Virus Transmission Modes and Mitigation Strategies, Part 4

Additional Virus Mitigation Strategies

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Part 4 of this four-part article builds upon the virus mitigation strategies started in Part 3 in August's *ASHRAE Journal*. It looks at emerging technology,[1] disinfectant treatments and other mitigation methods in single zone HVAC systems.

In-Room Air Cleaning and Upper-Room UVGI

Single zone systems can often have limitations on the amount of outdoor air, the total airflow rate and the pressure drop they can successfully handle. Limitations may also exist on the length and size of ductwork that is routed to a space, making ultraviolet (UV) installation in the ductwork difficult. In-room solutions can be effective in these situations.

In-room air filtration is one method to provide additional ventilation air to a space. Portable air filtration units are often rated according to their clean air delivery rate (CADR). The Association of Home Appliance Manufacturers (AHAM) created a standard[2] for evaluating portable air filters based on pollen (particle size range 5 µm to 11 µm), dust (particle size range 0.5 µm to 3 µm) and tobacco smoke (particle size range 0.09 µm to 1 µm).[3,4] The tests are performed in a 1,008 ft^3 (28.5 m^3) room and are based on the measured difference in decay or removal rates with the air cleaner in operation and with no air cleaner in operation[3] (*Figure 1*).

A study by Foarde compared the CADR rate for an air cleaner and the clean air removal rate for microbiological aerosols (CARm).[5] The study found that both the CADR and the CARm of the device were consistent with the filter efficiency of the air cleaner and the design volumetric flow rate.[5] In the study the CADR of the smoke, dust and pollen tracked closely to the CARm of the microorganisms tested.[5] For particles, the AHAM recommends that the maximum room size be based on an 80% reduction in steady-state particle concentrations in the smoke, dust and pollen size ranges (no recommendations for CARm are given).[4] For a room with an 8 ft (2.4 m) ceiling, the CADR rate can by multiplied by 1.55 to get the recommended maximum room size. Due to the limitations of the testing, the CADR scale goes up to a maximum of 400 to 450 depending on the particle size.[2]

Another way to quantify in-room filtration is by effective air change rate (eACH). A study by Miller-Leiden, et al., looked at portable air filter and ceiling-mounted air filter efficiency for tuberculosis control.[6] Compared

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FIGURE 1 Clean air delivery rate equation.[2]

$$CADR = V(k_t - k_n)$$

k_n = Natural decay constant rate (no air cleaner in the test chamber)

k_t = Test decay constant

V = Volume of test chamber (ft^3)

CADR = Clean air delivery rate (cfm)

k decay constant is calculated by:

$$C_{ti} = C_{to}e^{-kti}$$

C_{ti} = Concentration at time ti (particles/cc)

k = Decay constant

C_{to} = Concentration at t=0 (initial)

t_i = Time at $t = I$ (minutes)

FIGURE 2 Indoor concentration of particles formula.[6]

$$C(t) = \frac{G}{(ACH_V + \eta_F ACH_F)V}\left(1 - e^{-(ACH_V + \eta_F ACH_F)t}\right)$$

Transient concentration:

$$C^T = \frac{1}{T}\int_0^T C(t)\,dt$$

Steady-state concentration:

$$C^S = \frac{G}{(ACH_V + \eta_F ACH_F)V}$$

$C(t)$ = Concentration (# m^{-3}) of airborne particles at time t(h)

G = Emission rate of droplet nuclei (# h^{-1})

V = Volume of space (m^3)

$ACH_V = Q_v/V$ = air-exchange rate due to ventilation (h^{-1})

$ACH_F = Q_F/V$ = air-exchange rate due to filtration (h^{-1})

η_F = Single-pass filter efficiency of air filter

t = h

Q_v = Room ventilation rate ($m^3\ h^{-1}$)

Q_F = Recirculating airflow rate through the filter ($m^3\ h^{-1}$)

with a base case condition of 2 ach of outdoor air, the study showed that droplet nuclei concentrations could be reduced between 30% to 90% by adding in-room filtration.

