Evaluating Virus Containment Efficiency Of Air-Handling Systems

BY RENAT MANASSYPOV, PH.D., P.ENG., MEMBER ASHRAE

Direct contact with infected surfaces and exposure to the virus aerosol ejected by an infected person are primary sources of infection transmission. However, the air-handling system serving the infected space can transfer the infection agent through the ductwork to other spaces in dangerous doses. The system becomes a secondary source of infection agent in the building. This article presents a model predicting the virus propagation through central air-handling systems and a simple method for evaluating the virus containment efficiency of the systems, as well as the impact of engineered measures preventing the viral infection spread. It recommends simple engineered measures that can improve the system's virus containment efficiency during virus infection outbreaks.

How a Virus Can Travel from Space to Space

A recent work in virus fluid dynamics demonstrated that a coughing or sneezing person ejects mucosalivary droplets with a short-range trajectory and a high-momentum turbulent multiphase cloud (a puff).[1] The puff consists of warm and moist air and carries trapped droplets for distances of up to 8 m (27 ft). The size of the droplets with the short-range trajectory can reach 60 µm to 100 µm.[2] The Wells evaporation-falling curve[2] in *Figure 1* shows that the droplets fully evaporate along the trajectory before settling on the floor. The residue that contains a virus, known as virus-laden aerosol, contains much smaller droplet sizes and can persist in the air for hours.[3] The settling velocity of a 10 µm particle in still air was estimated using the Stokes's law[4] as 0.003 m/s (0.5 ft/min). More accurate data might be available.

A typical air-handling system creates air movement in the space with a velocity of 0.1 m/s to 0.25 m/s (20 ft/min to 50 ft/min). The air movement spreads the virus-laden aerosol throughout the space and, along with the thermal currents from human bodies, lighting and office equipment, prevents it from settling.

The air from the space is brought to the air-handling unit via return air grilles typically located at the ceiling level. The upward vector of the air velocity created by the system in m/s can be estimated as hourly space air change rate × space height/3,600 s. The design air change

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Nomenclature

C	Concentration of contamination (genome copies/m^3)
CCE	Contamination containment efficiency
Exposure	The period during which the occupants are exposed to infection, h
E_F	Virus retention efficiency of air filter
E_z	Zone air distribution efficiency
FA	The ratio between the floor area of source space and total floor area served by the system
HIIDR	Human inhalation infectious dose risk factor
K_1	Medium tissue culture infectious dose, genome copies (in virology known as $TCID_{50}$)
K_2	Human inhalation infectious dose (in virology known as ID_{50})
OA	The percent of outdoor air in total supply airflow rate

rate varies from 8 to 20. Therefore, the minimal upward air velocity is 8 × 2.5 m/3,600 s = 0.005 m/s or (1 ft/min).

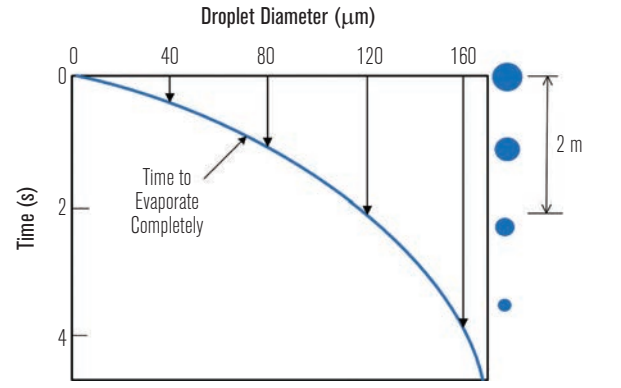
The horizontal and vertical air velocity vectors created by the system are greater than the settling velocity. This simple calculation allows us to make a conclusion that the air movement entrains the aerosol and transfers it through the ductwork from the infected space to the other spaces. Swabs taken from the exhaust air outlets in a hospital room with a SARS-CoV-2 (COVID-19) infected patient tested positive,[5] supporting the conclusion.

Recently, Finnish researchers[6] used a supercomputer to simulate the fluid dynamics of a 20 µm virus aerosol in a grocery store. The simulation demonstrated that the aerosol can transfer from one aisle to another with upward air currents.

