AIRAH

Ecolibrium

THE VOICE OF AUSTRALIAN HVAC&R | SUMMER 2025–26 VOLUME 24.4

PRINT POST APPROVAL NUMBER PP352532/00001

Fit for a QUEEN

The ingenious HVAC system behind Brisbane's iconic Queens Wharf development

IN FOCUS

Advancing airborne infection control in healthcare: Insights from ASHRAE 241

BY
Patrick Chambers, Affil.AIRAH

Abstract

It has long been suggested that hospitals and healthcare facilities are, paradoxically, both places of healing and disease propagation. Certainly, some of the major breakthroughs in our understanding of germ theory came from observations of disease transmission within healthcare facilities (Reid, 1975).

In reflection of Florence Nightingale's sentiment within her seminal work *Notes on Hospitals* (1859) *"It may seem a strange principle to enunciate as the very first requirement in a Hospital, is that it should do the sick no harm"*, we have certainly come a long way in understanding how, and where, infections can proliferate within hospital environments. However, in the context of infectious diseases that can be transmitted through air, there continues to be evolution in our understanding of best practice, and considerable innovation within industry to adapt to evolving needs. This paper presents insights from industry on the learnings from the COVID-19 pandemic, and the extent to which the industry is appropriately positioned to address future needs in airborne infection control within healthcare facilities.

The COVID-19 pandemic highlighted numerous examples of nosocomial healthcare-associated infections (HAIs) (Baker et al, 2022), and in the wake of the COVID-19 pandemic, the awareness of airborne disease transmission has become front and centre of public discourse. Thanks to the works of esteemed academics working determinedly against initial institutional responses (Morawska and Milton, 2020), the scientific community and industry agree that respiratory aerosols are a dominant form of infection transmission, and that poor indoor air quality (IAQ) can significantly contribute to increased transmission. However, until recently it has been unclear which aspect of IAQ the industry should be most concerned about, and what are the best engineering controls to mitigate against this.

This paper addresses the multifaceted challenge of airborne infectious disease transmission by situating the problem within the broader context of IAQ. It provides an overview of the newly introduced ASHRAE 241 standard and its practical applications, followed by an example case study to demonstrate the standard's calculation method. Through exploration of key findings from literature and industry trends, comparisons are made regarding the relative effectiveness of various ventilation strategies in mitigating airborne infection risks. By integrating these insights, the paper aims to provide actionable guidance for current industry practices and seeks to identify future research directions in the evolving field of airborne infection control.

Distinguishing airborne infection control from broader IAQ challenges

IAQ is a complex subject. Where people with vulnerabilities such as allergies or asthma may be particularly susceptible to suspended particles in the air (Delfino et al, 2005), immunocompromised people are generally at significantly higher risk of becoming infected from an airborne pathogen (Marr et al, 2009). By extension, a student seeking an ideal studying environment will suffer in a room with high CO_2 concentration (Satish et al, 2012), and a newborn is at higher risk to microbiological infections from airborne moulds and bacteria (Fisk et al, 2007).

These are but some of the many IAQ challenges, and each issue has scenario-specific constraints that are potentially best dealt with via scenario-unique engineering controls. The multifaceted nature of IAQ and the convenience of applying the simple but effective method of increasing ventilation rates to solve IAQ problems has made it challenging for the industry to pivot quickly in response to the pandemic. Recommendations and guidelines for reducing airborne infectious transmission have led to many different approaches to ventilation system design philosophies and engineering controls.

It is important to define (and confine) the problem: airborne infection transmission occurs when a sufficient quantity of viable infectious bio-aerosols is inhaled by an individual, leading to infection. Therefore, the goal is to reduce suspended aerosols within the breathing zone. The biological, physical and behavioural aspects of this phenomenon are complex, making it difficult to undertake quantitative risk assessments of airborne infection within a given environment. It is challenging to develop and apply risk assessment methods that are scalable to a multitude of different indoor scenarios.

A key recent development within the field is the ASHRAE 241 publication: *Control of Infectious Aerosols* (2023). The catalyst for this publication was a consultation between ASHRAE and the White House COVID-19 Response Team in 2022, which highlighted a need for better IAQ standards to specifically address the concern of airborne pathogen control. What makes this document important in the context of industry response to COVID-19 (and infectious disease transmission generally) is that it specifically *'**does not** address requirements for maintaining **acceptable indoor air quality**'*, but rather seeks to *'establish minimum requirements for* ***control of infectious aerosols to reduce risk of disease transmission*** *within occupied spaces'* (ASHRAE, 2023, p4, Section 2). This is particularly helpful for the industry, as the complexities of IAQ can obfuscate decision-making around engineering controls specifically intended to reduce airborne infection control.

ASHRAE 241 – calculation method case study

ASHRAE 241 has been heralded as a significant breakthrough in industry response to airborne infectious disease transmission (Bahnfleth 2023).

One of the significant developments is the introduction of the concept of "equivalent clean airflow" [EACi] within the occupant breathing zone, in lieu of traditional measures such as "air change rate" or "ventilation rate". The suffix of "within the breathing zone" is important, because it opens the discussion on air change effectiveness as an important parameter that is often missed when using conventional metrics. This speaks directly to the root cause of airborne infection transmission, which occurs when a sufficient quantity of viable infectious bio-aerosols is inhaled by a susceptible individual, leading to infection.

The standard proposes that to suitably minimise the risk of infection within an indoor environment, an ECAi flowrate is established on a per-person basis. The proposed rates are as per Table 1, with recommended benchmarks for healthcare facilities highlighted.

