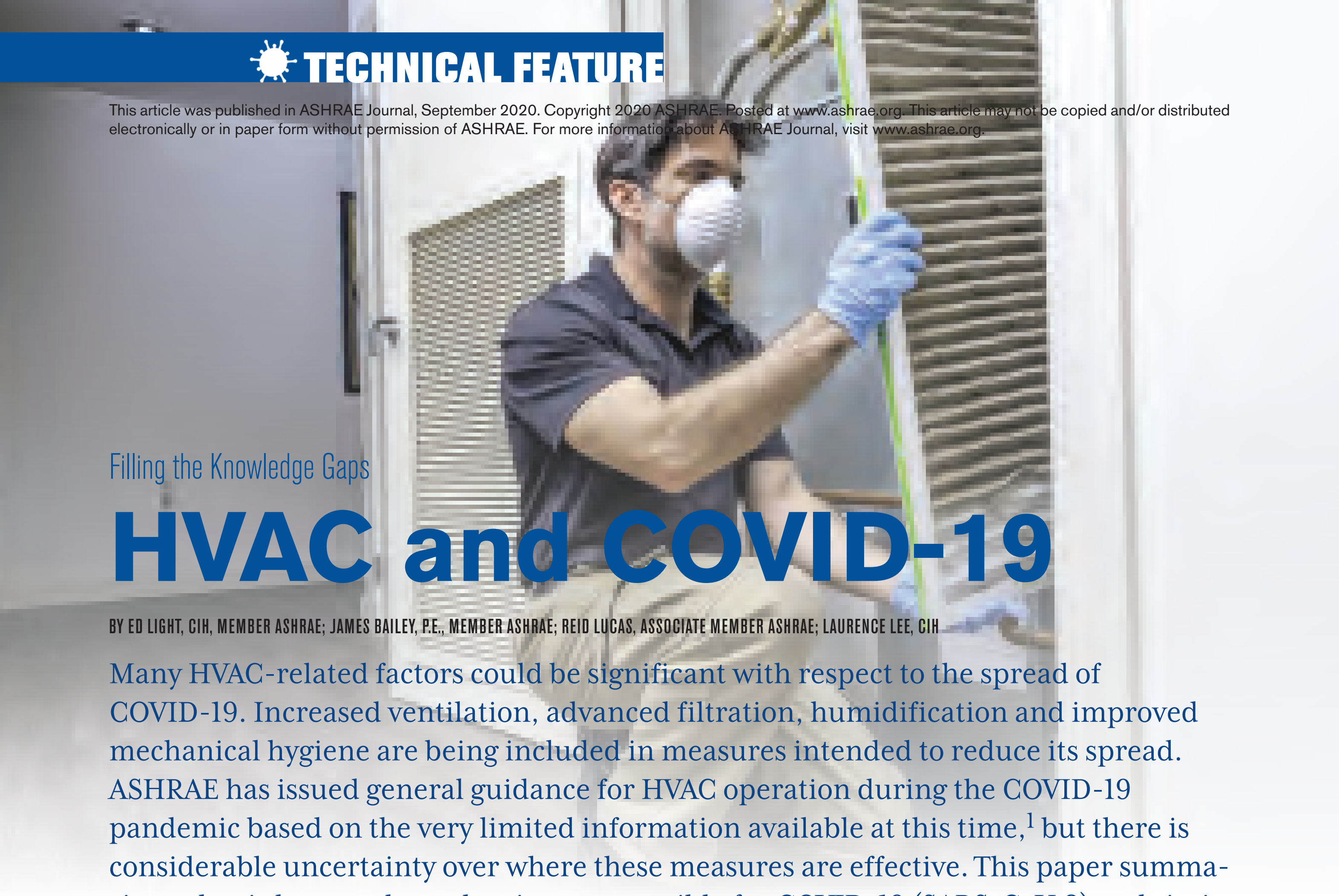

TECHNICAL FEATURE

Filling the Knowledge Gaps

HVAC and COVID-19

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Many HVAC-related factors could be significant with respect to the spread of COVID-19. Increased ventilation, advanced filtration, humidification and improved mechanical hygiene are being included in measures intended to reduce its spread. ASHRAE has issued general guidance for HVAC operation during the COVID-19 pandemic based on the very limited information available at this time,[1] but there is considerable uncertainty over where these measures are effective. This paper summarizes what is known about the virus responsible for COVID-19 (SARS-CoV-2) and similar viruses regarding the role of HVAC in both the spread and control of infection. It also identifies critical information gaps and recommends research priorities.

Scientific publications were reviewed (including 2020 preprints of COVID-19 research) and papers previously published on related viruses such as SARS (2003 pandemic). The authors considered this information based on their experience as mechanical engineers specializing in HVAC design and operation and as industrial hygienists specializing in indoor air quality. It should be noted that this subject is rapidly evolving as efforts to control the pandemic continue.

Significance of Airborne Transmission

Transmission of respiratory infections through the air is classified as direct contact (within a few meters) or airborne (i.e., beyond a few meters). SARS-CoV-2 is infectious until it degrades (inactivated), but it has not been established how long the virus remains infectious in air. Because viruses generally have a minimum dose at which they cause infection and show a dose-response relationship, health risk is related to concentration in air and duration of exposure. These factors are not known for SARS-CoV-2.

CDC and WHO guidelines for COVID-19 response assume that the important routes of COVID-19 transmission are direct contact with the patient, short-range droplet exposure and transfer from surfaces where aerosols have settled (fomites).[2] Based on this assumption, recommended response measures by public health agencies are generally limited to social distancing, face coverings, handwashing and surface sanitizing. However, increasing evidence suggests that smaller aerosols remain suspended in the air, where they expose occupants (airborne transmission).