The "ASHRAE Position Document on Airborne Infectious Diseases"[7] has general recommendations to increase outdoor air volume and install UVC germicidal lights to better protect the indoor environment from airborne virus diseases.

The simplified engineering analysis and the publications indicate that virus spread by air-handling systems is a valid concept.

FIGURE 1 The Wells evaporation-falling curve for droplets (reformatted from source[2]).



Existing Ventilation Standards

ASHRAE Standard 62.1-2019[8] provides minimum ventilation air requirements for nonresidential buildings, assuming a consistent source of contamination in the building. The standard allows recirculating a portion of the indoor air for most occupancies. For spaces with hazardous contamination, the standard excludes the recirculation. Virus-laden aerosol is not a consistent contamination and is not addressed by the standard.

The standard requires air filters to have a minimum efficiency reporting value (MERV) of not less than 8 in all systems with a cooling coil. The MERV-8 filter[9] retains 70% of particle sizes 3 µm to 10 µm. Viruses may have smaller sizes. For example, the influenza A virion has an average size of 2.5 µm.[10] The SARS-CoV-2 virion has sizes in the range of 0.6 µm to 1.4 µm.[11]

Many systems in public and institutional buildings are equipped with a MERV-4 to MERV-8 filter.[12] These filters have no tested capacity to capture particles of the virion sizes below 3 µm. Systems for hospitals and other special facilities typically have filters rated MERV-13 or higher. As per ASHRAE Standard 52.2-2017,[9] a MERV-13 filter should remove only 50% or less of 0.3 µm to 1 µm particles at the standard air velocity across the filter bank.

The air recirculation and limited air filter efficiency make potentially infectious particles/droplets spread from space to space highly probable.

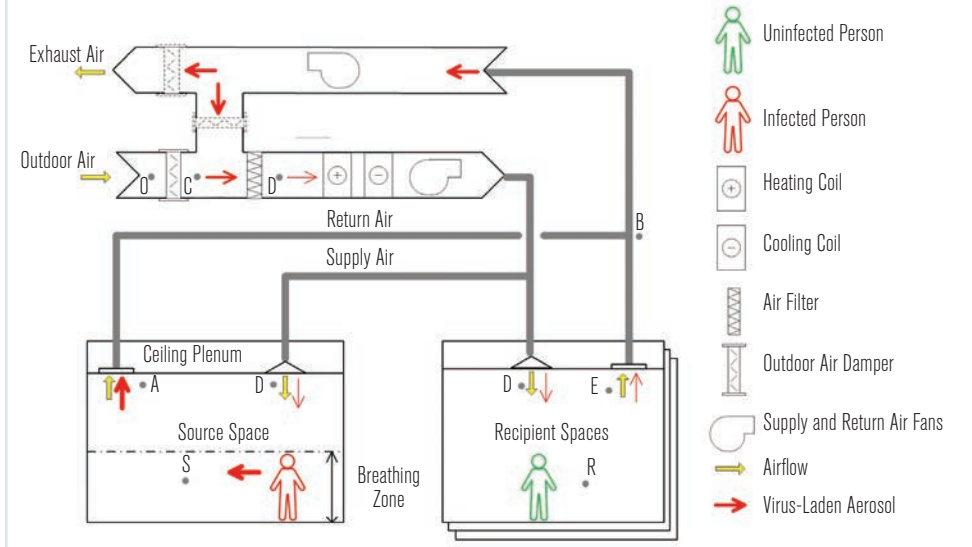
The next section describes a simple mathematical model estimating the virus spread.

Renat Manassypov, P.Eng., Ph.D., is a solutions development engineer at the Honeywell Energy Services Group Canada, Markham, Ontario.

Modeling Virus Propagation Through an Air-Handling System

Figure 2 shows a typical air-handling system. The air-handling unit delivers conditioned air to the spaces through ceiling diffusers and returns the air to the unit through ceiling-mounted return air grilles. To provide space ventilation, the unit adds outdoor air to the supply airstream. Yellow arrows show the air pathway between the unit and spaces.

FIGURE 2 Diagram of the virus-laden aerosol travel through air-handling system.



