Measures to Improve Indoor Air Quality and Energy Efficiency in Buildings and Reduce the Spread of the SARS-CoV-2 Virus

Robert Mowris, Verified Inc.

ABSTRACT

The SARS-CoV-2 virus has significantly impacted human health worldwide with more than 537,353,020 infections and 6,314,405 deaths. Based on Super-Spreader Event (SSE) data, 99.8% of infections occur indoors from virus aerosols and 0.2% occur outdoors. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) provides five recommendations to reduce infection including face masks, MERV-13 air filters, increasing outdoor airflow, air distribution, and commissioning. The Center for Disease Control and Prevention (CDC) recommends HEPA filters, Upper Room Ultraviolet Germicidal (UR-UVG) lamps, increasing ventilation, social distancing, face masks, and vaccination (CDC 2021). The US Environmental Protection Agency (EPA) provides similar recommendations as well as bipolar ionization in portable air cleaners and HVAC systems that meets UL 2998 standard certification for zero ozone emissions and laboratory data to demonstrate efficacy of virus deactivation (EPA 2022, UL 2020). Face masks prevent exposure to virus aerosols with zero energy impacts, but reusable masks with antibacterial and antiviral properties and rapid diagnostics of viruses on used masks are needed. HEPA filters remove SARS-CoV-2 and other pathogens but may increase fan energy use by 100 to 150%. UR-UVG lamps can deactivate SARS-CoV-2 within 20 minutes and maintain safe levels of UVG exposure in occupied spaces, but installation costs and energy use are significantly greater than bipolar ionizers. Combining bipolar ionizers with MERV-10 air filters reduces the SARS-CoV-2 virus by 97.6% in 60 minutes with 10 to 18% less energy than MERV-13 air filters, 38% less energy than UR-UVG lamps, and 63% less energy than HEPA filters.

Introduction

The SARS-CoV-2 virus causing the COVID-19 pandemic has had a major worldwide impact on human health. According to the World Health Organization (WHO), the virus has caused more than 537,353,020 infections and 6,314,405 deaths (WHO 2022). A major factor driving the pandemic is Super Spreader events (SSEs), where one gathering of people results in numerous infections spreading the chain of transmission to other people. Based on the SSE open-access database 99.8% of infections occur indoors from virus aerosols and only 0.2% occur outdoors (Swinkels 2020). Indoor live events such as audiences for concerts or sports, with no masks or distancing, are huge risks (1,831 cases per instance) versus participating in sports which is not high risk (13 cases per instance). Prisons, nursing homes, and healthcare facilities are tragically huge common hotspots and make up 62.2% of all cases tied to SSEs. While funerals and weddings only account for 1.3% combined and demonstrations only 0.1%, smaller, socially optional gatherings such as bars/clubs, restaurants, religious services, and small private gatherings make up a larger share or 7.3% of SSEs. About 72% of SSEs make up 81% of cases associated with those events, and 10% of infected individuals typically cause 80% of additional transmissions. Avoiding SSEs is a major step towards ending the pandemic, where SSEs and infections are dominated by aerosol transmission in buildings through the Heating, Ventilating, Air Conditioning (HVAC) system (Li 2021, Allen 2020, Tufekci 2020).

Numerous studies have evaluated the mechanisms of virus aerosol generation and emission from the respiratory tract during breathing, talking, coughing, and sneezing (Mao 2020), particle size distribution and virus concentration (Morawska 2020), indoor transport, and deposition (Zhou 2021), biological decay rate and dose-response analysis (Zhang 2020). Gupta et al. confirmed aerosols dissipated quickly within 1 meter (m) from the mouth, while larger droplets fell to the surrounding surfaces quickly, smaller particles (with diameter less than ten µm or microns) were deposited onto upward, downward, and vertical surfaces at different rates (Gupta 2010). Van Doremalen et al. reported similar half-lives of SARS-CoV-2 as SARS-CoV-1 – about 1.1–1.2 hours in the environment at 69.8 to 73.4F (21–23C) temperature and 65% relative humidity (Van Doremalen 2020). Regarding susceptibility, the dose-response model links the infection risk with an exposure dose (Cheng 2013). Exposure dose represents the number of virus units inhaled over an exposure period, whereas infection risk predicts the probability of one susceptible person getting infected. The Quantitative Microbial Risk Assessment (QMRA) of occupational exposure to SARS-CoV-2 in various buildings was modeled in two research studies (Jones 2021, Ren 2021). Ventilation volume and exposure duration are important to the SARS-CoV-2 exposure dose (Kong 2021). Pease calculated the theoretical potential aerosol transmission and infectivity of SARS-CoV-2 through central ventilation systems and confirmed the effectiveness of increasing outdoor airflow and air filtration to reduce virus aerosol transmission (Pease 2021). Minimum Efficiency Reporting Value 13 (MERV-13) air filters provide removal efficiencies of 50% for particles from 0.3 to 1.0 microns, 85% for 1.0 to 3.0 microns, and 90% for 3.0 to 10.0 microns. MERV 10 air filters do not remove particles from 0.3 to 1.0 microns and have efficiencies of 50% for 1.0 to 3.0 microns and 80% for 3.0 to 10.0 microns (EPA 2022). The SARS-CoV-2 virus is about 0.1 microns in size, but when the virus is expectorated from an infected person and encapsulated in globs of mucus, saliva, and water, the virus aerosol droplet size can vary from 0.3–20 microns, and virus aerosol particles can linger in the air or be circulated in an HVAC system in sufficient quantities to cause infection (Jayaweera 2020).[1]

ASHRAE provides five recommendations to reduce infection including face masks, MERV-13 air filters, increasing outdoor airflow, air distribution, and commissioning (ASHRAE 2021). The CDC recommends High-Efficiency Particulate Air (HEPA) filters, UVG-CC lamps. and increasing overall ventilation (CDC 2021). The US EPA provides similar recommendations as well as bipolar ionization in portable air cleaners and HVAC systems that meets UL 2998 standard certification for zero ozone emissions and laboratory test data to demonstrate efficacy of virus deactivation (EPA 2022, UL 2020). The paper describes measures to improve indoor air quality and energy efficiency in buildings and reduce the spread of the SARS-CoV-2 virus. Measures include face masks, air filtration, HEPA filters, UR-UVG lamps, and bipolar ionizers.

[1] The Center for Disease Control (CDC) has not established an infectious dose for SARS-COV-2. Some experts estimate that exposure to as few as 1000 SARS-CoV-2 virus particles can cause an infection. This dose of the virus could occur by inhaling 1000 infectious virus particles in a single breath, 100 virus particles in 10 breaths, or 10 virus particles in 100 breaths.