A group of Australian and Chinese researchers concluded that there is now sufficient evidence of airborne transmission of COVID-19 to justify improving ventilation and filtration where this would reduce SARS-CoV-2

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exposure,[3] and ASHRAE has adopted that position.[4]

Environmental epidemiology provides the most direct way to establish the significance of airborne transmission in the spread of COVID-19 and the efficacy of measures to limit airborne exposure. Environmental epidemiological studies require collaboration between engineers and health scientists to consider the location and timing of cases and environmental conditions associated with these.

The following epidemiological studies suggest airborne transmission of COVID-19.

Poorly Ventilated Restaurant. A detailed engineering evaluation was performed of conditions at the time of a COVID-19 outbreak at a restaurant in China. After mapping case locations, conditions experienced by both infected and unaffected customers and staff were characterized. The role of different transmission routes was evaluated by comparing factors influencing exposure of the two groups. Findings from this study included:

- Ten of the 73 restaurant customers were infected.
- Those 10 were seated at three adjacent tables on one side of the dining room, approximately 1 m to 5 m (3 ft to 16 ft) from a customer who had just arrived from Wuhan before community spread in the rest of China.
- HVAC consisted of five fan coil units (FCU) with no outside air and exhaust fans (off at the time).
- Measured ventilation rates (infiltration only) were an order of magnitude below ASHRAE Standard 62.1-2019.
- Modeling of airflow patterns established that a "bubble" was formed by each FCU, dividing the room into five separate zones containing contaminants released in that zone.
- Modeling results also suggested that discharge from the FCUs directed air in the breathing zone between customers.
- The three impacted tables were within the same zone.
- Air from the contaminated zone did not mix significantly with the rest of the room, and no customers were infected in those areas.
- Surveillance videos showed that close contact between individuals and fomite contact were not significant.
- Waiters did have brief contact with infected customers, but that was insufficient to cause infection.

