The Probability of the Airborne Spread of COVID-19 and Applicable Technologies for Ventilation Systems and Enclosed Environments

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Abstract

The advent of the COVID-19 pandemic has resulted in an increased interest towards understanding how the virus is transmitted in an attempt to address its transmission. Although the different forms of transmission are not completely understood, the threat posed by airborne transmission cannot be dismissed as negligible. Therefore, researchers have investigated not only the mechanics of airborne transmission, but also different available technologies and methods with the purpose of mitigating this transmission mode and reducing its effect. Many of these technologies and methods are widely available and well established after having been researched and scrutinized for decades, such as fibrous air filters. Other existing technologies and methods have shown potential by illustrating their effectiveness in experimental settings but lack sufficient data and work regarding their practical effectiveness and potential safety concerns. This poster features a comprehensive review to provide perspective and a discussion on the research and development status of various applicable technologies and methods to address the spread of COVID-19 and other airborne viruses in typical indoor spaces. The featured technologies and methods are increased ventilation, air filtration, air ionization, environmental condition control, ultraviolet germicidal irradiation, and filter coatings. Research gaps are discussed regarding future work and the current limitations, and recommendations for applying the technologies and methods are provided.

Introduction and Objectives

- The transmission of COVID-19 is facilitated by the airborne spread of respiratory droplets produced by an infected person.
- In an enclosed environment, the viral aerosols have the potential to remain airborne for extended periods of time, enabling them to travel significant distances and through ventilation systems.
- **Several factors impact the probability of infection, but it may be controlled to some degree by limiting the exposure time or the concentration of viral particles that a person is exposed to [1].**
- **It is possible to decrease the probability of infection or conversely increase the acceptable exposure time by removing viral particles from a space.**

Objectives:

- Present a mathematical model to quantify the probability of viral infection for a typical, healthy individual.
- Review technologies and methods capable of reducing the probability of infection from COVID-19 for an individual in an enclosed space.
- Discuss the applications and limitations of the available technologies and methods.

Infection Probability Model

Based on the Wells-Riley model with the latest additions by Bazant and Bush [2].

1. $D(ER) = IR \cdot \int_0^T \left[n_0 e^{-\lambda_c(r)\cdot t} + \frac{ER \cdot I}{\lambda_c(r)\cdot V}\left(1 - e^{-\lambda_c(r)\cdot t}\right)\right] dt$
2. $P = 1 - e^{-D(ER)}$
3. $\boldsymbol{\lambda_c(r) = \lambda_a + \lambda_f(r) + \lambda_s(r) + \lambda_v(r)}$

D = dose received
ER = emission rate
P = probability of infection
IR = inhalation rate
T = time interval
n_0 = initial number of viral quanta
I = number of infectious subjects
V = volume of enclosed space
λ_c = infectious viral removal rate
λ_a = air exchange rate
λ_f = air filtration and duct losses rate
λ_s = sedimentation rate
λ_v = inactivation rate
r = radius of viral particle

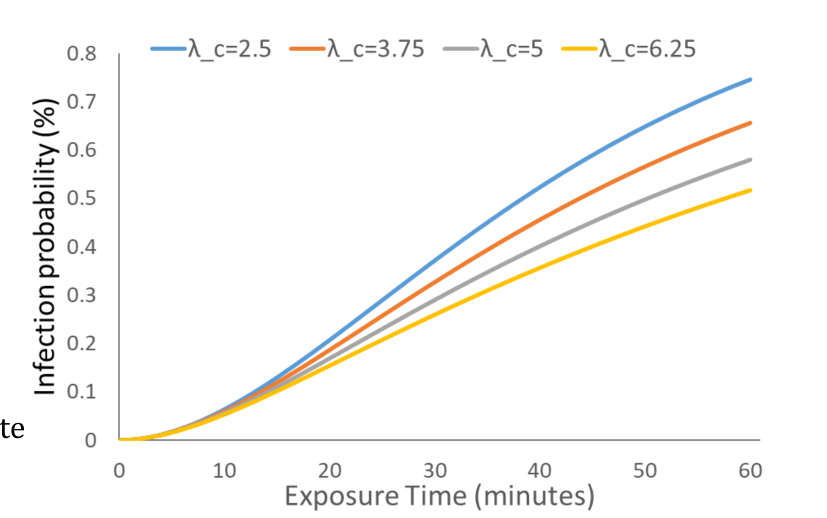

Figure 1. Example of infection probability for different removal rates as a function of time