ASHRAE Recommendations

The ASHRAE Epidemic Task Force provides core recommendations for reducing airborne infectious aerosol exposure (ASHRAE 2021). The ASHRAE recommendations assume ventilation, filtration, and air cleaners can be deployed flexibly to achieve exposure reduction goals subject to comfort, energy use, and costs. Targets are set for an equivalent clean air supply rate based on the performance of filters, air cleaners, and other removal mechanisms. ASHRAE's first recommendation is to follow all current regulatory and statutory requirements and recommendations, including vaccination, face masks and other Personal Protective Equipment (PPE), social distancing, administrative measures, circulation of occupants, hygiene, and sanitation (Liao 2021). ASHRAE's second recommendation is to maintain the required minimum outdoor airflow rates for ventilation per codes and standards, combine air filters and air cleaners to achieve MERV-13 or better performance, and only use air filters or cleaners with scientific evidence of effectiveness and safety to reduce exposure and minimize energy penalties (ASHRAE 2020, ANSI/ASHRAE/IES 2019). ASHRAE's third recommendation for air distribution is to promote mixing of space air without causing strong air currents that increase direct transmission from person to person where directional airflow is not required based on risk assessment. ASHRAE's fourth recommendation for HVAC system operation is to maintain temperature and humidity design setpoints, maintain equivalent clean air supply by design when occupied, when necessary flush spaces between occupied periods, operate systems to achieve three air changes per hour of equivalent clean air supply, limit re-entry of contaminated air from energy recovery devices, outdoor air, and other sources to acceptable levels. ASHRAE's fifth recommendation is to verify HVAC systems function as designed with system commissioning or re-commissioning.

Face Masks to Prevent Respiratory COVID-19 Transmission

Since the outbreak of the COVID-19 pandemic, most countries recommended social distance, hand hygiene, and face mask-wearing. However, many citizens did not adopt face mask-wearing due to a perception that scientific evidence is lacking to support face masks to prevent transmission. Liao et al. provide a technical review of face mask-wearing to prevent respiratory COVID-19 transmission based on design and function of face masks and materials (Liao 2021). An overview is provided of mask specifications, laboratory tests, respiratory virus transmission trials, and future development of reusable masks. Face masks provide a barrier to prevent respiratory tract exposure to virus droplets and aerosols. Physical interception reduces the risk of Respiratory Virus Illness (RVI). Studies show that SARS-CoV-2-containing particles can be ejected several meters (m) from a coughing or sneezing patient. These particles vary significantly in size, which, in turn, affects the distance from the source that the particles travel through the air. Aerosols are suspensions in the air (or in a gas) of solid or liquid particles, small enough to remain airborne for prolonged time periods due to low settling velocities. For spherical particles, settling times for a 3-meter fall are 10 seconds for 100 microns, 4 minutes for 20 microns, 17 minutes for 10 microns, and 62 minutes for 5 microns. Particles with a diameter less than 3 microns do not settle (Knight 1980, Tellier 2006). Particles expelled by coughing or sneezing rapidly shrink in size by evaporation, increasing the number of particles that behave as aerosols. Droplets as large as 20 microns containing virus particles can be shrunk by evaporation and behave as aerosols that do not settle where they can be circulated by HVAC systems and inhaled by humans. Once inhaled, virus particles exposed to humid air in the lungs swell in size causing infection (Tellier 2006).

Developing reusable masks will reduce the shortage of medical masks since the standards for general-public protection are less than those for medical and healthcare professionals. Unlike single-use medical masks that intercept most particles and droplets by electrostatic interaction, reusable masks work by filtering barriers such as hydrophobicity and porosity. Many researchers and manufacturers are developing reusable and low-cost mask designs to provide better protection against COVID-19 infections. Market development includes new fiber materials and cloth fabrications with new properties and functions, including reusable, degradable, environment-friendly, cheap, easy, and comfortable (Karim 2020). Meanwhile, resilient microbial viability on common face masks poses a big threat to the population of long-time mask-wearing because most bacteria remain active even after 8 hours. To address this problem, bactericidal (bacterial killing and bacteriostatic) surface coatings with biocompatible properties are being evaluated to support expanding demands for more effective reusable face masks. Materials with enhanced antibacterial and antiviral properties will improve reusable face mask protection (Zhong 2020, Huang 2020). Apart from masks in the role of health protection, direct sampling, and analysis of trace constituents in exhaled breath aerosols can be achieved on a used face mask, a simple and non-invasive approach (face mask microextraction), to provide rapid diagnostic information regarding human physiological and pathological states (MacIntyre 2020, Yuan 2020). International standardization and guidance for reusable masks for general use are emerging from infection control organizations and regulatory bodies to guide manufacturing and testing. This evolving process will drive new research and fulfill the current gaps in antiviral tests and assessment, drawing closer relevance to the properties and functioning of face masks.

Air filtration and Outdoor Airflow to Reduce Virus Aerosol Transmission

Several research studies have confirmed the effectiveness of increasing outdoor airflow and air filtration to reduce virus aerosol transmission (Pease 2021, Thompson 2021, Conway-Morris 2021). Pease evaluated the concentrations and probabilities of infection for both building interior and exterior exposure sources using a well-mixed model in a multiroom building served by a central air handling system (without packaged terminal air conditioning) (Pease 2021). The influence of filtration, air change rates, and the fraction of outdoor air were compared. When the air supplied to rooms comprises both outdoor air and recirculated air, air filtration lowers the concentration and probability of infection most in connected rooms. Increasing the air change rate removes the virus from the source room faster and increases the exposure rate in connected rooms. Therefore, slower air change rates reduce infectivity in connected rooms at shorter durations. Increasing the fraction of virus-free outdoor air is helpful unless outdoor air is infective, in which case pathogen exposure inside persists for hours after a short-term release. Increasing the outdoor air to 33% or the filter to MERV-13 decreases the infectivity in connected rooms by 19% or 93%, respectively, relative to a MERV-8 filter with 9% outdoor air based on 100 quanta/hour of 5-micron droplets, a breathing rate of 0.48 m3/h, and the building dimensions and air handling system considered.

For typical recirculation levels, air filtration is most effective in lowering the virus aerosol concentration and probability of infection via HVAC systems as air filters block the path of virus aerosols. For example, MERV-8 filters reduce the risk of infection from 1.5% (no filter) to 0.2% in the connected rooms. In theory, higher filtration levels result in higher levels of protection. However, the risks of infection are all small beyond MERV-8 (e.g., 0.04% and 0.01% risks of infection for MERV-11 and MERV-13, respectively). A study by the University of Colorado, the National Renewable Energy Laboratory (NREL), and Lawrence Berkeley National Laboratory (LBNL) reported that MERV-13 air filters installed in HVAC systems could lower virus aerosol concentrations by 10% with an 11% increase in fan energy compared to MERV-10 air filters (Faulkner 2021).[2] As shown in Figure 1 for Permanent Split Capacitor (PSC) motors, replacing MERV-10 with MERV-13 air filters decreases airflow and fan power by about 8 to 10% as static pressure increases by about 36% (e.g., 143 to 195 Pa or 0.575 to 0.785 in H2O). Reducing airflow by 8 to 10% for PSC fan motors, will increase cooling and heating energy by 4 to 5%. Figure 2 shows airflow decreasing by 8% and fan power increasing by 18% for constant-torque Brushless Permanent Magnet (BPM) motors for same pressure increase (USDOE 2013). Constant-airflow BPM motors provide constant airflow with an 18% power increase for the same pressure increase (Fazil 2021).