This study concluded that SARS-CoV-2 was transmitted by a combination of close contact (i.e., droplet exposure within 2 m [7 ft]) and aerosol exposure beyond that distance (extended short-range airborne). Poor ventilation resulting in little dilution of the virus was considered a very important factor. This study cannot be used to draw general conclusions on the prevalence of airborne transmission due to the atypical HVAC configuration. Lack of customer infection in adjacent zones suggests that SARS-CoV-2 was sufficiently isolated to prevent disease transmission. Lack of waiter infection suggests that brief contact was not sufficient to transmit COVID-19.[5]

Poorly Ventilated Bus. One hundred twenty-six people traveled to a religious event in China in two buses, each with a recirculating air-conditioning system (no outside air). An infected individual from Wuhan was on one of the buses. All passengers mixed with the infected individual at a three-day religious event, along with 172 other attendees who had not been in the buses. Thirty persons subsequently contracted COVID-19, and they were classified as follows:

- No passengers on the bus without the infected individual had COVID-19.
- Seven attendees who had not been in the buses contracted COVID-19 but were in close contact with the infected individuals during the event.
- Twenty-three riders on the bus with the passenger from Wuhan were infected. By location, there were more cases in individuals sitting beyond 2 m (7 ft) of the infected passenger.[6]

Poorly Ventilated Conference Center. Also in China, 30 people attended a three-day event with an infected individual from Wuhan in a building with poor ventilation (HVAC cycled on only 15 minutes per four hours). It was not determined who had been in close proximity to the infected individual, and thus within droplet range. Fifteen attendees were subsequently infected. Investigators concluded that some infections were due to airborne exposure after comparing the infection rate to similar outbreaks and that ineffective dilution because of poor ventilation appeared to be a major contributor.[6]

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Well Ventilated Cruise Ship. Epidemiological investigation of the 696 COVID-19 cases aboard the Diamond Princess provided an opportunity to evaluate the role of a recirculating HVAC system that was reported to be operating with ventilation rates consistent with ASHRAE standards. Infection cases were classified into three categories: (a) individuals interacting without restriction (i.e., passengers prior to quarantine); (b) passengers quarantined in their cabin with no COVID-positive individuals present; and (c) passengers quarantined in their cabins where they were directly exposed to an infected person. Infections only occurred in categories (a) and (c). Passengers quarantined in cabins free of infected individuals continued to be exposed to recirculated air from spaces with infection. The lack of cases in category (b) suggests that circulation and dilution of air through the HVAC system did not cause infection.[7]

Korean Call Center. All 1,145 occupants of an office/apartment building were tested for COVID-19, and a cluster of cases was found on one floor, a densely occupied call center. There, 44% of the employees tested positive, and 94% of those were located on one side of the building. Only five cases were found on the rest of the floor, where the majority of employees worked. Any contact between occupants of the affected side of the floor with the other employees was very brief. Uniform spread throughout the affected area suggests there was airborne transmission beyond direct contact. No information was provided to determine the relationship between case location and HVAC zoning.[8]

Other COVID-19 studies sampled SARS-CoV-2 in air and on surfaces but did not correlate this with infection patterns. While measured contaminant concentrations established airborne exposure away from the infected individual, it was not determined if this exposure transmitted the infection to others.

Oregon Hospital. Surfaces were tested for SARS-CoV-2 inside a recirculating HVAC system with COVID-19 patients in some rooms. Sites with positive samples included the prefilter receiving mixed air (return and outside) and supply air dampers after filtration. These recently reported results establish, for the first time, that the virus can be transmitted through the HVAC system. Analysis did not determine if the virus was still infectious (airborne virus inactivates over time), and air quality was not tested.[9]

Two Wuhan Hospitals. Airborne SARS-CoV-2 was sampled at two Chinese hospitals and nearby outdoor locations. Investigators classified some samples by particle size and estimated surface deposition rates. Findings included:

- Virus was detected in the air at most sites with patients present.
- Concentrations were lower in the temporary hospital, where air infiltration was greater than in the permanent hospital.
- Elevated airborne concentrations were found in a bathroom (potential fecal contribution).
- Deposition tests associated particle settling with fomite contamination.
- Airborne virus settled on surfaces beyond the immediate area surrounding the source and subsequently resuspended, contributing to airborne exposure.
- Elevated air concentrations were measured in a staff changing area with used personal protective equipment (PPE) (suggesting resuspension of settled virus).
- Concentrations were lower in the staff changing area after more rigorous sanitizing was instituted.
- Particle size distribution varied, with >1 micron (droplets) dominating at one site, <1 micron (airborne) dominating at another, and a third site equally divided between droplets and small particles.

Investigators concluded that their findings supported airborne transmission.[10]

Nebraska Hospital. This study also detected SARS-CoV-2 in the air more than 2 m (7 ft) from the patient, including in the adjacent hall.[11] SARS-CoV-2 was not detected in the air around infected patients in Singapore and Iranian hospitals. Insufficient information was provided to determine if negative results were due to methodological limitations.[12,13]

A similar virus to SARS-CoV-2 was artificially generated and measured for infectivity. Infectious virus was detected after three hours in the air and three days on surfaces.[14] Another study found airborne virus infectious after 12 hours.[15]

Sampling studies represent occupant exposure, but not necessarily disease transmission. Most analyses cited above were by polymerase chain reaction (PCR), which measures total SARS-CoV-2 RNA, including viruses that have been inactivated and can no longer cause infection. Methods are also available that measure only infectious virus.

Research on Similar Viruses

To understand the spread of COVID-19, it is instructive to review research on similar viruses. During the severe acute respiratory syndrome (SARS) pandemic in 2003, public health agencies and some researchers concluded that respiratory infections were primarily spread by direct exposure to droplets at close range. Other investigators, however, concluded that the disease was also being spread by airborne transmission.

SARS in Hong Kong Hospital. Infections spread from one patient (index case) to patients and medical students in a ward with four rooms, each a separate HVAC zone. Outside air was provided by a central system and mixed with recirculated air from a fan coil unit (FCU) in each room. Air was returned to each FCU from a hall running adjacent to the rooms. A model of air distribution and bioaerosol was developed to estimate relative concentrations of airborne virus by location. Simulated exposures generally correlated with actual cases of infection as follows:

- Twenty-one people were infected in the zone with the index case. Some of these were within 3 m (10 ft) of the index case, but others were further away.
- Eleven people were infected in the room across the hall. Because the return grilles for each zone were near each other in the hall, air mixed between zones.
- Approximately six people were infected in the two rooms further down the hall. They return from the same hall, but airborne virus would be more dilute.[16]

SARS in Apartment Building. In Hong Kong, a major SARS outbreak was clustered within certain areas of an apartment building. The location of infected individuals was mapped and compared to environmental conditions. Investigators found the disease pattern consistent with airborne transmission. One suggested that sewer gas was a contributor. Others concluded infection sites occurred with typical air distribution in high-rise apartment buildings.[17,18]

SARS in Airliner. A study of how respiratory infections spread on an airliner mapped the location of passengers who developed infection in relation to their distance from the index case (individual already infected). Passengers were classified as either within 2 m (7 ft) or further away. An equal number of infected passengers were seated near the index case compared to those seated further away. The same paper examined three flights with clusters of H1N1 (swine flu). Each flight showed different case patterns, one with nearby passengers dominating and the other two with similar numbers of nearby and distant cases.[19]

Overall, these findings suggested that the spread of SARS included airborne transmission.[16]

HVAC Operations

Ventilation

The studies cited above establish that SARS-CoV-2 can be airborne beyond the immediate vicinity of an infected individual and that concentrations can be diluted by increasing ventilation.[20] SARS (2003 pandemic) investigators suggested that increased air exchange may have reduced disease spread, but they lacked information to support a minimum ventilation rate.[21,22] At least one investigator has suggested that proper ventilation could play a key role in containing the spread of COVID-19.[23]

Although window opening has been suggested as an option to reduce the risk of COVID-19 transmission, no studies related to this were available.

