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Strategies from ASHRAE's Epidemic Task Force

Managing Aerosols Using Space Flushing

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The concept of flushing a space to remove contaminants between uses is not new, but applying that strategy to remove a specific aerosol, such as SARS-CoV-2, requires a process to target a specific particle size and range. Since the beginning of the COVID-19 pandemic, ASHRAE's Epidemic Task Force (ETF) has suggested flushing spaces between occupancy, and flushing is currently a Core Recommendation.[1] The ETF's Building Readiness guide[2] recommends that the pre- or post-occupancy flush should be no less than two hours if space-specific flushing calculations are not performed. Following the process outlined in that guidance, as described in this column, will typically result in a flushing time that is a fraction of that two-hour minimum and, therefore, that requires much less additional energy use.

The prime question with flushing is, "What airflow should be used in that calculation?" This leads to potential answers, phrased as questions, that include "Is it only outdoor airflow rate?," "Is it the total supply airflow rate?," and "Should it be the 'uncontaminated airflow' calculated using the Wells-Riley equation?" The answer, for removing aerosols, is the equivalent outdoor airflow. Equivalent outdoor airflow is known as the noninfectious air delivery rate to the space or equivalent clean air delivery rate. This equivalent outdoor air is the combination of the outdoor air plus the percentage of filtered or inactivated recirculated air (i.e., air that contains broken RNA of the virus).

As an example, consider a variable air volume air-handling unit with mixing box filters, cooling coil, potential airstream ultraviolet germicidal irradiation (UVGI) and a supply fan delivering the air to the spaces as shown in *Figure 1*. We assume that no people, and therefore no aerosol generation, are in the space during the flushing process.

Because they are in such widespread use, the system type shown in *Figure 1* is used as an example in the Building Readiness guidance, including in the Google sheet[3] linked in that document to help automate these calculations. But as my first HVAC professor, Gren Yuill, Ph.D., P.E., Fellow/Life Member ASHRAE, said to our

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class to make sure we understood the data and calculations when doing psychrometric analysis, "Goes into equals goes outta!" This applies to this Google sheet since it is built for the system shown in *Figure 1*, but the sheet can be applied, with the appropriate modifications, to any system type.

The simplest component of equivalent outdoor air to determine is actual true outdoor air that the system is delivering to the space. It is only necessary to calculate how much of the system outdoor air is delivered to each space in terms of air changes per hour. Now, we need to calculate the remaining equivalent outdoor air for a specific aerosol.

FIGURE 1 UVGI air-handler schematic.

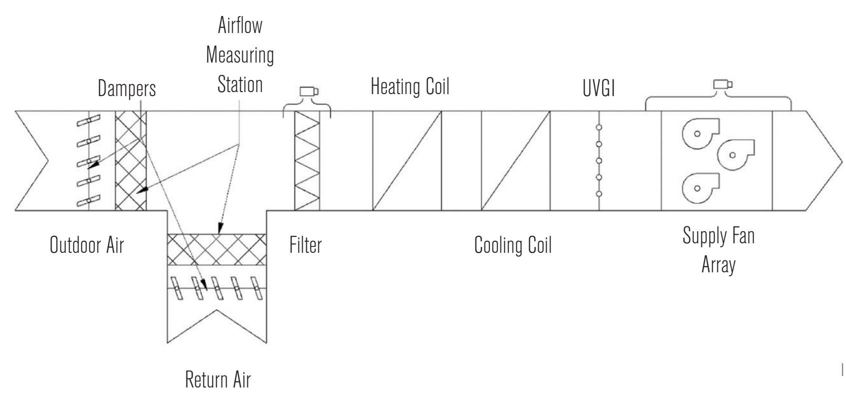

TABLE 1 Anticipated distribution of virus in airflow by particle size.

FILTER RANGES (PARTICLE SIZE)	ANTICIPATED DISTRIBUTION OF VIRUS
E1 (0.3 µm to 1 µm)	20%
E2 (1 µm to 3 µm)	29%
E3 (3 µm to 10 µm)	51%

The equivalent outdoor air produced by cleaning and inactivation of the recirculated air is dependent on the HVAC system being evaluated, its components and the order of those components. It also depends on if any in-room air cleaners, and what type, are used in spaces served by the system. Based on *Figure 1*, we will analyze the impact of the filter and then the UVGI. Finally, we will consider the ability to use in-room portable HEPA filter units to improve the aerosol removal from the spaces.

The impact of the filter on the recirculated air depends on the performance of the filter at the different particle sizes that may be carrying the virus. Ideally, the performance of a filter should be based on its actual test results per ASHRAE Standard 52.2-2017, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*. Each manufacturer should be able to provide their filters' performance in the three particle ranges: E1 (0.3 µm to 1.0 µm), E2 (1.0 µm to 3.0 µm) and E3 (3.0 µm to 10.0 µm). Note that 1 µm = 100 nm.