Other results showed that HEPA filter media and 90% efficient filter media performed the same in their test. Since the droplet nuclei emitted into the room were unconfined, the single-pass efficiency had less bearing on the results because the droplet nuclei could bypass the filter to enter the breathing zone of a susceptible person. If the source to receptor path can be disrupted, greater protection can be obtained. The results also showed that increasing the eACH rates sometime increased efficiency and other times decreased the efficiency. This effect could be due to the increased eACH affecting the airflow patterns in the room.[6]

A simulation by Qian, et al., of portable HEPA air cleaners found that the "strong supply air from the portable HEPA filter interacted with the room airflow pattern and became dominant, introducing global airflow mixing in the room."[7] The impact of the in-room filtration unit should be taken into account when evaluating a room's air distribution design. An equation for the rate of change of the indoor airborne concentration can be used to evaluate the relationship between ventilation and filtration. *Figure 2* shows a transient version (both the infectious person and the susceptible person enter an initially clean room) and a steady-state version (the infectious person has been in the room long before the susceptible person enters).

Upper-room germicidal irradiation (UVGI) uses wall-mounted or ceiling-suspended fixtures in an occupied room to treat the air above the occupants and kill microorganisms. Louvers or shields are used to block the UV-C from eyesight to keep the occupants safe. In 1937 Wells, et al., successfully used upper-room UVGI to prevent the epidemic spread of measles in suburban Philadelphia day schools.[8] Between 1969 and 1972 Riley and others conducted model room studies to evaluate the use of upper-room UVGI to reduce the concentration of aerosolized test organisms in the lower room.[8] In these tests, mixing between the upper and lower room was shown to be imperative for effective disinfection and that high humidity reduced the effectiveness of the UVGI.[8]

Effective doses for UVGI have been established for a wide range of microbial species, but some of these doses were determined for organisms on Petri plates instead of in aerosolized form and could overestimate the dose required for inactivation.[9] Viruses like influenza, smallpox and adenovirus lack a cell wall and are more easily inactivated than vegetative bacteria or spores.[9] A dose that inactivates *Mycobacterium tuberculosis* will be more than adequate to inactivate most respiratory viruses.[9]

In spaces that are poorly ventilated, ceiling fans (at low and medium speeds) can be used to promote the vertical air movement and rapid transport of microorganisms to the upper portion of the room and increase the performance of the upper-room UVGI system.[10] However, there is some indication that high fan speeds don't increase performance, but can reduce the time the microorganism stays in the UV irradiation field and increase the probability of inhalation before they are inactivated.[10]

Performance of upper-room UVGI can also be indicated in equivalent air change rates (eACH). Studies have shown aerosolized mycobacteria can be disinfected in the range of 10 eACH to 20 eACH.[9] Additionally, a study by Beggs, et al., has shown that upper-room UVGI can be effective against COVID-19.[11] In 2009 the Department of Health and Human Services published guidelines for upper-room UVGI for control of tuberculosis in health-care settings.[12] Many of these recommendations would also apply to virus mitigation.

The guidelines showed that UV fluence rates below 12 μW/cm^2 (1.2 eACH) in the upper irradiated zone produced minimal inactivation of microorganisms. UVGI irradiance of 30 μW/cm^2 to 50 μW/cm^2 is recommended for inactivating *Mycobacterium tuberculosis*, and UVGI distribution should be as uniform as possible. Combining ventilation air and upper-room UVGI resulted in an increase in total efficiency (for well-mixed rooms), up to 6 ach of ventilation.[12] Above 6 ach the effectiveness of the UVGI can decrease (although the overall effectiveness may still be high).[12] Lastly, for optimal results, room relative humidity should be controlled to 60% or less.[12]

Emerging Technology

Several types of air cleaning technology can be classified as emerging. These technologies might not be new to the industry, but their viral effectiveness may be unproven or still require additional third-party testing.

Bipolar ionization has received a lot of attention since the start of the current pandemic. Ionization is typically classified as either needlepoint ionizers or corona discharge ionizers (dielectric barrier). Ionizers produce positively charged ions, negatively charged ions, or both. A study by Hyun, et al., looked at the effect of corona discharge-generated air ions on aerosolized bacteriophage MS2.[13] The test separated the antiviral efficiency of the ozone produced in the ion creation process (30 ppb at 4.52%). The results showed that the antiviral efficiency for bipolar ions was greater than either positive or negative ions individually, and the antiviral efficiency of the bipolar air ions at 10^7 ions/cm^3 concentration was 64.3%, 89.1% and 96.4% with exposure times of 15, 30 and 45 minutes.[13]

A study by Berry, et al., looked at the effect of ionic air cleaners on particle ratios in a residential environment.[14] One thing the study showed was that uninhabited chamber experiments may not reflect actual performance in a space. Another study by Fletcher, et al., showed that as ion generation rates increase, the electrodynamic effects due to the ions become increasingly important, with wall deposition becoming the dominant ion removal mechanism.[15] It is important to note that the high ion generation rate used in chamber tests may not be practical to produce in an occupied space. While several chamber tests have been completed, more research needs to be done to determine the required effective ion density for virus inactivation in an occupied space.