Air Distribution

The authors' field evaluation of wall-mounted fan coil units has identified situations where supply air blows directly on occupants, potentially transmitting virus from an infected individual to other occupants. Our examination of airflow patterns reported in the Guangzhuo restaurant outbreak study[5] suggests that this could have been a contributing factor. Air blowing directly on surfaces can also resuspend settled aerosols containing virus.[10] Air distribution also determines whether infectious droplets disperse or concentrate locally. Relative pressurization can also contain or spread contamination. No data were found relating airflow patterns to COVID-19 transmission.

Advertisement formerly in this space.

Filtration

Newly reported surface sampling inside recirculating HVAC systems in an Oregon hospital provides an indicator of filter efficiency. The amount of virus collected on the prefilter, final filter and supply air damper allows for comparison of virus in mixed air before and after prefilters (MERV 10) and after discharge from the final filters (MERV 15). The amount of virus collected on surfaces decreased by approximately 70% after passing through the prefilters but did not decrease further after the final filters.[9]

A modeling study of influenza spread found that higher efficiency air filters could lower flu infection risk.[24] Although COVID-19 response measures now include installation of filters with higher MERV ratings, there have been no studies to determine whether filter rating makes any difference in transmission of the disease.

Experience suggests that, with appropriate design and positioning, HEPA filtration units within a space could potentially reduce SARS-CoV-2 exposure by directly capturing air in the vicinity of infected patients or by removing airborne virus near susceptible individuals. However, designers must also be aware that discharge air could also blow virus between occupants and resuspend settled virus from surfaces.

Air Disinfection

Ultraviolet (UV) light systems for infection control can either be in the space (upper-room) or HVAC system (in-duct). These systems are occasionally used in hospitals to help control airborne infectious agents but are rarely used in non-healthcare facilities.

Upper-room UV was found in one study to prevent the spread of measles, mumps and chicken pox. However, the authors also noted that it might not be effective in the protection of susceptible individuals against other pathogens.[25] No studies were found related to the use of UV to control SARS-CoV-2.

Humidity Control

Coronaviruses survive under dry conditions, and occupants can be more susceptible to respiratory infection at lower relative humidity (RH). Humidification has been suggested as a means of controlling flu. Comparison of initial COVID-19 cases by region or country suggested that infection rates might be greater in areas with higher humidity.[26] However, COVID-19 also spread during initial stages of the pandemic in humid areas.[27]

Continuing high rates of COVID-19 in the United States this summer further suggest that humidity is not an important factor. The National Academy of Sciences concluded that differences in humidity only explain a small fraction of the overall variation in COVID-19 transmission rates.[28]

Wastewater

SARS-CoV-2 has been found in feces, urine, sewage, toilet surfaces and air in restrooms. The release of droplets containing virus from these sources is likely, but no monitoring results were found.

Mechanical Hygiene

SARS-CoV-2 on surfaces inside HVAC systems was recently documented where hospital systems recirculated air in zones with COVID-19 patients. The virus was detected on prefilters receiving mixed air, the surface of final filters receiving air after prefiltration and supply air dampers after the final filters.[9] In an earlier study, the surface of an exhaust outlet in a Singapore hospital tested positive.[12]

Preliminary Conclusions

Further study is needed to determine whether HVAC systems actually transmit COVID-19 infection and if HVAC modifications can help control its spread. Review of available information revealed very little detail in this regard.

Airborne Transmission. Limited sampling has established that SARS-CoV-2 is airborne and can expose (but not necessarily infect) occupants well beyond 2 m (7 ft). Recent findings further establish that the virus can circulate through some HVAC systems. While several outbreaks of COVID-19 infection have suggested airborne transmission, these have generally been in areas with poor ventilation, raising the possibility that dilution by code-required building ventilation inhibits disease transmission.