It is worth noting a key limitation of the standard: the recommended benchmarks for ECAi are based on the Wells-Riley risk assessment method, which assumes the scenario of long-range transmission only, and thus considers that the ventilation system provides complete and ubiquitous air mixing, and that infectious aerosols released by an infected person are spread uniformly

	ECAi	
Occupancy category	**cfm/person**	**L/s/person**
Correctional facilities		
Cell	30	15
Dayroom	40	20
Commercial/retail		
Food and beverage facilities	60	30
Gym	80	40
Office	30	15
Retail	40	20
Transportation waiting	60	30
Educational facilities		
Classroom	40	20
Lecture hall	50	25
Industrial		
Manufacturing	50	25
Sorting, packing, light assembly	20	10
Warehouse	20	10
Healthcare		
Exam room	40	20
Group treatment area	70	35
Patient room	70	35
Resident room	50	25
Waiting room	90	45
Public assembly/sports and entertainment		
Auditorium	50	25
Place of religious worship	50	25
Museum	60	30
Convention	60	30
Spectator area	50	25
Lobbies	50	25
Residential		
Common space	50	25
Dwelling unit	30	15

Table 1 – Minimum equivalent clean airflow per person in breathing zone in IRMM (excerpt from ASHRAE 241)

Air distribution and natural ventilation

Clean airflow rate

The clean airflow rate to each zone, as shown in Figure 1, shall be greater than or equal to the minimum *equivalent clean airflow* required, as expressed by the following equation:

$$\sum [z_f \times (V_{or} + V_{MVS})] + \sum V_{ACS} + V_{NV} \geq V_{ECAi}$$

where

z_f = the zone air fraction, calculated as the supply airflow rate to the zone divided by the total supply airflow rate to all zones

V_{or} = the outdoor air intake flow rate, cfm (L/s)

V_{VMS} = multizone *air cleaning* system *equivalent clean airflow* rate, computed as VACS from Section 7 for an *air cleaning* system whose output is shared amongst zones, cfm (L/s)

V_{ACS} = *air cleaning* system *equivalent clean airflow* rate, determined per Section 7 typically as a function of the recirculated airflow rate to be treated (V_{RC}), cfm (L/s)

V_{NV} = outdoor airflow rate from natural ventilation, cfm (L/s)

V_{ECAi} = the minimum *equivalent clean airflow* rate required in the breathing zone, cfm (L/s)

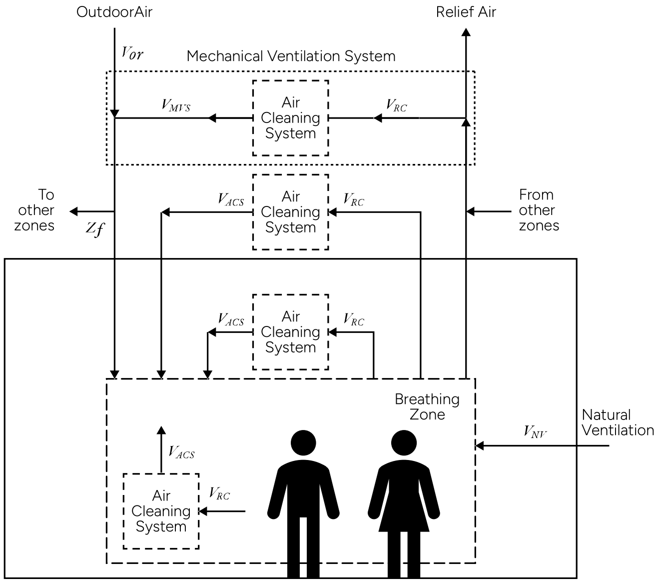


Figure 1: Equivalent clean airflow calculation excerpt from ASHRAE 241

throughout the space (i.e. not within isolated locations). The difficulties in undertaking accurate risk assessments of short-range transmission make it exceedingly difficult for a guideline to normalise or standardise an appropriate benchmark for engineering controls, because the inputs to the localised transmission scenario are so bespoke to the application. Some argue that this remains a key research gap, and that future iterations of the standard should consider and test some key short-range transmission scenarios, and/or strategies that address the immediate aerosol release event to reduce the long-range transmission calculation. This is discussed further within this paper.

The key breakthrough in the standard is that it allows a multitude of ways to achieve the EACi, leveraging the concept of equivalency. For example, the standard considers fully filtered or sterilised air, free of suspended viable pathogens (which can be achieved via air cleaning technologies), as equivalent to fresh outside air. A calculation method is provided to enable an element of partially cleaning an airstream to contribute to the total EACi, including a test method for new technologies to be appropriately measured and benchmarked. This allows for quantitatively considering the benefit of filtration and opens the door to enable air cleaning technologies such as UV-C, ionisation, electron beam radiation, catalyst filters, portable air purifiers, and others to be considered in the calculation of the total EACi recommended according to the space type.

For example, to achieve an ECAi rate of 45L/s/p for a waiting room in a healthcare setting, this could be comprised of 15L/s/p of outside air, 15L/s/p of ECAi from recirculated air a via ducted HVAC system, and 15L/s/p of EACi from a portable air purifier. This calculation procedure is represented diagrammatically below, noting that the efficiency of all air cleaning devices (filters or others) can be determined through experimental test procedures defined within ASHRAE 241.

Figure 1 above is a visual representation provided in ASHRAE 241 to help designers consider multiple contributions to the total ECAi rate calculation that can come from a multitude of different sources.