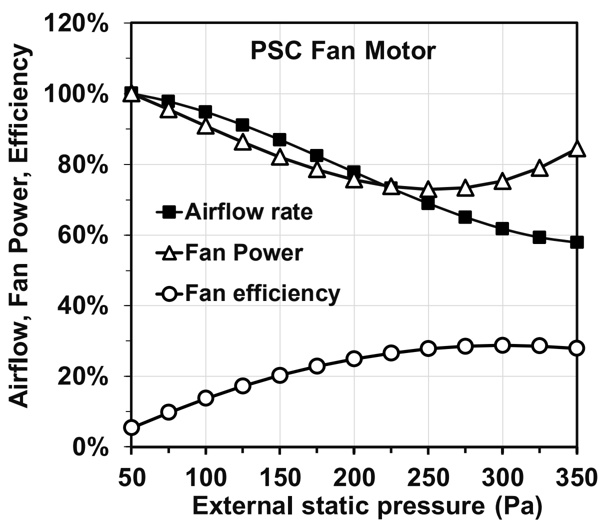

Figure 1. Fan performance for PSC motors

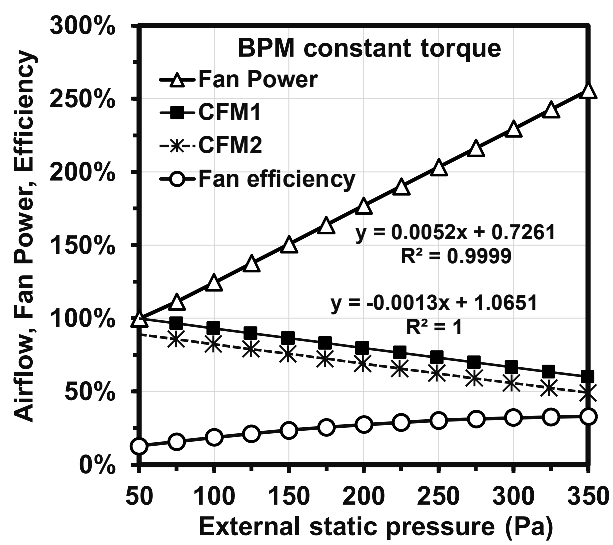

Figure 2. Fan performance for BPM motors

Outdoor air is the third most effective measure to reduce aerosol transmission via the HVAC system behind air filtration and bipolar ionizers. When the fraction of outdoor air increases from 0% to 33%, the risk decreases from 0.22% to 0.16%. Given its significant impact on energy use and thermal comfort in the heating- or cooling-dominated climate zones, ventilation should be increased thoughtfully. Increasing the air change rate should also be considered with caution because it may increase the rate of viral aerosol spread via HVAC

[2] Faulkner et al. 2021. p. 5: "MERV 13 filter shows about a 12% increase in fan energy usage." At "least one infection is predicted in the zone for both filtration strategies, but the probability of a second infection is reduced by about 30% using MERV 13 level filtration." Total static pressure was modeled with a 13.2% increase (143 to 162 Pa), but MERV-13 would increase total static pressure by 36.5% (143 to 192.3 Pa) compared to MERV-10.

systems. When Air Changes per Hour (ACH) are increased from 1.8 to 12, the time-to-peak virus aerosol concentration in connected rooms decreases from 30 minutes to 11 minutes with a significant increase in energy use.

HEPA Filtration

Research at a hospital with COVID-19 confirmed that portable HEPA filters effectively remove SARS-CoV-2 virus particles from the air (Greenhalgh 2021). The results suggest that HEPA filters can be used to reduce the risk of patients and medical staff contracting SARS-CoV-2 in hospitals. Despite the proper use of personal protective equipment, hospitals reported a substantial spread of SARS-CoV-2 from patients to healthcare workers. One suspected cause of such cases is viral aerosol particles - one of the main drivers of SARS-CoV-2 transmission. Earlier experiments that tested air filters' performance assessed their ability to remove inactive particles while operating in carefully controlled environments (Chia 2020). HEPA air cleaners were installed in two fully occupied COVID-19 wards: 1) a general ward and 2) an Intensive Care Unit (ICU). Air samples were collected during a week when the HEPA air cleaners were operating and two weeks when they were not operating. In the general ward, the SARS-CoV-2 particles were detected in the air when the HEPA air cleaners were not operating. However, no SARS-CoV-2 particles were detected when the HEPA air cleaners were operating. The study suggests that portable HEPA air cleaners are a cheap and easy way to reduce risk from airborne pathogens. The HEPA air cleaners also removed Staphylococcus aureus, Escherichia coli, and Streptococcus pyogenes. Retrofitting HEPA filters on central HVAC systems designed for MERV-10 or MERV-13 air filters may require replacing fans with higher power ratings to deal with the higher static pressure of approximately 1 inch of water (H2O) (248.84 Pascal) for clean HEPA filters versus 0.17 in H20 (42.3 Pa) for MERV-10 or 0.38 in H20 (94.5 Pa) for MERV-13. Installing more powerful fans to maintain airflow rates with HEPA filters may increase fan energy by 100 to 150% (see Figures 1 and 2).

UVG Lamps

The Center for Disease Control (CDC) recommends Upper Room (UR) Ultraviolet Germicidal (UVG) lamps, over ventilation with outdoor air, and improved HVAC filtration to slow the spread of the SARS-CoV-2 virus (CDC 2021). As noted above, increasing outdoor airflow to 33% or the filter to MERV-13 decreases the infectivity in connected rooms by 19% or 93%, respectively, relative to a MERV-8 filter with 9% outdoor airflow. UR-UVG lamps provide a 200 to 280 nanometers (nm) "C" wavelength (50 to 100 µW/cm2) to destroy the Deoxyribonucleic Acid (DNA) of viruses and bacteria over an exposure time of several seconds to many hours depending on intensity of UVG lamp, distance, airflow, or surface (ASHRAE 2020a, Luongo 2017). Most UR-UVG lamps contain mercury but mercury-free LED UVG lamps are available. Table 1 and Figure 3 provide Bio-Safety Level 3 (BSL-3) laboratory tests of a 29.6W wall-mounted UR-UVG system (253.7 nm UV-C operating at 230V) to evaluate the effectiveness of deactivating the SARS-CoV-2 delta variant virus (Innovative Bioanalysis 2020). Testing was conducted per BSL-3 standards in a sealed chamber with 7.4 m2 (80 ft2) floor area and 18.1 m3 (640 ft3) volume. The UR-GUV system deactivated 99% of aerosolized SARS-CoV-2 virus within 10 minutes with fans operating continuously directing air towards the ceiling. In a larger 36.24 m3 (1280 ft3) chamber, deactivation times would be longer. For example, tests of ceiling fans with UR-UVG (UV-C) lamps indicate 99.9% of aerosolized viruses are deactivated above the fan in 20 minutes.[3] Laboratory tests indicate UR-UVG is more effective at reducing virus concentration than over ventilation, air filtration, or bipolar ionizers. However, UR-UVG installation and energy costs are significantly greater than other technologies.[4]