Electrostatic precipitators (ESPs) impart a charge on airborne particles, which are then directed to and deposited on a metallic collection plate. Traditional ESPs have size-dependent collection efficiencies with the collection efficiencies of particles in the submicron and nanometer size range being low.[16–18] Particles in the 0.1 μm to 1 μm range are harder to charge and exhibit low electrical and mechanical mobility.[17] To improve the collection of small particles and viruses, soft X-ray emitters (0.12 nm to 0.41 nm wavelengths) can be added to the electrostatic precipitators.[16–18] These emitters aid in charging the particles by producing additional bipolar ions and by direct photoionization.[16,17]

A study by Hogan, et al., found that at low voltages (below corona inception) the soft X-ray irradiation decreased the fraction of uncharged particles, significantly improved particle capture efficiency on ultrafine particles and inactivated microbes prior to collection.[18] Two other studies[16,17] showed that at higher applied voltages the virus capture efficiency went up (even without the soft X-rays) because the corona discharge produced bipolar ions. Corona discharge was present at –10 kV, –8 kV, +8 kV and +10 kV, but it's important to note that ozone is present during corona discharge as well.[16] Peak ozone concentrations occurred at –10 kV with ozone levels reaching 156 ppm, which is well over the exposure limit for ozone.

Photocatalytic oxidation (PCO) uses a UV light to enable chemical change (oxidation or reduction) by photon activated catalysis.[19] The most common catalyst is titanium dioxide (TiO_2), but others are also used.[20] A study by Guillard, et al., showed that photocatalysis provided an 80% reduction in the avian influenza virus (A/H5N2), not counting the UV light.[21] When the UV light was added, the virus was completely eliminated in a single pass.[21]

Studies have shown inactivation of viruses by photocatalysis is initiated by their adsorption onto the catalyst's nanoparticles followed by an attack on the protein capsid.[22] Other studies suggest the inactivation is due to free hydroxyl radicals.[22] Another study by Kozlova, et al., found that the vaccinia virus and influenza A virus (H3N2) were inactivated 90% to 99.8% after 30 minutes of exposure.[23] However, despite the promising results, PCO has the potential for production of by-products like formaldehyde due to incomplete oxidization.[19,20] Also, there is a potential reduction in catalyst efficiency over time.[19,20] These limitations should be evaluated when implementing this technology.

Far-UV-C refers to devices that operate in the 207 nm to 222 nm wavelength range.[24] UV-C light in this range is strongly absorbed by biological materials and doesn't penetrate through the outer dead-cell layers (stratum corneum) on the surface of human skin or the outer tear layer of the eye.[24] Since far-UV-C can only penetrate a few micrometers, it cannot reach living human cells in the skin or eyes.[25] However, this light can still inactivate bacteria and viruses with efficiencies comparable to UV-C in the 254 nm wavelength due to the virus's smaller cell size.[24] Buonanno, et al., found that low doses (1.2 mJ/cm^2 to 1.7 mJ/cm^2) of 222 nm light inactivated 99.9% of the airborne human coronavirus tested.[25]

Welch, et al., also found that 2 mJ/cm^2 of 222 nm light could inactivate 95% or more of aerosolized H1N1 influenza virus.[24] The threshold limit value (TLV) for 222 nm light to which the public can be exposed is 23 mJ/cm^2 per eight-hour exposure.[25] Based on far-UV-C exposure set at the regulatory limit, continuous exposure could result in 90% viral inactivation of airborne viruses in about eight minutes, 95% in 11 minutes, 99% in 16 minutes and 99.9% in 25 minutes.[25]

Many of the emerging technologies listed above also have the potential to produce ozone. ASHRAE Standard 62.1–2019[26] requires air-cleaning devices that can produce ozone to be listed and labeled per UL 2998, Environmental Claim Validation Procedure (ECVP) for Zero Ozone Emissions from Air Cleaners.

Disinfectant Treatments

Some treatments being used for disinfection may be acceptable in certain situations. These treatments are often only used during unoccupied times, since they are often harmful to occupants in the space. These treatments may also require the space to be purged before occupation.