The below snapshot highlights the calculation method for considering the benefit of an in-duct F8/MERV 14 filter to contribute to the EACi. The procedure first acknowledges via clause 7.2.1 that an in-duct air cleaning system can contribute to EACi via a simple percentage efficiency multiplier of the total recirculated airflow. It then provides a calculation method in clause 7.3.1 to determine the efficiency of the filter (or any air cleaning technology) via weighted average of the effectiveness at removing particles in the size ranges of 0.3–1, 1–3 and 3–10 microns. To enable the calculation

Calculated effectiveness of air cleaning systems

In-duct air cleaning systems that clean air in the air-handling unit, ductwork, or plenum

each air cleaning system located inside an air-handling unit (AHU), ductwork, or plenum that cleans air inside the AHU, ductwork, or plenum shall have an effectiveness reported as an infectious aerosol reduction efficiency (ε_{PR}). The ε_{PR} shall be determined by a single-pass test in accordance with Section 7 and Normative Appendix A. The *equivalent clean airflow* rate shall be calculated in accordance with the following equation:

$$V_{ACS} = \boxed{\left[\frac{\varepsilon_{PR}}{100}\right]} \times V_{RC}$$

where

V_{ACS} = *air cleaning* system *equivalent clean airflow* rate due to the in-duct *air cleaning* system, cfm (L/s)

ε_{PR} = infectious aerosol reduction efficiency, determined in accordance with Section 7.3.1, Section 7.4.1.1, or Normative Appendix A, %

V_{RC} = recirculated airflow rate cleaned by the *air cleaning* system, cfm (L/s)

Infectious aerosol removal efficiency for mechanical fibrous filters installed in-duct

the infectious aerosol removal efficiency (ε_{PR})of mechanical fibrous filters installed within AHUs, ductwork, or plenums shal be determined in accordance with the following equation:

$$\varepsilon_{PR} = W_{E1}\varepsilon_{E1} + W_{E2}\varepsilon_{E2} + W_{E3}\varepsilon_{E3}$$

where

ε_{PR} = infectious aerosol removal efficiency, %

W_{E1} = fraction of the infectious aerosol in the 0.3 to 1.0 micrometer (μm) particle size range, dimensionless

W_{E2} = fraction of the infectious aerosol in the 0.1 to 3.0μm particle size range, dimensionless

W_{E3} = fraction of the infectious aerosol in the 3.0 to 10.0μm particle size range, dimensionless

ε_{E1} = particle removal efficiency in the 0.3 to 1.0μm particle size range, %

ε_{E2} = particle removal efficiency in the 1.0 to 3.0μm particle size range, %

ε_{E3} = particle removal efficiency in the 3.0 to 10.0μm particle size range, %

The weighting fractions for use in the above equation shall be W_{E1} = 0.30, W_{E2} = 0.30, and W_{E3} = 0.40.

Infectious aerosol removal efficiency (ε_{PR}) for mechanical fibrous filters

ANSI/ASHRAE Standard 52.2 MERV (Prior to 1/1/2025) MERV-A (After 1/1/2025)	ISO 16890 ePM	Weighted ε_{PR}
<11		0%
11	ePM2.5 50%	60%
12	ePM2.5 65%	71%
13	ePM1 50%	77%
14	**ePM1 70%**	**88%**
15	ePM1 85%	91%
16	ePM1 95%	95%
HEPA[a]	ISO 20E[b]	99%

a. High-efficiency particulate air (HEPA) filters are not tested under ANSI/ASHRAE Standard 52.2 or ISO 16890-1. However, HEPA filters are included here for completeness.

b. Tested in accordance with ISO 29463.

Filtration standard used				Estimated smoke filtration efficiency (%)
AS1324.1 (2001)	EN779 (2012)	ASHRAE 52.2 (2017)	EN1822 (2009)	
F4/F5	G4	MERV7-9	N/A	<20%
F5	M5	MERV10	N/A	20–35%
F6	M6	MERV11-12	N/A	35–50%
F7	F7	MERV13	N/A	50–65%
F8	**F8**	**MERV14**	**N/A**	**65–80%**
F9	F9	MERV15-16	N/A	80–90%
N/A	N/A	N/A	E11	95–98%
N/A	N/A	N/A	H14	99%+

Figure 2: Filtration effectiveness calculation diagram – material from ASHRAE 241

method to be applied to conventional scenarios and immediately scalable (i.e., air handling units with conventional filters), the standard provides normalised values for conventional filter products in Table 7. Importantly, these figures highlight that there is no benefit for filter products that are below MERV 11 (or < F6) filtration efficiency. This is an important benchmark because there are numerous healthcare facilities around Australia with F5 filters as standard. Only recently have F8 filters become more commonplace.

ASHRAE 241 represents a significant advancement in the industry's approach to airborne infection control by emphasising the importance of ECAi as a more meaningful metric for designing ventilation and air cleaning systems. The standard's flexibility in incorporating emerging air cleaning technologies – such as UV-C, ionisation, and advanced filtration – is complemented by its focus on safety, addressing concerns such as ozone generation or harmful byproducts from certain technologies. However, potential gaps remain, particularly in addressing the impact of directional airflows, occupant interactions, and behavioural factors. These parameters introduce complexities not fully accounted for in the recommended ECAi benchmarks. Future iterations of the standard could address these gaps, enabling a more holistic approach to infection control in both healthcare and other high-risk environments.

Ventilation, air mixing, and infection risk: Unpacking the assumptions of the Wells-Riley model

ASHRAE 62.1-2002 defines "ventilation" as the *"process of supplying air to or removing air from a space for the purpose of controlling air contamination levels, humidity, or temperature within the space"*. This definition intertwines parameters that impact thermal comfort with those that impact air contamination and air quality, thus potentially contributing to an inconsistent industry response. Aside from the fairly broad ASHRAE 62.1 definition, "ventilation rate" is universally acknowledged as the exchange of outside air. For the purposes of the discussion on airborne infection, confining the interpretation of ventilation to being associated with the dilution of the indoor environment with outside air is adopted here within.