Table 1: Collectible SARS-CoV-2 Delta Variant with and without UR-UVG

Test	**0 minutes**	**2 minutes**	**5 minutes**	**10 minutes**	**20 minutes**
Control (TCID50/mL)	6.32×10^6	5.96×10^6	5.84×10^6	4.84×10^6	3.48×10^6
% Reduction – Control		5.70%	7.59%	23.42%	44.94%
Experiment (TCID50/mL)	6.32×10^6	1.03×10^6	1.83×10^5	6.32×10^2	1.20×10^2
% Reduction – Experiment		83.70%	97.10%	99.99%	99.998%
% Reduction – Exp vs. Control		80.91%	96.87%	99.99%	99.997%

Source: Innovative Bioanalysis 2021

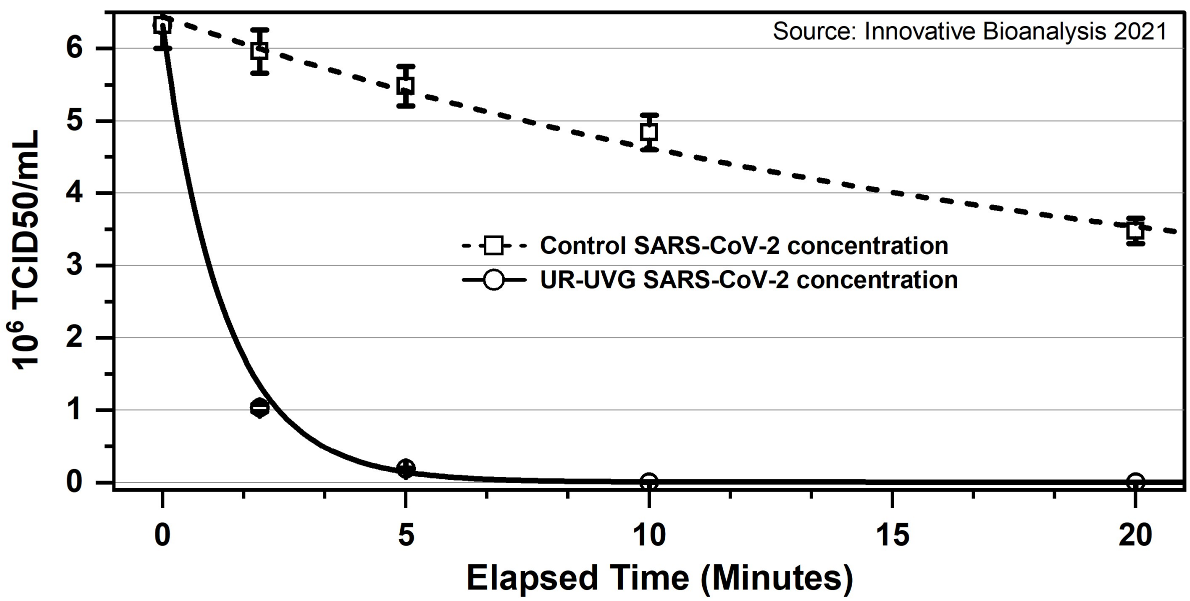

Figure 1: Collectible SARS-CoV-2 Virus with and without UR-UVG

A key difference between surface decontamination and airborne inactivation of organisms is exposure time. SARS-CoV-2 virus particles 5 µm (microns) and smaller may not settle for hours or even days inside a building (https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html). Residence time is typically seconds or fractions of seconds for in-duct UVG lamps. In airstreams, UVG exposure time is limited by the effective distance of

[3] LEDs Magazine. 2020. UV-C LEDs fan out in air circulation offerings. https://www.ledsmagazine.com/lighting-health-wellbeing/article/14188485/uvc-leds-fan-out-in-air-circulation-offerings

[4] For a small building with 111.5 m2 (1200 ft2) of floor area, 7 UR-UVG lamps would need to be installed at a cost of $14,000 using 207.2W of power which is equivalent to 41% of a 500W HVAC fan and significantly greater than 2.6W for bipolar ionizers.

average irradiance. For example, deactivation of aerosolized viruses with UVG radiation can take 0.12 seconds at 0.3408 meters (one foot) and airflow rate of 2.54 m/s (500 fpm). Therefore, UVG lamp neutralization methods against aerosolized viruses must be effective in seconds or fractions of a second, depending on the device characteristics, and UVG lamp intensity and/or more in-line depth is required. Conversely, when irradiating surfaces in an HVAC system, exposure time is continuous, so lower levels of UVG intensity are required. A field study of UVG lamps in Singapore showed a 10% increase in heat transfer, 13% decrease in pressure drop, and 9% fan energy savings by reducing biofilms on evaporator coils (Wang 2016).

Bipolar Ionizers combined with air filtration

Bipolar ionizers deactivate or agglomerate virus aerosol particles circulated in an HVAC system to improve air filtration and prevent airborne transmission (Hagbom 2015, Sanders 2020, Tierno 2017, Park 2016, Thompson 2021, Conway-Morris 2021). One study suggests that bipolar ionization may decrease some volatile organic compounds (VOCs such as xylenes) but increase other VOCs (e.g., acetone, ethanol, and toluene) with negligible net changes in estimated PM2.5 loss rates, indicating a need to control VOCs at the source and combine air filtration with bipolar ionization (Zeng 2021). The US EPA recommends bipolar ionization in portable air cleaners and HVAC systems that meets UL 2998 standard certification for zero ozone emissions and laboratory test data to demonstrate efficacy of virus deactivation (EPA 2022, UL 2020). Table 2 and Figure 4 provide BSL-3 laboratory tests of a bipolar ionizer to evaluate the effectiveness of deactivating the SARS-CoV-2 delta variant virus (Innovative Bioanalysis 2022). Testing was conducted per BSL-3 standards in a sealed chamber with 14.9 m2 (160 ft2) floor area and 36.24 m3 (1280 ft3) volume. The bipolar Ionizer was placed at the outlet of a custom 12-inch diameter ductwork system with a fan attached. The airflow velocity of the fan was measured at approximately 1.03 m/s (204 fpm), providing a calculated volumetric airflow of approximately 75.5 liters per second (160 cfm or one cfm per ft2 of floor area) to emulate the airflow provided by an HVAC system. The ductwork system was set on a stainless-steel table 36" above the ground and positioned in the center against the 8 feet chamber wall. Four variable-speed mixing fans (~30 cfm each) were placed on the floor at a 45-degree angle in each corner to encourage air mixing. Air sampling was collected using four calibrated programmable vacuum devices sampling 0.177 cfm (5.02 liter/min) located 6 feet off the chamber floor. Before testing, the chamber was pressure tested and visually inspected for leaks, and all internal lab systems and equipment were reviewed before testing. Sample collection volumes were set to 10-minute draws per time point. The air sampler operated with a removable sealed cassette and was manually removed after each sampling point. Cassettes had a delicate internal filtration disc to collect virus samples, which was moistened with a virus suspension media to aid in the collection. Table 2 and Figure 4 show the number of collectible SARS-CoV-2 delta variants for the control and bipolar ionizer over 60 minutes (Innovative Bioanalysis 2022). The control plot shows a natural viability loss over time, decreasing to a virus concentration of approximately 1.68 x 10^6 Median Tissue Culture Infectious Dose per milliliter (TCID50/mL) at 60 minutes. Experimental tests with the bipolar ionizer device show significantly greater reduction against the SARS-CoV-2 Delta variant. After 15 minutes of device operation, the SARS-Cov-2 Delta variant concentration was reduced by 45% to 2.22 x 10^6 TCID50/mL. After 30 minutes, the SARS-Cov-2 delta variant concentration was reduced by 74.5% to 1.03 x 10^6