HVAC Operation

- **HVAC system operation is related to λ_a and λ_f.**
- Fresh air may be provided by simply opening a window, or by increasing the HVAC fresh air supply.
- Properly sized conventional air filters also facilitate particle removal.
- The size of the particles will impact the effectiveness of the filters.
- Morawska et al. [4] proposed a four-mode fit to describe respiratory aerosols.
- Particle size and concentration is dictated by the kind of expiratory activity, such speaking or coughing.
- Bulk airflow is responsible for the transport of airborne droplets through their environment.

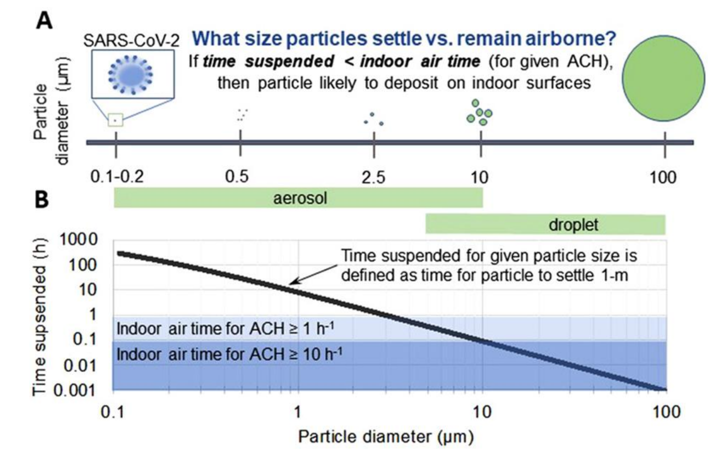

Figure 2. Suspension time and size range of aerosols and droplets [3]

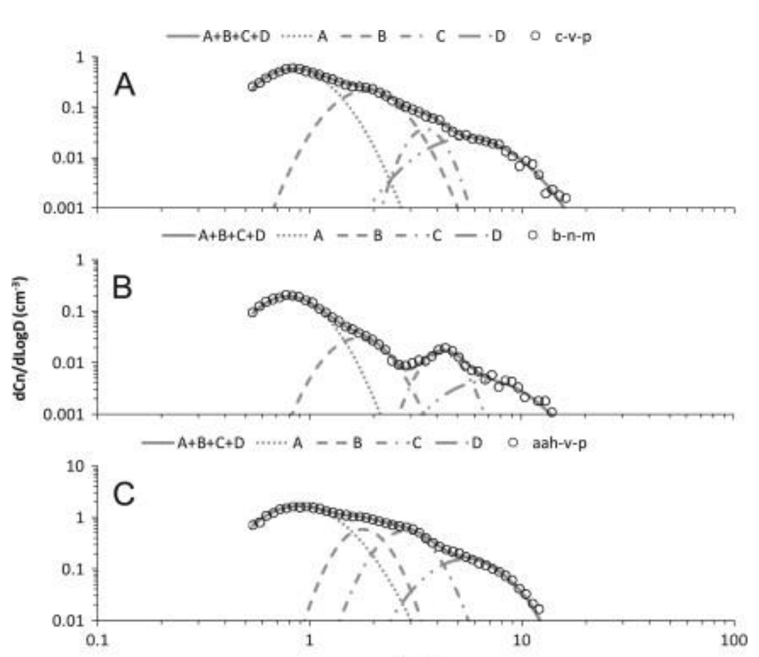

Figure 3. Size distributions of respiratory aerosols generated through voiced counting (A), natural breathing (B), and a vocalized "aah" sound (C) [4]

Ultraviolet Germicidal Irradiation

- **Ultraviolet Germicidal Irradiation (UVGI) is related to λ_v.**
- UV light corrupts a virus's DNA, effectively removing its ability to replicate.
- UVGI effectiveness is related to the emitted wavelength, intensity of the light, and exposure time.
- No current standards exist for UVGI implementation.
- UVGI technology is usually applied by installing lamps inside air ducts, directly in rooms, and in portable air circulating units.
- UV light is known to cause mutations in viruses and skin cells.
- Ozone may potentially be generated by emitting certain wavelengths of light.