There are, however, important aspects of temperature and humidity to acknowledge in the discussion of airborne infection:

- Low relative humidity can exacerbate aerosol transmission, due to increased concentrations of aerosolised particles within exhaled air (Morawska et al, 2009) and the evaporation of larger droplets into smaller droplets, which extends the suspension time of aerosols in air.
- The combination of temperature and relative humidity informs dew point temperature, which is a significant contributor to the growth of mould spores (Viitanen and Ritschkoff, 1991).
- Generally speaking, high indoor relative humidity can contribute to increased instances of microbiological issues and fungal growth on surfaces, and within air (WHO, 2009).

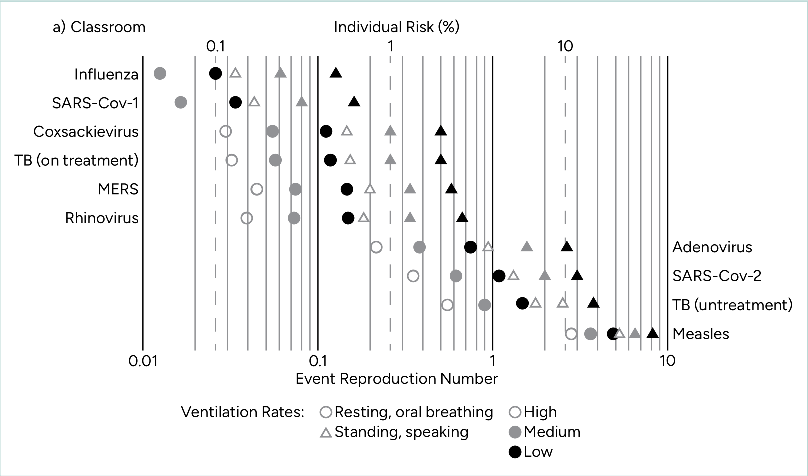


Figure 3: Event reproduction number assessment from Mikszewski et al (2021)

The study of the effectiveness of ventilation rate (supply of outside air to dilute the indoor air) in reducing the risk of airborne infection typically applies in the Wells-Riley risk assessment model. This method calculates the probability of infection based on the outside air ventilation rate and several scenario-specific inputs (such as number of infectors, number of susceptible, pulmonary ventilation rate, and others) (Guo et al, 2021).

In applying the Wells-Riley model, Nardell et al (1991) highlighted how the sensitivity of the infection risk has a diminishing return relationship to the ventilation. As the ventilation rate continues to increase, the relative reduction in infection risk does not reduce linearly, therefore, there are practical limits of protection achievable by increasing ventilation alone.

Mikszewski et al (2021) used the Wells-Riley model to assess how ventilation affects the transmission risk of various diseases, aiming to reduce the event reproduction number to <1 (Note, event reproduction number [R0] indicates the average number of secondary infections caused during an event, where >1 indicates the infection can spread widely, and <1 implies the infection will eventually die out). The study associates different aerosol release profiles according to either resting or standing, and applies different ventilation rates to establish a relative risk profile. As per the below plot, for highly contagious diseases such as tuberculosis (TB) or measles, even with high ventilation rates the event reproduction number is considerably higher than 1, and thus there is a high risk of secondary infection.

One of the fundamental assumptions of the Wells-Riley risk assessment model is that when air is supplied into a space and/or infectious aerosols are released into the space, the air and infectious aerosols are mixed uniformly. This approach ignores the impact of localised airflow patterns, and as highlighted by Noakes & Sleigh (2009), the influence of strategically positioned supply and exhaust vents can potentially reduce pathogen dispersion and infection risk significantly.

Leveraging computational tools to address airborne transmission risks

In the technical report produced by the AIRAH Innovation Hub regarding the analysis of future energy use in hospitals (Miller et al, 2022), the section titled "Effectiveness of Pandemic Mode Ventilation Strategies" leveraged computational fluid dynamic (CFD) analysis to calculate residual concentrations of airborne aerosols within a typical hospital ward environment. The below summarises this work, and how it can contribute to the discussion on addressing risks associated with airborne transmission.

Assessment methodology

CFD modelling was used to simulate aerosol dispersion in a typical hospital ward, assessing various ventilation configurations. The modelled space included patient rooms, staff areas, and shared zones, with simplifications made for non-critical details. The below figures show the 15-bed functional area used as the basis of the investigation.

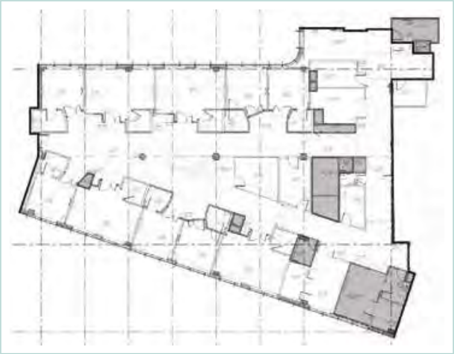


Figure 4: Extract of modelled region (excluded areas greyed out)