TCID50/mL. Compared to an initial viral concentration of 4.03 x 10^6 TCID50/mL, the bipolar ionizer reduced the collectible SARS-CoV-2 Delta variant by 97.55% to 9.85 x 10^4 TCID50/mL at 60 minutes. When installed with a MERV-8 to MERV-10 air filter the time required to remove or deactivate the virus aerosol concentration is estimated to be reduced by about 80 to 90% like UR-UVG. Laboratory tests of ceiling fans with bipolar ionizers indicate 99.99% deactivation of aerosolized SARS-CoV-2 virus above the fan in 20 minutes.[5]

The Clean Air Delivery Rate (CADR) is used by the Association of Home Appliance Manufacturers (AHAM), Consumer Reports, research communities, and the U.S. Environmental Protection Agency (EPA) to represent an air purifier's efficiency in terms of how fast an air purifier can filter the whole air (volumetric) of a room within a specific time (AHAM 2014).[6] Compared to the control, the bipolar ionizer reduces the SARS-CoV-2 virus aerosol concentration by 94.1% after 60 minutes. Based on 160 cfm of volumetric airflow and 94.1% effectiveness compared to the control, the bipolar ionizer CADR* is 150.6.[7] Combining the bipolar ionizer with a MERV-13 air filter will provide about the same deactivation rate as a HEPA air filter but require a more powerful fan using 2.7 times more fan energy than a BPM fan motor providing the same airflow, and roughly the same fan power and 42% less airflow than a PSC fan motor. Combining the bipolar ionizer with a MERV-8 or MERV-10 air filter will improve PM1.0 effectiveness by 50 to 100% and deactivate or remove the virus aerosol concentration in less than 60 minutes with 10 to 18% energy savings compared to MERV-13 air filters (GPS 2022). This strategy uses 2.7 times less energy than HEPA filters. The bipolar ionizer only uses 2.6W of power per 2500 cfm of treated air with no increase in static pressure.

Table 2: Collectible SARS-CoV-2 Delta Variant with and without Bipolar Ionizer

Test	**0 minutes**	**15 minutes**	**30 minutes**	**60 minutes**
Control (TCID50/mL)	4.03 x 10^6	2.69 x 10^6	2.13 x 10^6	1.68 x 10^6
% Reduction – Control		33.25%	47.18%	58.16%
Experiment (TCID50/mL)	4.03 x 10^6	2.22 x 10^6	1.03 x 10^6	9.85 x 10^4
% Reduction – Experiment		44.95%	74.50%	97.55%
% Reduction - Experiment vs. Control		17.5%	51.6%	94.1%

Source: Innovative Bioanalysis 2021

[5] Ibid.

[6] CADR is a measure of the appliance's ability to reduce smoke, dust, and pollen particles in the 0.10 to 11 micron size range from the air. CADR is defined as "the rate of contaminant reduction in the test chamber when the unit is turned on, minus the rate of natural decay when the unit is not running, multiplied by the volumetric airflow rate measured in cubic feet per minute."

[7] The bipolar ionizer 150.6 CADR* is for comparison only since tests were performed in a 1280 ft3 chamber and the test method only includes pollen, smoke, and dust and does not include the SARS-CoV-2 virus. CADR is tested in a 1008 ft3 test chamber size which is an integral part of the definition and is standardized in ANSI/AHAM AC-1-2006 to ensure that comparisons between units that have been evaluated using the standard are fairly made. This standardized room size chamber limits the maximum CADR measurement (or value) to 450 (pollen and smoke) and 400 (dust).

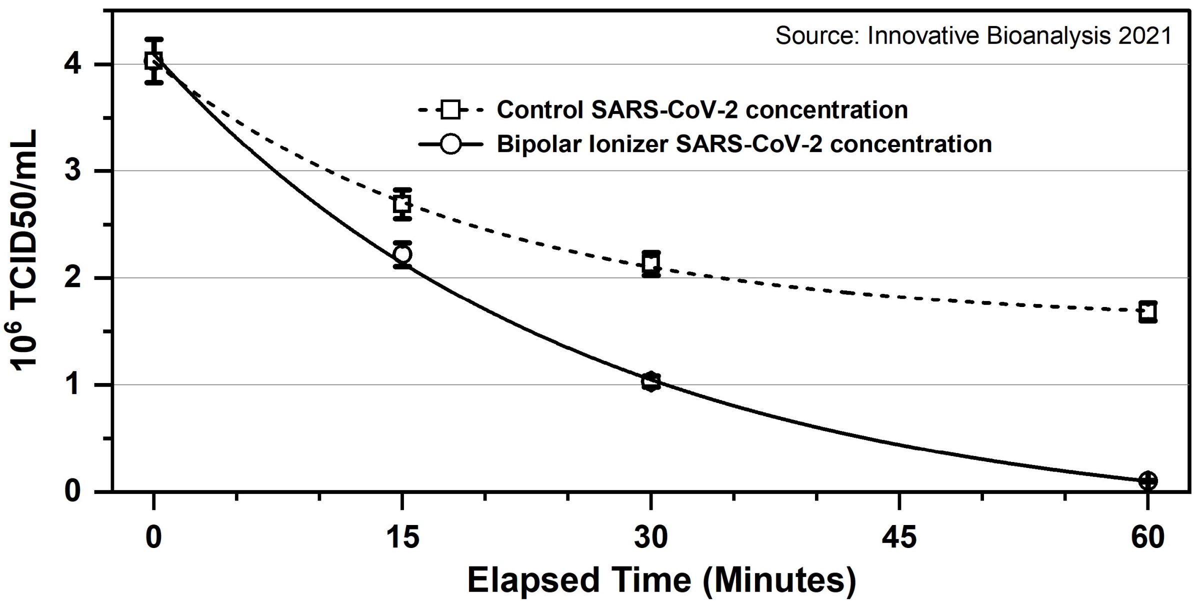

Figure 2: Collectible SARS-CoV-2 Virus with and without Bipolar Ionizer

Table 3 and Figure 5 provide the bipolar ionizer 24-hour ozone concentration test results performed by Intertek per Underwriters Laboratory (UL) Standard 867, Canadian Standards Association (CSA) 22.2 #184, and UL Standard 2998 (zero ozone) (UL 2018, CSA 2020, UL 2020). Test results show zero ozone over 24 hours to meet the UL 2998 standard and California Air Resources Board (CARB) requirements (CARB 2020, ASHRAE 2020).