The infected person(s) emits the viral contamination with a consistent over time rate into the breathing zone of one of the spaces. This space becomes a source of contamination for the other spaces. In this paper, the space with the infected person will be referred to as "source space," and the other spaces as "recipient spaces."

The return airflow in the source space entrains the contamination and distributes it with a reduced concentration to the recipient spaces. The contamination pathway is shown by red arrows.

Typical space occupancy (exposure to contamination) varies from 4 hours to 24 hours. Typical hourly air change rates of 8 to 20 mean that the time required for the contamination to travel from the source to recipient spaces is 8 minutes to 3 minutes, respectively. The potential travel time is incomparably lower than the exposure period. The comparison allows us to assume that after a number of cycles, the virus concentration in the source space (Points S and A) and recipient spaces (Points E and R) and in the air-handling unit (Points O, C and D) in *Figure 2* have achieved a steady state. The assumption was made to exclude time from the model.

A suite of steady-state mass balance equations has been constructed at critical points in the contamination pathway using the following rationale and assumptions. The air density difference at the points has been neglected.

In the source space, the contamination concentration at the return air grille (C_A) and in the breathing zone (C_S) are different and relate as follows: $E_z = (C_A - C_D)/(C_S - C_D)$.[8] The variable E_z is the zone air distribution efficiency. The concentration gradient in the recipient spaces is substantially lower than in the source space and was neglected: $C_R = C_E$.

The return airflow at Point B mixes the contamination from the source space with the one from the recipient spaces with the ratio: $C_B = FA\,C_A + (1 - FA)C_R$, where variable FA is the ratio of the source space's floor area to the total floor area served by the system. The ceiling height and air change rate of all spaces is assumed to be the same.

The unit adds the outdoor air with a concentration of $C_O = 0$ to the airstream and reduces the concentration from C_B to C_C based on the following the equation: $C_C = (1 - OA)C_B$. The variable OA is the percent of outdoor air in the total airflow rate provided by the system's controls when the system operates in the minimum ventilation mode.

The air filter further reduces the virus concentration in the airstream as per the following equation: $C_C(1 - E_F) = C_D$. Coefficient E_F is the air filter's efficiency to capture selected contamination.

The equations have been solved to determine the relationship between the virus concentration in the recipient spaces (C_R) and the breathing zone of the source space (C_S):

$$C_R = (1 - CCE)C_S \quad (1)$$

The dimensionless coefficient *CCE* reflects the overall ability of the system to suppress potential spread of the contamination. It is a newly introduced characteristic of the air-handling system that will be referred to as contamination containment efficiency.

The efficiency is calculated by the following formula derived from the equations:

$$CCE = 1 - \{1 + [E_z\, FA\, (1 - OA)\, (1 - E_F)]^{-1} - (E_z\, FA)^{-1}\}^{-1} \quad (2)$$

Note: the same system may exhibit different containment efficiency for different contamination. The term "contamination" has been used to emphasize that *Equations 1* and *2* can be used for any airborne contamination.

Proposed Method of Predicting Virus Spread by Air-Handling Systems

In the engineering practice, *Equation 2* can be used to compare the contamination containment efficiency of air-handling systems as well as the impact of protective engineered measures. The comparative analysis does not require biological characteristics of the virus in question.

If the characteristics as described below are available, the method can be extended with an optional procedure of evaluating the contamination concentration in recipient spaces measured in human inhalation infectious dose risk (*HIIDR*)[10] factor and the engineering risk of a human acquiring the infection. The term "engineering" implies that the risk value depends only on the system's performance.

The procedure replicates the standard approach[10] that requires the following biometric characteristics of the virus received from virologists:

- K_1: the number of virus particles that infect 50% of cultured cells in a tissue culture plate; and
- K_2: the amount of virus inhaled by a human that signifies a 50% infection risk.