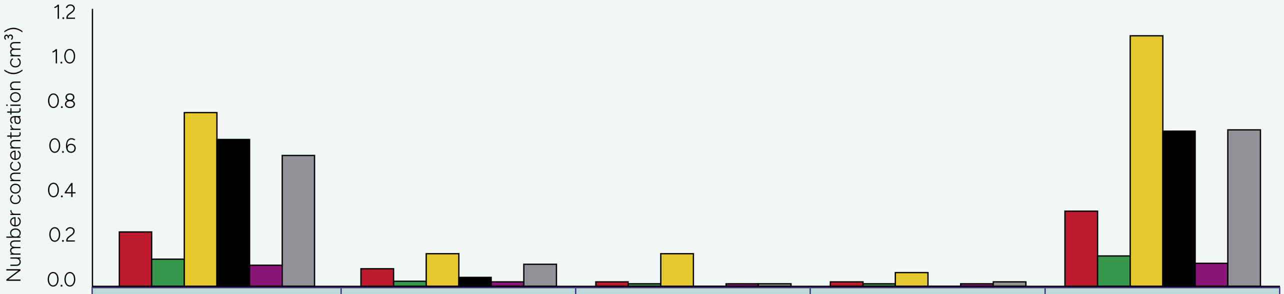
Figure 5: Generated model geometry

In the CFD model, aerosols were generated in the 11 patient-occupied rooms to mimic respiratory activities such as breathing, coughing and talking, with particle size distributions being based on findings from studies as indicated below:

Column 1 acronyms pertain to the following tested respiratory activities:

- **cvp:** alternately 10s of voiced counting and 10s of naturally paced breathing (2 min sample)
- **cwp:** alternately 10s of whispered counting and 10s of naturally paced breathing (2 min sample)
- **aahvp:** alternately 10s of unmodulated vocalisation (voiced 'aah') and 10s of naturally paced breathing (2 min sample)
- **aahwp:** 10s of unmodulated whisper (whispered 'aah') and 10s of naturally paced breathing for recovery to prevent drying of mouth or laboured breathing (2 min sample)
- **bnm:** naturally paced breathing, in through the nose and out through the mouth (2 min sample)
- **cough:** repeated coughing at an intensity and frequency which the volunteer felt comfortable with. In practice, for most volunteers, the resulting cough intensity can be best described as a mild throat clearing cough (30s sample).

A reference model or "base case" was established, against which all additional modelling could be compared. The setup of the reference model is intended to represent a typical design, balancing minimum compliant design and current design practices for this type of space. It involved a combination of all six types of respiratory activities defined in Figure 6, assigned at the discretion of the research authors, intended to represent a "realistic scenario".



	A, CMD≤0.80±0.08μm	B, CMD=1.80±0.3μm	C, CMD=3.5±0.7	D, CMD=5.5±1μm	Total
🟥 cvp	0.236	0.068	0.007	0.011	0.322
🟩 cwp	0.110	0.014	0.004	0.002	0.130
🟨 aahvp	0.751	0.139	0.139	0.059	1.088
⬛ aahwp	0.636	0.037	0.000	0.000	0.672
🟪 bnm	0.084	0.009	0.003	0.002	0.098
■ cough	0.567	0.093	0.012	0.006	0.678

Figure 6: Particle concentrations generated per size mode, per activity (Morawska et al, 2009)

Scenario		Notable features	Recirculation % considered
1	**Base case**	Two large return air grilles located in common areas. General doors open.	75% + 25% droplet recirculation
2	**100% outside air**	Geometry and ventilation rates identical to scenario 1 except with no droplet recirculation within the system. General doors open.	0% droplet recirculation
3	**Localised return**	Localised smaller return air grilles in each room as opposed to that considered in scenario 1. Doors closed (refer to Figure 4).	75% + 25% droplet recirculation
4	**Localised return** **Air purifiers in populous areas**	Identical to scenario 3 with the inclusion of 4x air purifiers located in populous regions within the common spaces. Doors closed (refer to Figure 4).	75% + 25% droplet recirculation
5	**Localised return** **Air purifiers in populous areas** **Individual purifiers per room**	Identical to scenario 4 with the inclusion of 15x smaller air purifiers located adjacent to each bed. Doors closed (refer Figure 4).	25% droplet recirculation

Table 2: CFD scenario summary

Note: for the purposes of this paper, the full modelling methodology has not been described. For the full details of inputs and assumptions such as grille diffuser locations, supply air rates and the like, refer to the full paper (Miller et al, 2002).

Eight scenarios were considered as part of this investigation with differing mechanical configurations, and two different droplet recirculation rates[1] for three of these configurations.

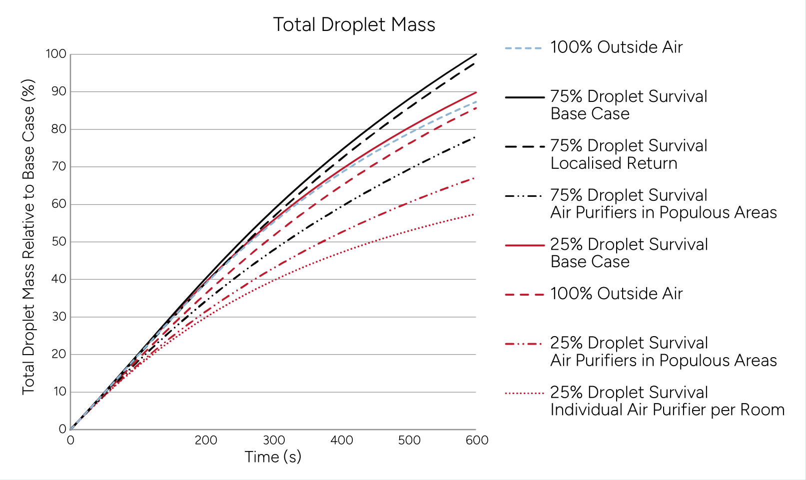


Figure 7: Net suspended aerosols after nine minutes

Note above: Figure 7 indicates that the simulations with the highest reduction in total droplet mass relative to the base case are those that include localised air purifiers in populous areas and/or each room. Table 3 below highlights the sensitivity of droplet recirculation rate (or in-duct droplet decay) to total mass of suspended respiratory aerosols, further reinforcing that this relatively ignored parameter has potentially significant impacts and warrants more industry consideration.