Table 3: Bipolar Ionizer 24-Hour Ozone Concentration - Intertek tests per UL 867

Description	**UL Ref.**	**Pass/Fail**	**Mean**	**Min**	**Max**	**Delta**	**Units**
Background C(t) O3:	40.4.3	PASS	0.001	0.000	0.001	0.001	[ppm]
Test 1min C(t) Ozone:	40.1.2	PASS	0.000	0.000	0.001	0.001	[ppm]
Test 5min C(t) Ozone:	40.1.2	PASS	0.000	0.000	0.000	0.000	[ppm]
Chamber Temperature:	40.4.2	PASS	77	77	77	1	[degF]
Chamber Humidity:	40.4.2	PASS	52	50	52	2	[%RH]
Chamber Static Pressure:	-	PASS	0.02	0.01	0.03	0.01	[in. H2O]
Chamber Supply Air Flow:	-	-	20	20	20	0	[SCFM]
Required to Test 2nd Sample:	40.1.1	NO					
Test Duration:	*40.4.6	24 hours					

Source: Intertek 2021

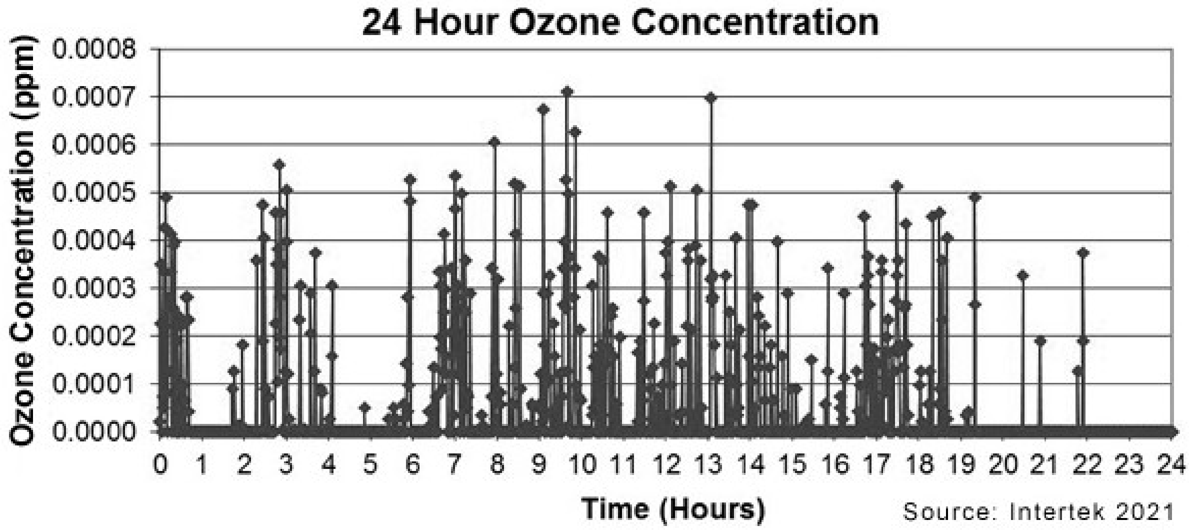

Figure 3: Bipolar Ionizer 24-Hour Ozone Concentration based on Intertek tests per UL 867

Energy Impacts for Measures to Reduce the Spread of SARS-CoV-2

Energy efficiency impacts for measures to reduce the spread of the SARS-CoV-2 are provided in Table 4. Energy impacts the difference from pre-existing conditions based on energy savings, or energy increases: low (0 to +5%), moderate (>5 to +10), or high (>10%).

Table 4: Estimated Energy Efficiency Impacts for Measures to Reduce SARS-CoV-2

Measure	Energy Savings	Low Impact 0 to 5%	Moderate Impact >5% to 10%	High Impact >10%
ASHRAE #1 Vaccines, Face Masks, etc.		0%		
ASHRAE #2 MERV-13 Min OA (62.1)			>5 to +10%	
ASHRAE #3 Air distribution and mixing		0 to +5%		
ASHRAE #4 3 ACH when unoccupied			>5 to +10%	
ASHRAE #5 Commissioning per design	0 to 5%			
Face masks to prevent transmission	0%			
Air filtration and outdoor airflow		+3 to +5%	>5 to +10%	
HEPA filtration				+100 to 150%
UR-UVG				+40%
Bipolar ionizers and air filtration	10 to 18%			

ASHRAE recommendation #2 (MERV-13 air filters) and #4 (3 ACH when unoccupied) increase HVAC energy use by 5 to 10%. The other ASHRAE recommendations provide an energy increase of 0 to 5% or a slight decrease of 0 to 5%. Face masks provide protection from virus aerosols with no energy impact. Air filtration and outdoor airflow increase energy by 3 to 10% due to increased static pressure and more HVAC energy to circulate and condition outdoor air. HEPA filters require more fan energy for portable air cleaners and more powerful fans to maintain design airflow with higher static pressure. UR-UVG lamps can deactivate SARS-CoV-2 and maintain safe levels of UVG exposure in occupied spaces, but installation costs and energy use are significantly greater than bipolar ionizers. Laboratory tests show bipolar ionizers improve air filter PM1.0 removal effectiveness by 100% for MERV-8 and 50% for MERV-10 with reduced HVAC energy use (GPS 2022). Combining bipolar ionizers with MERV-8 or MERV-10 air filters improves air filter effectiveness and reduces virus aerosol concentrations by 97% in 60 minutes with 10 to 18% less energy than MERV-13 air filters, 38% less energy than UR-UVG lamps, and 63% less energy than HEPA filters.

Conclusions

ASHRAE recommendation #2 (MERV-13 filters) and #4 (increase unoccupied outdoor airflow to 3 ACH) will increase HVAC energy use by 5 to 10%. Other ASHRAE recommendations provide an energy increase of 0 to 5% or a slight decrease of 0 to 5%. Face masks provide a barrier to prevent respiratory exposure from virus droplets and aerosols with zero energy impacts. Portable HEPA air cleaners are an effective method to remove SARS-CoV-2 and other pathogens in hospitals, health care, and other buildings. However, retrofitting HEPA filters on central HVAC systems designed for MERV-10 or MERV-13 air filters may require replacing fan motors with higher power ratings to maintain airflow rates which may increase fan energy use by 100 to 150%. BSL-3 laboratory tests show UR-UVG lamps can deactivate the SARS-CoV-2 virus within 10 minutes in small chambers with fans operating continuously directing air towards ceilings and 20 minutes with ceiling fans. While UR-UVG lamps are effective at reducing virus concentrations, UR-UVG installation and energy costs are significantly greater than other measures. BSL-3 laboratory tests indicate bipolar ionizers can deactivate the SARS-CoV-2 virus within 60 minutes with zero ozone. Combining bipolar ionizers with MERV-10 air filters will reduce the SARS-CoV-2 virus by 97.6% in less than 60 minutes with 10 to 18% less energy than MERV-13 air filters, 38% less energy than UR-UVG lamps, and 63% less energy than HEPA filters.