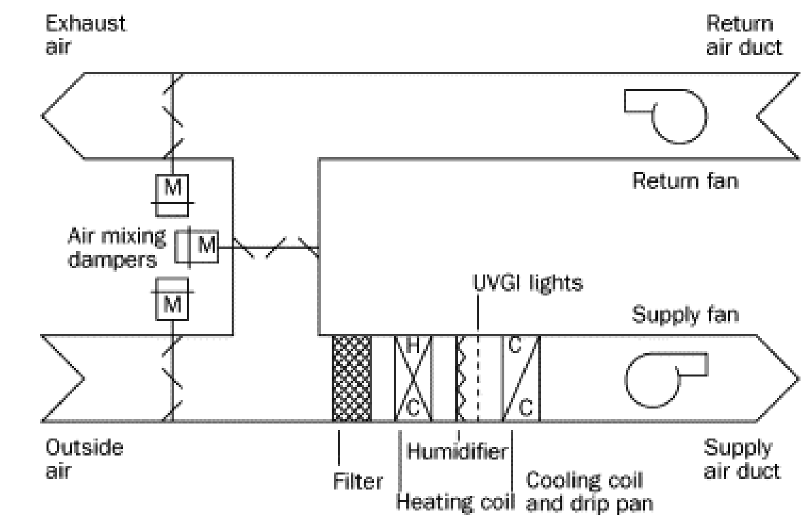

Figure 6. Possible configuration for HVAC integration of UVGI [7]

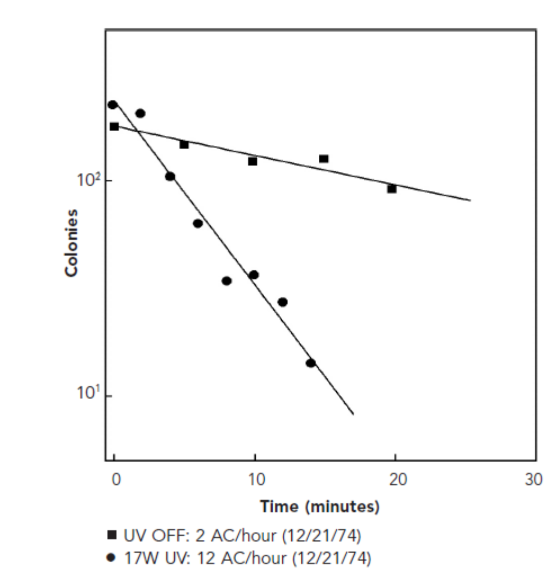

Figure 7. Decrease in Bacillus Calmette-Guerin with and without UVGI [8]

Filter Coatings

- **Filter coatings are related to λ_f and λ_v.**
- Nanoparticles are typically applied to fibrous air filters.
- Coatings may have antiviral properties, cause mechanical damage, or produce reactive oxygen species.
- Potentially increases the filtration efficiency while inactivating captured viruses.
- There are diminishing returns on the amount of coating added versus the antiviral efficiency.
- A slight increase in filter pressure drop results as the amount of coating is increased.
- There is a chance to introduce the filter coating as an aerosol into the environment.

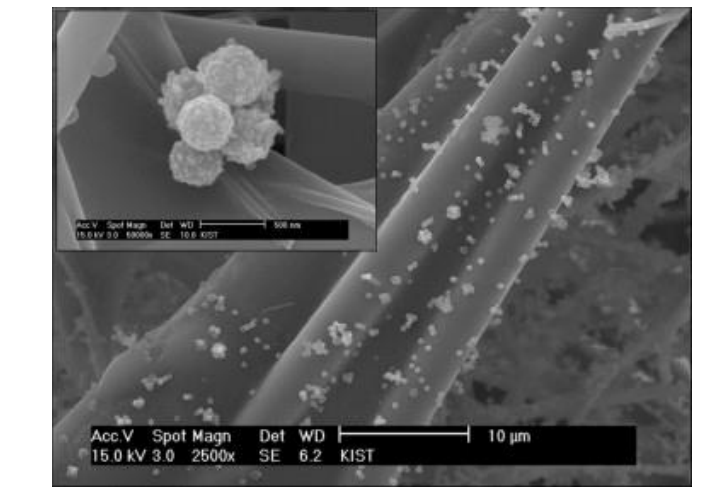

Figure 9. Antiviral nanoparticle fiber coating [10]