The concentration in recipient spaces (C_R) calculated by *Equation 1* is converted from the genome copies/m^3 (gc/m^3) units to the human inhalation infectious doses in proportion to the infection exposure period and the human air inhalation rate of 16 m^3/day for an adult:[15]

$$HIIDR = 16\ \text{m}^3/24\ \text{h}\ C_R\, Exposure/K_1/K_2 = 0.67\ C_R\, Exposure/K_1/K_2 \quad (3)$$

To evaluate the engineering risk of acquiring the infection transferred by the air-handling system, the following criterion has been established: if the calculated human inhalation infectious dose risk factor is greater than one, the risk is unacceptably high (more than 50%), and the system should be modified to mitigate the risk. The calculated *HIIDR* and actual risk of acquiring the infection is not a linear correlation. For example, *HIIDR* = three doses does not mean that the actual risk is 150%.

Sequence of Evaluating the Virus Containment Efficiency

The input data is:

- Virus average particle size; and
- Design and operational conditions of the system.

The procedure includes the following steps:

1. Select a reference system and an acceptable virus containment efficiency (CCE_{REF}).
2. Use ASHRAE Standards 62.1-2019[8] and 52.2-2017[9] and building drawings to determine the zone air distribution efficiency (E_z), the percent of outdoor air (*OA*) and the air filter efficiency (E_F) related to the virus.
3. Use *Equation 2* to calculate *CCE*.
4. If $CCE < CCE_{REF}$, modify the system and repeat the steps.

Example One

Evaluate Influenza A Virus Containment Efficiency of an Air-Handling System in a Public School

An air-handling system serves five classrooms. Evaluate the efficiency of the system to control potential spread of the influenza A virus if one of the spaces is infected. The reference system serves an emergency area in a hospital. The average size of the influenza A virion is assumed to be 2.5 µm.[10]

The system in question has a MERV-8 air filter with an estimated efficiency to retain the virus (E_F) of 10%.[9] As per Standard CSA-Z317.2-15,[13] the reference system has two air filters, MERV-8 and MERV-14, with an estimated retention efficiency of 75%.[9] The source space-to-total floor area ratio (*FA*) is 0.2 for both systems. For the system in question, the outdoor air ratio (*OA*) is 15%.[8] As per Standard CSA-Z317.2-15,[13] the *OA* ratio for the reference system is 33%.

The system in question is designed with a ceiling-to-ceiling air distribution pattern (*Figure 2*). In winter, the supply air temperature is higher than the indoor air

temperature. The source space ceiling height is 3.5 m (11 ft). For these conditions, the zone air distribution efficiency (E_z) is 0.7.[8]

The reference system has the same air distribution pattern, the ceiling height of 2.75 m (9 ft), and the supply air temperature is always less than the indoor temperature. For these conditions, $E_z = 1.0$.

The calculated virus containment efficiency of the system in question (*CCE*) is 69%, while for the reference system the value is 96%. To achieve the 96% efficiency of the reference system, the system needs modification. It can be achieved by increasing the outdoor air ratio from 15% to 75%.

The size of the SARS-CoV-2 virus is much smaller than the size of the influenza A virus. Therefore, the MERV-8 retention efficiency and, subsequently, the containment efficiency for the SARS-CoV-2 virus should be lower than the one for the influenza A virus. The high virulence of the SARS-CoV-2 virus requires an increase of the reference containment efficiency, for example, to 99%. To achieve this value, additional modifications to the system would be required.

Example Two

Estimate the Engineering Risk of Acquiring the Infection in Example One

Assume the occupants in the classrooms in Example One are exposed to the infection agent for 4 hours.

To complete the estimate, a reference virus concentration in the source space (C_S) is required. Concentration of the influenza A virus was measured in hospitals, day-care facilities and commercial passenger airplanes.[10] The average value was found as $(1.6 \pm 0.9) \times 10^4$ gc/m^3. The measurements were taken in spaces with an estimated average footprint area of 40 m^2 (430 ft^2), estimated average occupant density of 60 people/100 m^2 (60 people/1,076 ft^2), average air change rate of 10, air temperature of 22°C (72°F) and humidity of 40%.

Given the occupant density in the classrooms is 30 students/100 m^2 (30 people/1,076 ft^2), the concentration C_S was selected to be proportionally lower than the measured value and equal to 8,000 gc/m^3.

The virus concentration in the recipient spaces was calculated by *Equation 1*:

$$C_R = 8{,}000\,(1 - 0.69) = 2{,}480 \text{ gc/m}^3$$

For the influenza A virus, the estimated average value of K_1 is 452 genome copies (gc) and K_2 = (0.6 to 3.0) K_1 for the aerosol inhalation route.[10] For this example, assume $K_2 = 1.8\,K_1$.