References

Allen. J. 2020. We should focus on airborne transmission of COVID-19. Harvard School of Public Health (HSPH). Cambridge, MA: HHSPH. https://www.hsph.harvard.edu/news/hsph-in-the-news/op-ed-we-should-focus-on-airborne-transmission-of-covid-19/

American National Standards Institute (ANSI)/Association of Home Appliance Manufacturers (AHAM). ANSI/AHAM. 2014. AC-1: Method for Measuring the Performance of Portable Household Electric Room Air Cleaners. Washington, DC: ANSI

ANSI/ASHRAE/IES 2019. ASHRAE 62.1-2019. Standard 62.1. Standard Ventilation for Acceptable Indoor Air Quality. New York, NY: ANSI.

ASHRAE EPIDEMIC TASK FORCE. 2021. Core Recommendations for Reducing Airborne Infectious Aerosol Exposure. Atlanta, GA: ASHRAE

ASHRAE. 2020. Guidance for Building Operations During the COVID-19 Pandemic. Atlanta, GA: ASHRAE. ashrae.org/file%20library/technical%20resources/ashrae%20journal/2020journaldocuments/72-74_ieq_schoen.pdf

ASHRAE. 2020a. Handbook HVAC Systems and Equipment. Chapter 17 Ultraviolet Lamp Systems. Chapter 29 Air Filters for Particulate Contaminants. Atlanta, GA: ASHRAE.

Cai, J., S. Li, D. Hu, Y. Xu, and Q. He. 2022. "Nationwide Assessment of Energy Costs and Policies to Limit Airborne Infection Risks in U.S. Schools." Journal of Building Engineering 45, 103533. https://doi.org/10.1016/j.jobe.2021.103533.

California Air Resources Board (CARB). 2020. Regulation for Limiting Ozone Emissions from Indoor Air Cleaning Devices. California Code of Regulations. Title 17. https://ww2.arb.ca.gov/sites/default/files/2020-10/Final%20Regulations%20Order%20.pdf

Canadian Standards Association (CSA). 2020. Standard 22-2 No.187-20, Section 7, February 2015, Jan 2020. https://www.techstreet.com/standards/csa-c22-1-21?product_id=2204192

Center for Disease Control and Prevention (CDC). 2021. Ventilation in Buildings. https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html

Cheng, Y., C. Liao. 2013. Modelling control measure effects to reduce indoor transmission of pandemic H1N1 2009 virus. Building and environment, 63, 11–19. https://www.sciencedirect.com/science/article/abs/pii/S0360132313000292

Chia P., K. Coleman, Y. Tan. 2020. Novel Coronavirus Outbreak Research Team. Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients. Nat Commun. 2020;11(1):2800.

Conway-Morris, A., et al. 2021. The removal of airborne SARS-CoV-2 and other microbial bioaerosols by air filtration on COVID-19 surge units. https://www.medrxiv.org/content/10.1101/2021.09.16.21263684v1.full.pdf

Faulkner, C. et. al. 2021. MERV 13 Filtration for Office Buildings During COVID-19 Pandemic. Proceedings of the 12nd International Symposium on HVAC (ISHVAC 2021). Seoul, Korea, 24-26 November 2021. https://www.colorado.edu/lab/sbs/sites/default/files/attached-files/c60_merv13-filtration-office-buildings.pdf

Global Plasma Solutions (GPS). 2022. MERV8 and ERV10 PM1.0 Removal with Bipolar Ionizer Testes by Blue Heaven Technologies in AHAM Standard Test Chamber (10'x10'x10') per ASHRAE 52.2. https://globalplasmasolutions.com/third-party-testing

Greenhalgh, T. et. al. 2021. Ten scientific reasons in support of airborne transmission of SARS-CoV-2. Lancet. 2021;397(10285):1603-1605

Gupta, J., C. Lin, Q. Chen. 2010. Characterizing exhaled airflow from breathing and talking. Indoor air, 20(1), 31–39. https://onlinelibrary.wiley.com/doi/10.1111/j.1600-0668.2009.00623.x

Hagbom, M. et al. 2015. Ionizing air affects influenza virus infectivity and prevents airborne-transmission. https://www.nature.com/articles/srep11431.pdf

Huang, L., S. Xu, Z. Wang, K. Xue, J. Su, Y. Song, et al. 2020. Self-reporting and photothermally enhanced rapid bacterial killing on a laser-induced graphene mask. ACS Nano 2020, 14: 12045–12053. https://pubs.acs.org/doi/abs/10.1021/acsnano.0c05330

Innovative Bioanalysis. 2020. Efficacy of a Wall Mounted UV Device Against Aerosolized SARS-CoV-2. https://www.assets.signify.com/is/content/Signify/Assets/philips-lighting/global/20210301-innovative-bioanalysis-report-sars-cov-2.pdf.

Innovative Bioanalysis. 2022. Efficacy of the GreenFan Bipolar Ionizer Against the Aerosolized SARS-CoV-2 Delta Variant, Greenfan Bipolar Ionizer Model 1600-01.

Intertek. 2021. Ozone Test Report: Ozone Emissions Testing of Household Electrostatic Air Cleaners for Model: 1600-01. Report Number 104617012CRT-001. 9/28/21.

Jayaweera, M., H. Perera, B. Gunawardana, J. Manatunge. 2020. Transmission of COVID-19 virus by droplets and aerosols: A critical review on the unresolved dichotomy. Environmental research, 188, 109819. https://doi.org/10.1016/j.envres.2020.109819

Jones, B., P. Sharpe, C. Iddon, E. Hathway, C. Noakes, S. Fitzgerald. 2021. Modelling uncertainty in the relative risk of exposure to the SARS-CoV-2 virus by airborne aerosol transmission in well mixed indoor air. Building and environment, 191, Article 107617. https://www.sciencedirect.com/science/article/pii/S0360132321000305

Karim N., S. Afroj, K. Lloyd, L. Oaten, D. Andreeva, C. Carr, A. Farmery, I. Kim, K. Novoselov. 2020. Sustainable personal protective clothing for healthcare applications: a review. ACS Nano 2020, 14:12313–12340. https://pubs.acs.org/doi/pdf/10.1021/acsnano.0c05537

Knight V. 1980. Viruses as agents of airborne contagion. Annals of New York Academy of Science 1980, 353:147–156. https://nyaspubs.onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.1980.tb18917.x

Kong, X. et. al. 2021. Experimental study on the control effect of different ventilation systems on fine particles in a simulated hospital ward. Sustainable Cities and Society, Article 103102. https://www.sciencedirect.com/science/article/pii/S2210670721003851

Li C, Tang H. 2021. Comparison of COVID-19 infection risks through aerosol transmission in supermarkets and small shops. Sustain Cities Soc. 2022 Jan;76:103424. doi: 10.1016/j.scs.2021.103424. Epub 2021 Oct 2. PMID: 34631396; PMCID: PMC8487098.

Liao, M. et. al. 2021. A technical review of face mask wearing in preventing respiratory COVID-19 transmission. Current Opinion in Colloid & Interface Science. Volume 52. 101417. ISSN 1359-0294. https://doi.org/10.1016/j.cocis.2021.101417.