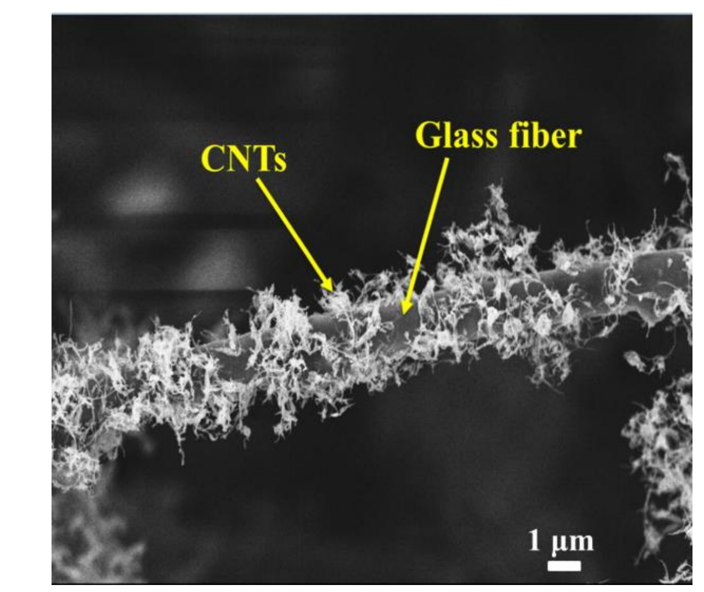

Figure 10. Carbon nanotube fiber coating [11]

Environmental Conditioning

- **Environmental control is related to λ_v and λ_s.**
- Temperature control will directly affect viral inactivation.
- Relative humidity control affects the droplet evaporation and the concentration of salts within a droplet.
- Smaller particles may remain airborne for longer periods of time [3].
- The evaporation-falling curve in Figure 5 is useful in understanding the relationship between size, relative humidity, and transmission [3].
- The transition point between droplet evaporation and settling is significantly impacted by the relative humidity.
- Environmental control may offer a unique compromise for viral mitigation while remaining in the thermal comfort zone [5].

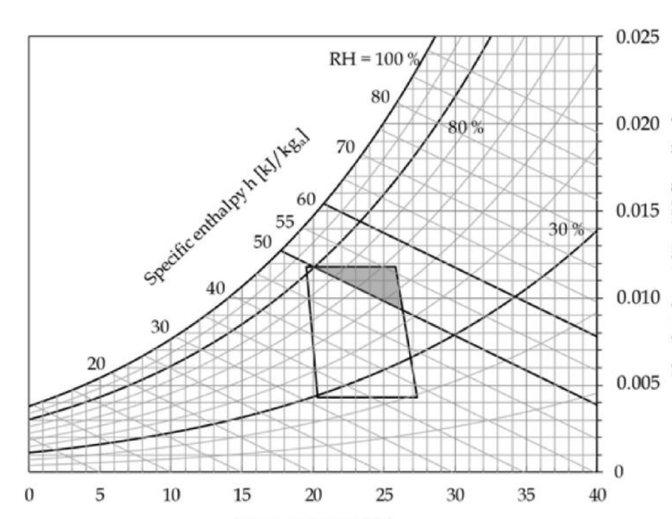

Figure 4. Thermal comfort range and highlighted suggested conditions for decreased viral survivability [5]

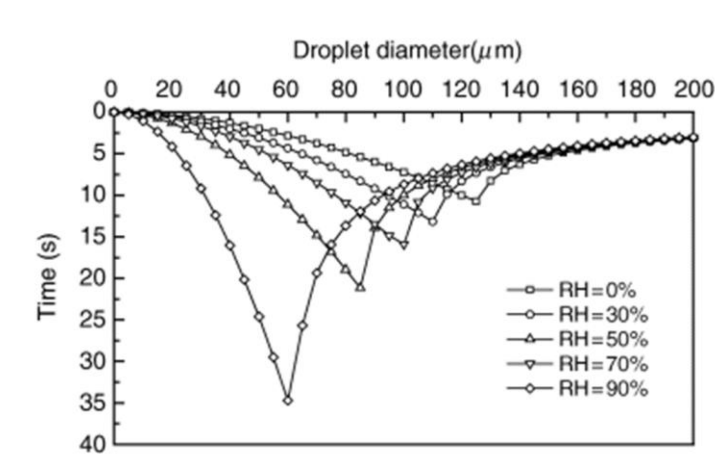

Figure 5. Evaporation time and falling time for droplets with different humidities [6]

