfortable environment for occupants. This is achieved by diluting concentration levels of hazardous contaminants and reducing the spread of airborne contaminants. The effectiveness of a ventilation system, however, depends on several factors related to the layout of the air distribution in the space.

With the help of CFD analyses, this study systematically evaluates the impact of the air distribution layout on the airflow patterns and the resulting risk of infection. This study demonstrates that even for a simple layout of a small office, the locations of supply and return air can affect the airflow patterns and the resulting risk of infection of the occupants.

The HVAC configuration with a single four-way supply diffuser and a single return grille can promote the formation of stagnant air recirculation zones, which can form pockets of high concentration of contaminants. With such a layout, the contaminated air can travel farther from the source, spreading the zone of high infection in a space. It indicates that poor airflow distribution can make the measure of social distancing less effective.

A symmetric layout of distributed supply and distributed return can form an aerodynamic containment (airflow envelope), which shows significant promise in improving the ventilation performance by reducing the risk of infection. Since the location of an infected individual is not known a priori, the aerodynamic containment with distributed supply and distributed return can help reduce the probability of infection in indoor spaces.

Based on these analyses the following guiding principles can help improve the ventilation effectiveness and reduce the risk of infection in indoor facilities. They are stated in the order of simplicity of implementation:

- Create a distributed supply layout by increasing the number of supply diffusers and strategically placing them over the occupied zone.
- Create a distributed return layout by increasing the number of exhaust outlets to create a path of least resistance for the contaminated air to exit the space.
- Create an aerodynamic containment by symmetric placement of supply diffusers and return grilles to minimize cross contamination between the symmetric zones of supply and return.

These studies demonstrate that CFD analyses can help identify the potential risk of infection in indoor spaces due to poor airflow distribution. Each space is unique; therefore, the impact of supply and return air configurations should be evaluated by performing such CFD analyses to improve the ventilation effectiveness before increasing the ventilation airflow rates.

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