The risk factor of inhaling infectious doses by the occupants in the recipient spaces during the exposure time was estimated using *Equation 3*:

$$HIIDR = 0.67 \times 2{,}480 \text{ gc/m}^3 \times 4 \text{ h}/452 \text{ gc}/1.8 = 8.2 \text{ doses}$$

For the reference system, the *HIIDR* is 1.01. Comparison of the *HIIDR* values shows the engineering risk of acquiring the infection spread by the system in question is substantially higher than the risk related to the reference system. To mitigate the risk, the system needs modifications.

The inputs in *Equation 3* carry measurement uncertainties. The standard deviation of the *HIIDR* for the system in question was evaluated using the input uncertainties and the common formula used for indirect measurements.[14] The resulting 90% confidence uncertainty interval around the *HIIDR* value of 8.2 was estimated as ±2.4. The estimate gives a hypothetical value that could be achieved if the input data were obtained by multiple repetitive experiments.

Conclusions

The analysis of existing ventilation standards, the basics of bioaerosol behavior and the design of standard air-handling systems demonstrated that during viral infection outbreaks, air-handling systems may become a source of infectious agent spread. Proposed herein is a mathematical model of the virus-laden aerosol propagation through air-handling systems.

The model has been used to develop a simple engineering method for evaluating the contamination containment efficiency of air-handling systems and the engineering risk of acquiring infection in recipient spaces based on standard units used in virology.

Acceptable contamination containment efficiency and associated engineering risk of acquiring infection should be provided by health-care authorities in consultation with an engineering board. The acceptable levels for specific types of contamination should be included in relevant standards. The method applies to any type of contamination and multiroom enclosures including cruise ships.

The method can be the basis of future collaborative works of HVAC engineers, virologists and other specialists in studying and improving protective qualities of air-handling systems. Wide-ranging experiments would further substantiate the system-induced virus transmission concept and advance the method with a knowledge database related to individual contamination.

Site measurements of SARS-CoV-2 virus concentrations and emission rates from the patients in hospitals and buildings in quarantine should be undertaken to determine vulnerable buildings and systems and provide an empirical base of the actual system's contamination containment efficiencies.

Overlaying the infected room and ductwork layouts in buildings that have already been in quarantine would allow confirmation of the concept on a statistical level. The unfortunate infection spread on the Diamond Princess cruise ship in January 2020 would be an appropriate case study. The suggested experiments would take a long time, while the current pandemic dictates quick actions. The proposed method allows an engineer to identify and implement the following measures:

- Mixed air systems serving educational, recreational and other facilities with air filters rated below MERV-9 should be examined for virus containment efficiency. For the systems with low efficiency, an emergency control sequence increasing the minimum outdoor air ratio to an amount predicted by the method should be implemented. The amount must correlate with the capacity of the system to condition a greater volume of outdoor air. The sequence will monitor the outdoor air conditions and interact with existing safety controls. The demand control and free-cooling sequences will be overridden if they conflict with the emergency sequence.
- Typical air-handling systems in hospitals with MERV-13 filters, for example the systems that serve emergency areas and patient wards, are efficient to control influenza A or similar size viruses. However, a pilot *CCE* analysis in this article suggests that the systems may not be efficient enough for controlling SARS-CoV-2 or other viruses of smaller size. If further works confirm the suggestion, the systems should be upgraded with UVC germicidal lights in the common return air duct in addition to the emergency outdoor air control sequence that is described above. The upgrade will reduce the virus count in recipient spaces and minimize the probability of infection.
- Houses heated by a 100% recirculating air furnace with a low-grade filter and floor-mounted air outlets exhibit the lowest protection from virus spread through the ductwork. This is particularly an issue if one member of the household has become infected. Development of protective measures in air-heated residences remains an open question, subject for further studies.

Acknowledgments

The author would like to express his special gratitude to Anton Neschadim, Ph.D., chief scientist, ImmunoBioChem Corporation, who provided valuable insights in interpretation and use of the virus-related characteristics and existing methods of viral infection evaluation.

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