The next step is to determine the anticipated distribution of virus-containing particles in the recirculated airstream in the E1, E2 and E3 sizes ranges of Standard 52.2-2017, so that a droplet nuclei-weighted efficiency of the filter can be identified. An article[4] that discusses the myths of the virus and the size it is distributed says it is best summarized by a June 2020 Tweet[5] from Linsey Marr, Ph.D., a professor at Virginia Tech, that says, in part, "viruses are not naked." The virus travels in the air connected to other materials and "gunk" that makes them larger.

The Building Readiness guidance used studies[6–10] of Influenza A to predict the distribution of particles for the calculations. As of this writing in April 2021, the research is incomplete on the distribution of particle sizes that contain the 0.06 µm to 0.14 µm-sized SARS-CoV-2 virus exhaled by the infected person.

Several research studies[6–10] have used quantitative polymerase chain reaction (q-PCR) to identify the presence of viruses in expelled droplets and offered insights not only into what size aerosols exist after expulsion from the human body, but in what size fractions viruses are present and are thus of most concern for infectious disease transmission. One study[11] provided a summary table of recent studies that used particulate matter samplers to detect influenza virus size that shows the mean viral distribution (*Table 1*).

This anticipated distribution of virus particles can then be multiplied by the filter's Standard 52.2-2017 efficiency in each of the ranges and the results combined to determine the single-pass removal rate. That percent would be multiplied by the recirculated airflow to determine the effective outdoor air quantity created by the filter. A conservative approach to determine how much aerosol the filter removes would be to assume that all viable virus particles are only found in the E1 range in lieu of using the anticipated virus distribution because it has the lowest efficiency for a typical mechanical filter.

The next component in the airstream in *Figure 1* is an ultraviolet germicidal irradiation (UVGI) airstream disinfection system. The UVGI and particle filter must be treated like filters in series. This means the UVGI system only acts on the virus-containing particles in the recirculated airstream not removed by the filter, which reduces its impact on overall removal efficiency. The clean airflow resulting from the combination of a mechanical filter and UVGI can be captured in the following equation:

$$Q_{e,c} = Q_R\left(1-\eta_f\right)\eta_C$$

where

- $Q_{e,c}$ = Equivalent outdoor airflow from the air cleaner (cfm)
- Q_R = Recirculated airflow (cfm)
- η_f = Single-pass removal of the filter (previously calculated)
- η_c = Single pass inactivation percentage of the air cleaner.

From $Q_{e,c}$ airflow, the air changes per hour of equivalent outdoor air from the air cleaner combination can be calculated using the following formula:

$$ACH_{e,c} = (Q_{e,c} \times 60)/V$$

where

- $ACH_{e,c}$ = Equivalent outdoor air changes from the air cleaner, after the filter on the recirculated air
- V = Volume (ft^3).

The effect of in-room fan-filter units or other in-room air cleaners used to increase the equivalent outdoor air in that space can then be added. If known, the equivalent clean airflow of fan-filter units should be assumed to be the clean air delivery rate (CADR) as determined by AHAM Standard AC-1.[12] Placement of these units and space configuration can impact the effectiveness of its distribution within the occupied space.

An adjustment to the equivalent clean air delivery is required to account for the fact that there is not perfect mixing in a space. This can be described by the air distribution effectiveness metric. An estimate of this correction is the zone air distribution effectiveness (E_z) given in ASHRAE Standard 62.1-2019 Table 6-4 that identifies the constant for different air distribution systems. An E_z value of 1.0 indicates perfect mixing. This value is typically only multiplied by the air delivered from the house HVAC system.

Once the equivalent outdoor air changes per hour (ACH_e) for a system or space are determined, the time it will take to flush it can be calculated. Equivalent air changes, ACH_e, are determined by finding the sum of the component air change calculated as described:

$$ACH_e = E_z(ACH_{oa} + ACH_f + ACH_{e,c}) + ACH_{ir}$$

where

- ACH_{oa} = Air changes from outdoor air
- ACH_f = Equivalent outdoor air changes from the filter on the recirculated air
- $ACH_{e,c}$ = Equivalent outdoor air changes from the air cleaner, after the filter on the recirculated air
- ACH_{ir} = Equivalent outdoor air changes from the in-room portable HEPA unit.

Flushing time is a function of ACH_e and the desired level of clearance, or contaminant removal. ASHRAE ETF guidance is based on 95% clearance as minimally acceptable, but some types of facilities use more stringent criteria, such as 99% or 99.9%. Clearance of 95% requires three air changes of equivalent outdoor air that is adjusted for ventilation effectiveness.

The following shows the equations used to calculate the contaminant removal:

$$C/C_0 = \exp(-Q_e/V) = \exp(-ACH \times t)$$

$$t = -\ln(C/C_0)/(ACH)$$

where

- C = Space concentration of contaminants
- C_0 = Space contraction when time equals 0
- Q_e = Equivalent outdoor airflow in the space (cfm)
- ACH = Air changes per hour
- V = Volume of the space (ft^3)
- t = Time to flush the space with Q_e.

Using this strategy for aerosol management in a space between occupancies can help reduce the potential for virus transmission when the space is reused. Using the equivalent outdoor air in flushing calculations will help reduce the energy impact of this process while achieving a safer indoor environment.

Acknowledgment

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