A summary of the scenarios is shown in Table 2. Note that the supply air ventilation configuration, in terms of quantity and location of supply air, is common to all scenarios, with the main changes being to the return and exhaust grille locations, and the addition of air purifiers.

Results

The results of the assessments showed that increasing outside air percentages had a limited impact on reducing aerosol concentrations, particularly if the in-duct droplet decay factor of the return/recirculation ductwork system is significant. That is to say, if aerosols are not removed in the return air duct and allowed to mix with supply air to exit through the supply air grilles, then there is minimal benefit in increasing the percentage of outside air within the supply airstream. For example, a shift to 100% outside air (from the base case of 25% outside air), assuming a droplet decay factor of 25% within the recirculated air system, only resulted in a 2.77% reduction in suspended aerosols over a 10-minute simulation period and laden with a 10–20% annual HVAC energy consumption penalty depending on climate zone (Zedan et al, 2002).

By far the most impactful engineering intervention was the addition of localised air purifiers in high-activity areas (e.g., staff stations), reducing aerosol mass by up to 42.38% in the most optimised configuration.

Figure 7 and Table 3 summarise the research findings.

Scenario		75% droplet recirculation	25% droplet recirculation
1	**Base case**	-0%	-9.89%
2	**100% outside air**	-12.38	-12.38%
3	**Localised return**	-1.45	-13.86%
4	**Localised return** **Air purifiers in populous areas**	-21.57	-32.39%
5	**Localised return** **Air purifiers in populous areas** **Individual purifiers per room**	N/A	-42.38%

Table 3: Comparison of percentage change in droplet mass

---

[1] The term "droplet recirculation rate" pertains to the percentage of respiratory aerosols that survive the journey through the ventilation system and reappear in the space through supply air diffusers via return air vents. It could also be referred to us "in-duct droplet decay". This is a term that does not attract much industry attention, but is a critical assumption in modelling the effectiveness of ventilation in diluting the indoor environment of suspended aerosols.

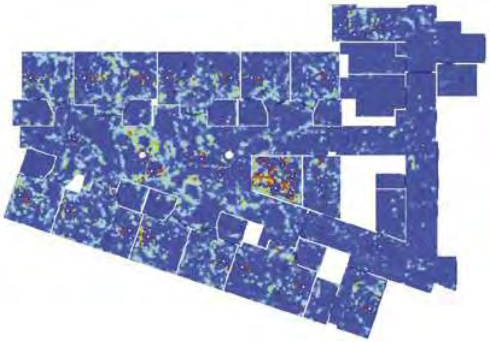
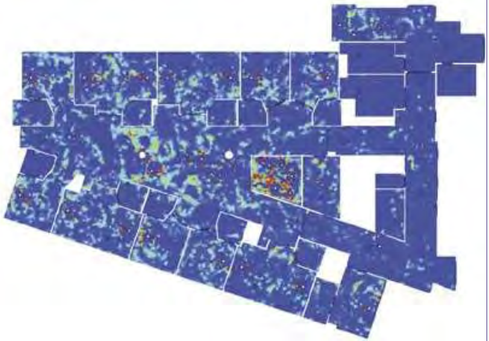
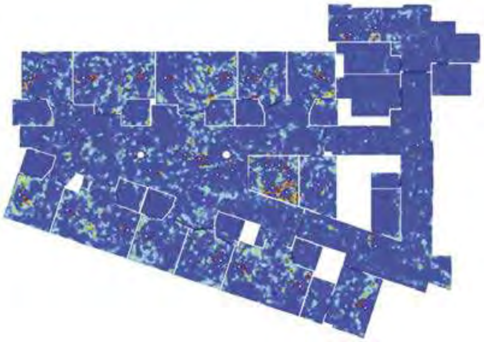
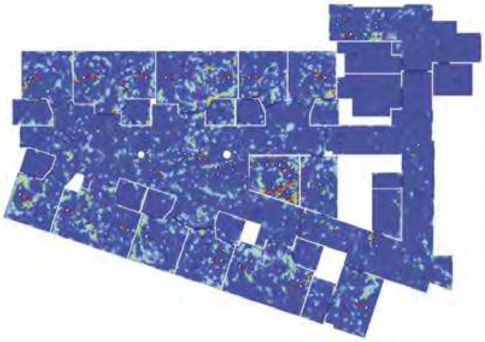
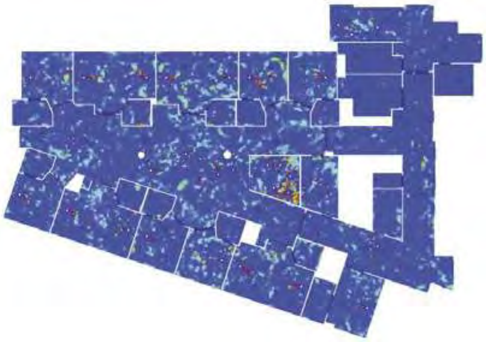
Scenario		75% droplet recirculation	25% droplet recirculation
1	**Base case**		
2	**100% outside air**		
3	**Localised return**		
4	**Localised return** **Air purifiers in populous areas**		
5	**Localised return air purifiers in populous areas** **Individual purifiers per room**	N/A	

Table 4: Contours of droplet concentrations at Z=1.5m AFFL after 600s (10 minutes)

Discussion and recommended future research areas

A key characteristic of industry response throughout the COVID-19 pandemic has been a focus on increasing outside air percentage within ventilation systems. This triggers an increased cooling/heating load on the system and increased energy consumption. In most cases, the ductwork and coil capacities are not appropriately sized for this change without significant upgrades. The capital and operational costs associated with this are at odds with sustainability objectives.