Air Ionization

- **Air ionization is related to λ_f and λ_s.**
- Uses positive and negative air ions to impart a charge to the viral particles.
- Charged particles have an increased deposition rate to surfaces, such as a wall or a filter.
- The particle removal efficiency is dependent on the ion emission rate, which is influenced by generator input power.
- May produce ozone if the generator input power is too high.
- Particles may be deposited to charged plates, similar to conventional air filters.
- Air ionization may be used with conventional air filters to increase their efficiency.

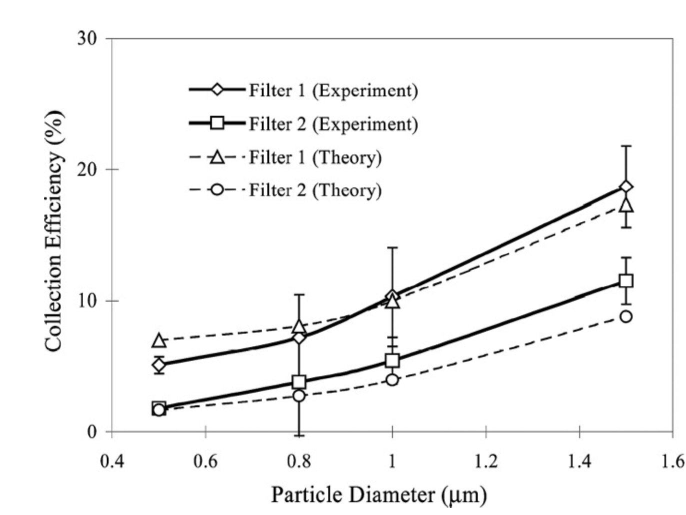

Figure 4. Filtration efficiency without using an air ionizer [9]

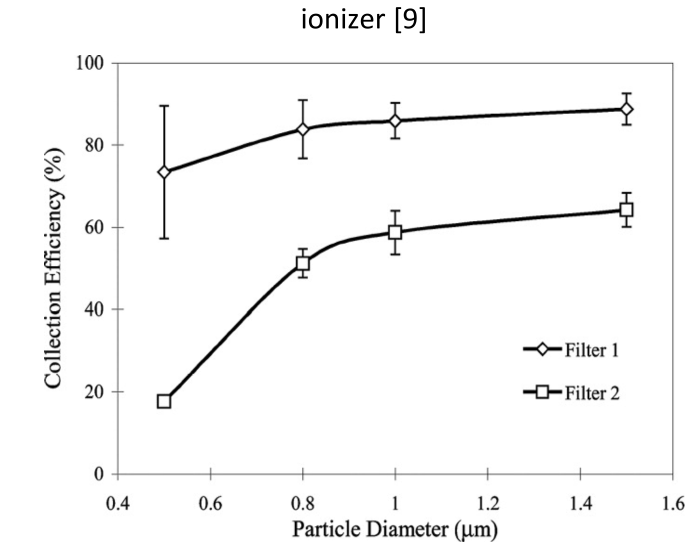

Figure 5. Increased filtration efficiency using an air ionizer [9]

Conclusions and Future Work

- A layered approach is recommended, as a single method is unlikely to completely remove viral particles and could yield diminishing returns on effectiveness.
- The ideal approach may be unique for each situation and will likely depend on factors such as the ability to introduce fresh air, or the configuration of an HVAC system.
- Most of the methods require more research for effective and safe implementation. However, all methods show potential for effective viral mitigation.
- There is a lack of useable cost analysis data surrounding the implementation of these technologies.

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* For brevity, the included citations were condensed to direct work. A comprehensive list of references may be found in the corresponding citation.

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