The first ozone generator was patented by Nikola Tesla in 1896.[27] Since then ozone has been used off and on for air and water purification. Lately, research showing the effect of ozone on occupant health has made the use of these devices as air purifiers unsafe in most situations.[20]

Ozone, even at low levels, can produce respiratory issues in humans and actually cause other health risks through the formation of formaldehydes and aldehydes.[20] ASHRAE states that based on current science there is "no consensus on the safe level of ozone."[20] ASHRAE Standard 62.1–2019, Table D-1[26] lists the eight-hour limit at 0.07 ppm, and the EPA and other agencies suggest avoiding the use of air cleaners that use ozone.[20,40]

A few studies have shown ozone can be used for virus inactivation. Dubuis, et al., found that "low" levels of ozone and high relative humidity (RH)—1.23 ppm and 85% RH, respectively—could inactivate bacteriophages two orders of magnitude after 40 minutes.[28] A study by Hudson, et al., also showed that norovirus could be inactivated on surfaces under high levels of ozone (20 ppm to 25 ppm).[29] Another study by Hiroshi, et al., showed similar results for influenza.[30] The half-life of ozone is about 20 minutes, and it quickly decays back to oxygen.[29]

The use of a catalytic converter can also speed up the removal of the gas.[29] Since these studies used levels of ozone that are higher than safe levels in an occupied space, use of ozone in an occupied space is not recommended. Use in an unoccupied space may be acceptable. However, other methods like ventilation make more sense for educational occupancies.

Chemical disinfectants like hypochlorite, peroxymonosulfate, alcohols, quaternary ammonium compounds and hydrogen peroxide are typical for surface disinfection of viruses.[31] Vaporized hydrogen peroxide (VHP) has also been used in engineered disinfection systems for control of viruses.[31] A study by Goyal, et al., has showed a 4-log reduction or greater for viruses dried on surfaces.[32] VHP requires spaces to be sealed to prevent the vapor from escaping. Also, the space must be unoccupied since high concentrations of VHP can be hazardous.[1]

Silver nanoparticles (AgNP) have been used in commercial virus sprays for surface disinfection of viruses. Silver has broad spectrum antimicrobial action against

various bacteria, fungi and viruses.[33] Studies have shown that AgNP concentrations between 10 ppm and 100 ppm have antiviral effect.[33] Jeremiah, et al., found that concentrations between 1 ppm and 10 ppm were able to inhibit SARS-CoV-2.[33] Regulations for AgNP are still in development with the current NIOSH recommended exposure limit for silver metal dust and soluble compounds at 10 µg/m^3 as an eight-hour time-weighted average airborne concentration.[34,35] This limit was developed to protect against argyria and argyrosis.[34]

Additional Methods

In addition to the methods listed above, several other methods have been proposed that still need to be vetted for applicability and performance. A few are below.

Vacuum UV (VUV) has been proposed as a method to inactivate airborne viruses. A study by Kim, et al., showed a 90% inactivation efficiency for MS2 viruses under a VUV irradiation time of 0.009 seconds using a photocatalysis process.[36] It should be noted that VUV produces ozone that would have to be mediated.

Enzyme filters can eradicate microbes by attacking the microbial cell membrane if they come into close contact with the microbes. However, the adhesion of particles over time on the filter surface can prevent the close contact between the enzymes and microbes on the filter and reduce its performance.[37] Preliminary studies have shown little difference in performance between filters with and without enzymes.[37]

Desiccant rotors have been adapted for indoor air cleaning. Silica gel rotors were shown in testing to provide high air cleaning efficiency (94% or higher for VOCs), which could be applied to virus mitigation as well.[37]

Research on essential oils and their effect on microbes has been a topic of study for many years. However, ambiguity in the research makes the reproducibility of many of these tests difficult.[38] Brochot, et al., found that an essential oil blend produced a 99% reduction in H1N1 and HSV-1 with a 60-minute contact time.[39] Since some of these essential oils may also be toxic to human cells or cause hypersensitivity reactions in some occupants, further research needs to be done.[37]

Conclusions

This series of articles in the March, April, August[41–43] and this issue of *ASHRAE Journal* has looked at viruses and their release into a space, the effect of environmental factors such as temperature and humidity, the effect of the air distribution system on the propagation of droplet nuclei and several common and less common mitigation techniques applicable to single zone systems. Traditional approaches to virus mitigation like ventilation and filtration generally have the most research in favor of their efficacy. However the operational and maintenance cost of these approaches have made many people look toward other technologies for answers. It is clear that more research and innovation are still needed in many of these cases to determine efficacy in the actual space and the long-term health benefits and risks when using this technology.

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