ASHRAE 241 provides a prescriptive methodology that considers the effectiveness of outside air ventilation in the context of many other strategies, including portable/local air purification systems, air cleaning technologies and base-building filtration systems. ASHRAE 241 does not promote or rank outside air as more beneficial than any other type of airstream that is free of infectious aerosols. A key limitation of ASHRAE 241 is that it applies the Wells-Riley risk assessment methodology to establish the recommended ECAi for various spaces, which does not fallow for more localised solutions that can potentially capture aerosols in short-range scenarios before they can mix and contribute to long-range transmission.

The CFD findings presented within Section 5 of this paper underscore the potential effectiveness of localised solutions over centralised systems, with the most optimised study indicating a potential reduction of suspended aerosols in the order of 40% in comparison to a traditional compliant design. The same optimised study resulted in approximately 30% fewer suspended aerosols over a 10-minute period than increasing outside air to 100%. The study furthermore highlighted that more ubiquitously distributed return air diffusers (such as local to each bedroom) can have considerable benefit in minimising the spread of aerosols from rooms into adjacent corridors and staff areas.

Furniture, fixture and equipment (FFE)-integrated ventilation systems

It is argued that the literature review findings and meta analysis conducted as part of this investigation indicate that designers of ventilation systems should potentially consider a shift from traditional ceiling-mounted return/exhaust grilles to local exhaust/filtration systems installed as close as possible to where respiratory activities are taking place, such as integration with furniture and/or other fixed building elements. This is a paradigm shift from conventional thinking; the effectiveness of filters and air cleaning devices in capturing or neutralising infectious aerosols provides an opportunity for these systems to be decentralised from traditional in-ceiling ventilation infrastructure.

Ventilation designers should consider that people are pollution sources and apply traditional exhaust capture strategies to areas with high respiration rate to reduce the quantity of potentially infectious-aerosols that are allowed to mix within the space. In most industry responses to airborne infection, the default focus is on providing clean supply air. This paper argues that industry also needs to consider strategic exhaust or capture systems as a key strategy for minimising airborne infection within buildings.

Application of advanced air cleaning technologies

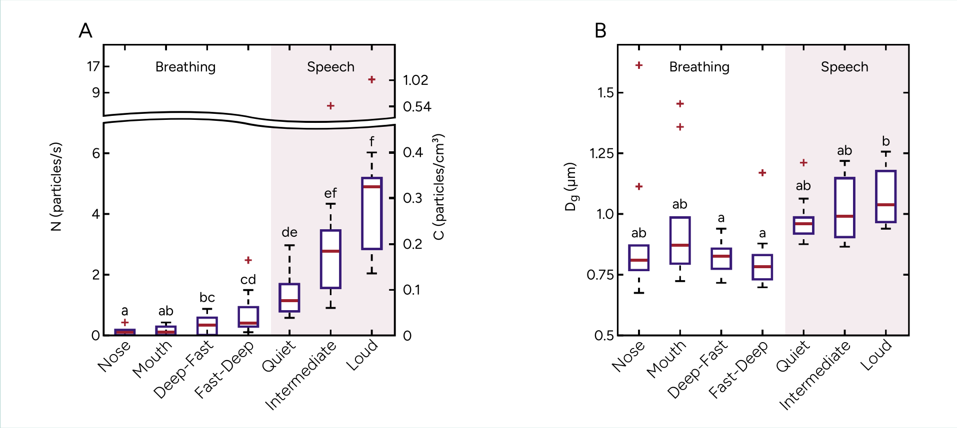
ASHRAE 241 paves the way for advanced air cleaning technologies to be broadly adopted in industry by recognising their ability to contribute to ECAi alongside traditional ventilation methods. Through its calculation framework, the standard allows technologies such as UV-C disinfection, ionisation, electron beam radiation, catalytic filters, and portable air purifiers to be quantitatively assessed and integrated into overall infection control strategies. By establishing test methods and benchmarks for these technologies, ASHRAE 241 (Section 7) ensures they can be evaluated for both efficacy and safety, promoting innovation while maintaining occupant health.

Droplet decay factors within ductwork systems

It is proposed that in-duct droplet decay (previously introduced and defined above) should form a key focus of future research and response in industry. In the absence of research findings to inform what in-duct droplet decay factors are for any given system types, a simple means such as correlating the pressure drop through the recirculated air system to an in-duct droplet decay factor would allow easier market uptake. The result would be a more informed basis for recommending increasing outside air percentage for specific ventilation system types.

Scaling CFD modelling of aerosol behaviour in buildings

CFD modelling is expensive and time-consuming. It is impractical to assume that CFD models can be undertaken for all types of spaces and account for all scenarios of occupant behaviour. However, there are many types of spaces (particularly in healthcare facilities) that do have standard HVAC configurations and consistent occupant



behaviour. Calzolari & Liu (2021) proposed that CFD modelling activities should be applied to more typical scenarios within healthcare facilities. Results could be assessed using AI/deep learning techniques that can potentially apply pre-established modelling results to bespoke applications accurately.