Ventilation. Increasing outdoor air dilutes the concentration of airborne SARS-CoV-2. Minimum acceptable ventilation rates have not been established for operation of buildings where infected occupants may be present. It is not known whether increasing ventilation rates above ASHRAE minimums actually reduces disease transmission. Natural ventilation has not been evaluated with respect to COVID-19.

Air Distribution. Studies suggest that how air is discharged and circulates within a space could be an important factor determining whether exposure is sufficient to cause disease. For example, wall-mounted FCUs can discharge air into the breathing zone, potentially directing virus to other occupants. Relative pressurization can also contain or spread contamination. No field data were available showing the impact of air distribution on COVID-19 exposure.

Filtration. Recently reported results of surface sampling inside recirculating HVAC systems provide an indicator of filter efficiency. Data suggest that a MERV 10 prefilter reduced the amount of deposited SARS-CoV-2 by approximately 70% and that a MERV 15 final filter may not have removed additional virus. Insufficient field data are available to guide filter selection for COVID-19. Filtration within the space (i.e., portable HEPA units) could reduce virus exposure in localized areas with appropriate design and placement.

UV Disinfection. Although UV light has the potential to reduce virus exposure in some situations, there are insufficient data to support widespread application.

Humidity Control. It has been demonstrated that coronaviruses survive longer and occupants are more susceptible to respiratory infection in drier conditions. Although COVID-19 initially spread in areas with drier (i.e., winter) conditions, there was also community spread in humid areas (i.e., tropical climates and southern hemisphere summer). Continuing high rates of COVID-19 in the United States this summer further suggest that humidity is not an important factor. Available information does not support humidification when the RH is below 40% as a control for COVID-19.

Sewage. SARS-CoV-2 has been found in feces and urine, making sewer gas and sewage a potential source of exposure. Studies are needed to develop effective strategies to avoid infecting occupants.

Mechanical Hygiene. SARS-CoV-2 has been detected on surfaces inside recirculating HVAC systems. It is not known if this can contaminate the airstream.

Recommendations for Expedited Research

Research is urgently needed to identify and implement cost-effective measures to operate buildings during the pandemic. While basic research can take years, valuable data could be compiled much faster using available epidemiology and by testing buildings.

Environmental Epidemiology. Studies can suggest the relative role played by the various routes of disease transmission and evaluate the efficacy of control measures. To accomplish this, engineers and health scientists collaborate to compile exposure factors (i.e., ventilation, airflow patterns, filtration, occupant density and spacing) to determine their relationship with case location and timing. If outbreak investigations, contact tracing and evaluation of widespread testing could include the collection of environmental information, findings would help support the selection of HVAC response measures. Critical questions that could be addressed by epidemiological studies include:

- What do infection patterns suggest with respect to the significance of airborne and fecal transmission as the cause of infection?
- How do ventilation, air distribution and humidity affect infection rates?
- How effective are various filtration and air disinfection measures in reducing exposure?

Field Studies. Valuable information can be produced by sampling for contaminants in occupied buildings for airborne and surface SARS-CoV-2 (both total RNA copies and infectious virus). Comparison of data collected in buildings with varying systems, uses and infection rates would provide valuable information to guide response efforts. Field measurements of particular value include:

- Concentrations of SARS-CoV-2 in air with recirculating HVAC systems in spaces with and without infected individuals;
- Both air and surface SARS-CoV-2 in ducts and air units recirculating air from spaces with infected individuals;
- SARS-CoV-2 concentrations over time after removal of infected occupants;
- SARS-CoV-2 in air over time in relation to opening windows;
- SARS-CoV-2 concentration in air associated with different ventilation rates and filter efficiencies;
- Pilot testing of space conditioning measures, such

as portable HEPA filtration and UV light; and

- SARS-CoV-2 exposure associated with sewage and sewer gas.

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