Luongo, J., J. Brownstein, S. Miller. 2017. Ultraviolet germicidal coil cleaning: Impact on heat transfer effectiveness and static pressure drop. Building and Environment. Vol. 112. Pp. 159-165. ISSN 0360-1323. https://doi.org/10.1016/j.buildenv.2016.11.022.

MacIntyre C., A. Chughtai. 2020. A rapid systematic review of the efficacy of face masks and respirators against coronaviruses and other respiratory transmissible viruses for the community, healthcare workers and sick patients. Int J Nurs Stud 2020, 108:103629. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7191274/

Mao, N., C. An, L. Guo, M. Wang, L. Guo, S. Guo, E. Long, 2020. Transmission risk of infectious droplets in physical spreading process at different times: a review. Building and

Environment, Article 107307. https://www.sciencedirect.com/science/article/pii/S0360132320306788

Morawska, L., J. Cao. 2020. Airborne transmission of SARS-CoV-2: The world should face the reality. Environment international, 139, Article 105730. https://www.sciencedirect.com/science/article/pii/S016041202031254X

Mowris, R. 2017. Laboratory and Field Tests of an Efficient Fan Controller in Cooling and Heating Mode on Residential HVAC Systems. 8th EEDAL'17, Irvine, CA, USA, 2017. http://www.bpi.org/sites/default/files/Ecostella_docs/Laboratory%20and%20Field%20Tests%20of%20an%20Efficient%20Fan%20Controller.pdf

Park. J. et al. 2016. The bactericidal effect of an ionizer under low concentration of ozone. BMC Microbiol. 2016; 16: 173. PMID: 27475908. ncbi.nlm.nih.gov/pmc/articles/PMC4967512/

Pease, L. et. al. 2021. Investigation of potential aerosol transmission and infectivity of SARS-CoV-2 through central ventilation systems. Building and Environment, 197, Article 107633. https://www.sciencedirect.com/science/article/pii/S0360132321000457

Ren, C., C. Xi, J. Wang, Z. Feng, F. Nasiri, S. Cao, F. Haghighat. 2021. Mitigating COVID-19 Infection Disease Transmission in Indoor Environment Using Physical Barriers. Sustainable cities and society, Article 103175. https://www.sciencedirect.com/science/article/pii/S221067072100456X

Sanders, E. 2020. COVID-19 Successfully Neutralized in Testing of Aviation Clean Air's Interior Purification System. Executive and VIP Aviation International. https://www.evaint.com/covid-19-successfully-neutralized-in-testing-of-aviation-clean-airs-interior-purification-system/

Swinkels, K. (2022). SARS-CoV-2 Superspreading Events Database. https://kmswinkels.medium.com/covid-19-superspreading-events-database-4c0a7aa2342b. SARS-CoV-2 Superspreading Events from Around the World - Google Sheets

Tellier R: Review of aerosol transmission of influenza a virus. Emerg Infect Dis 2006, 12:1657–1662. https://pubmed.ncbi.nlm.nih.gov/17283614/

Thompson T. 2021. Real-world data show that filters clean COVID-causing virus from air. Nature. 2021 Oct 6. doi: 10.1038/d41586-021-02669-2. Epub ahead of print. PMID: 34616095. https://www.nature.com/articles/d41586-021-02669-2

Thompson T. 2021. Real-world data show that filters clean COVID-causing virus from air. Nature. 2021 Oct 6. doi: 10.1038/d41586-021-02669-2. Epub ahead of print. PMID: 34616095. https://www.nature.com/articles/d41586-021-02669-2

Tierno, P. 2017. Cleaning Indoor Air using Bi-Polar Ionization Technology. New York University School of Medicine. NY: NY. US.

Tufekci, Z. July 2020. We Need to Talk about Ventilation. Washington, DC: The Atlantic. theatlantic.com/health/archive/2020/07/why-arent-we-talking-more-about-airborne-transmission/614737/

UL. 2020. Environmental Claim Validation Procedure (ECVP) for Zero Ozone Emissions from Air Cleaners UL Environment Standard 2998 (UL 2998), Edition 3 Edition Date: July 2020.

Underwriters Laboratory (UL). 2018. Electrostatic Air Cleaners, UL 867, Section 40, Fifth Edition, August 4, 2011.Revision: August 7, 2018. Northbrook, IL: UL

United States Environmental Protection Agency (EPA). 2022. Indoor Air Quality: What is a MERV Rating? https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating-1

US Environmental Protection Agency (EPA). 2022. Air Cleaners, HVAC Filters, and Coronavirus (COVID-19). Air Cleaning Devices that use Bipolar Ionization, including Portable Air Cleaners and In-duct Air Cleaners used in HVAC Systems. https://www.epa.gov/coronavirus/air-cleaners-hvac-filters-and-coronavirus-covid-19

USDOE. 2013. Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Residential Furnace Fans. mercatus.org/system/files/1904-AC22-DOE-RIA-Energy-Conservation-Standards-for-Resdiential-Furnace-Fans.pdf

Van Doremalen et. al. 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. New England journal of medicine, 382(16), 1564–1567. https://www.nejm.org/doi/10.1056/NEJMc2004973

Wang, Y. et. al. 2016. Effectiveness of an ultraviolet germicidal irradiation system in enhancing cooling coil energy performance in a hot and humid climate, Energy Build. 130 (2016) 321–32 https://pennstate.pure.elsevier.com/en/publications/effectiveness-of-an-ultraviolet-germicidal-irradiation-system-in-

World Health Organization (WHO). 2022. Rolling Updates on COVID 19. Geneva CH: WHO. https://covid19.who.int/

Y. Zeng, et. al. 2021. Evaluating a commercially available in-duct bipolar ionization device for pollutant removal and potential byproduct formation. Building and Environment. Vol. 195. 107750. ISSN 0360-1323. www.sciencedirect.com/science/article/pii/S036013232100158X

Yuan Z., W. Li, L. Wu, D. Huang, M. Wu, B. Hu B. 2020. Solid-phase microextraction fiber in face mask for in vivo sampling and direct mass spectrometry analysis of exhaled breath aerosol. Anal Chem 2020, 92:11543–11547. https://pubmed.ncbi.nlm.nih.gov/32786499/

Zhang, X., Z. Ji, Y. Yue, H. Liu, J. Wang. 2020. Infection risk assessment of COVID-19 through aerosol transmission: a case study of South China Seafood Market. Environmental science & technology, 55(7), 4123–4133. https://pubs.acs.org/doi/10.1021/acs.est.0c02895

Zhong, H., Z. Zhu, J. Lin, C. Cheung, V. Lu, et al, 2020. Reusable and recyclable graphene masks with outstanding superhydrophobic and photothermal performances. ACS Nano, 14:6213–6221. https://pubs.acs.org/doi/abs/10.1021/acsnano.0c02250

Zhou, Y., S. Ji. 2021. Experimental and numerical study on the transport of droplet aerosols generated by occupants in a fever clinic. Building and Environment, 187, Article 107402. https://www.sciencedirect.com/science/article/pii/S0360132320307708