Application of smart sensor technology and remote air cleaning strategies

The behaviour of occupants within buildings is varied and diverse. Specific respiratory activities and individuals' infection status are parameters that are almost impossible to capture in computational models. However, studies undertaken on respiratory aerosol release profiles have shown patterns that could be detected by smart sensor technology within buildings. As an example, Asadi et al, (2019) has highlighted that loud speaking produces significantly higher concentrations of respiratory aerosols than other types of activities, and thus this could be used as a trigger for mechanical ventilation interventions.

It is proposed that industry could explore using autonomous robots equipped with sensor technology and an onboard air purification system. Such a device could move autonomously throughout a building, taking IAQ measurements and reporting real-time patterns within the space. It can also mobilise to localized areas of high aerosol-generating activities, such as staff rooms during lunch breaks. By filtering air directly at the source of respiratory aerosols, it could significantly reduce long-range transmission risks by removing aerosols while they are still in high concentrations, preventing them from mixing uniformly within the space. The findings from the studies presented within this paper suggest this could significantly reduce the risk of infectious disease transmission in buildings. The author proposes that simple computational modelling exercises to test the sensitivity of localised aerosol capture for reducing long-range transmission risk could help inform a standardised calibration of the Wells-Riley risk assessment method, and a reduced ECAi target.

References

ASHRAE 241: Control of Infectious Aerosols American Society of Heating, Refrigerating and Air-Conditioning Engineers (2023)

ASHRAE: *ASHRAE Handbook – Heating Ventilating and Air-Conditioning Applications*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, (2019)

Baker, M. A., Sands, K. E., Huang, S. S., Kleinman, K., Septimus, E. J., Varma, N., & Perlin, J. B. (2022). The impact of COVID-19 on healthcare-associated infections in intensive care units in US hospitals. *The Lancet Regional Health – Americas*, 13, 100293.

Bahnfleth, W. P. (2023). ASHRAE Standard 241: A new benchmark for infection control in indoor environments. *ASHRAE Journal.*

Calzolari, G., Liu, W., (2021) Deep learning to replace, improve or aid CFD analysis in built environment applications: A review.

Delfino, R. J., Sioutas, C., & Malik, S. (2005). Potential role of ultrafine particles in associations between airborne particle mass and cardiovascular health. *Environmental Health Perspectives*, 113(8)

Fisk, W. J., Lei-Gomez, Q., & Mendell, M. J. (2007). Meta-analyses of the associations of respiratory health effects with dampness and mold in homes. *Indoor Air*, 17(4), 284–296.

Florence Nightingale – Notes on Hospitals, 1859

Health Effects Institute & UNICEF, *State of Global Air 2024*, 2024, https://www.stateofglobalair.org/resources/report/state-global-air-report-2024

L. Morawska, G. Buonanno, 'The physics of particle formation and deposition during breathing', *Nature Reviews Physics*, 3 (2021), 300–301, https://doi.org/10.1038/s42254-021-00307-4

L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C.Y.H. Chao, Y. Li, D. Katoshevski, 'Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities', *Journal of Aerosol Science*, 40 (2009), 256–269, https://doi.org/10.1016/j.jaerosci.2008.11.002

L. Morawska, Yuguo Li, Tunga Salthammer, 'Lessons from the COVID-19 pandemic for ventilation and indoor air quality', *Science*, 385:6707 (2024), 396–401

Marr, K. A., Bow, E. J., Chiller, T., Maschmeyer, G., & Ribaud, P. (2009). Fungal infections in transplant and oncology patients: An overview. *The Journal of Infectious Diseases*, 200(6), 108–115.

Mikszeqski et al, 'The Airborne Contagiousness of Respiratory Viruses: A Comparative Analysis and Implications for Mitigation', *Journal of Infectious Diseases*, (2021)

Miller, W., Liu, A., Ma, Y., Zedan, S., Bonney, B., Sanders, J., Campbell, M., Chambers, P., Leb, C., Lansell-Kenny, D., Garbett, W., *LLHC 4 Technical Analysis – Analysis of Hospital Future Energy Use*, Innovation Hub, (2022)

Morawska, L. & Buonanno, G., 'The physics of particle formation and deposition during breathing', *Nature*, May 2021

Morawska, L. & Cao, J., 'Airborne transmission of SARS-CoV-2: The world should face the reality', *Environment International*, 2020

Morawska, L. et al, 'A paradigm shift to combat indoor respiratory infection: Building ventilation systems must get much better', *Science Galley*, 372(6543), 2021, pp. 689–691

Morawska, L., Johnson, G. R., Ristovski, Z. D., et al. 'Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities', *Aerosol Science*, 2009

Morawska, L., & Milton, D. K., 'It Is Time to Address Airborne Transmission of COVID-19', *Clinical Infectious Diseases*, 71(9), 2020, 2311–2313

Murdoch, J., & Hughes, W., *Construction Contracts: Law and Management* (4th ed.), Taylor & Francis, 2008

Nardell, E.A., Keegan, J., Cheney, S.A., Etkind, S.C., 'Airborne Infection: Theoretical Limits of Protection Achievable by Building Ventilation', 1991

Noakes, C. J., & Sleigh, P. A., 'Mathematical models for assessing the role of airflow on the risk of airborne infection in hospital wards', *Journal of the Royal Society Interface*, 6(6), 2009, 791–800

Raub, J. A., Mathieu-Nolf, M., Hampson, N. B., & Thom, S. R., 'Carbon monoxide poisoning—a public health perspective', *Toxicology*, 145(1), 2000, 1–14, https://doi.org/10.1016/S0300-483X(99)00217-6

Reid, R. W., *Microbes and Men*, Saturday Review Press, 1975

Rosner, D., & Markowitz, G., *Dying for Work: Workers' Safety and Health in Twentieth-Century America*, Indiana University Press, 1987

Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., & Fisk, W. J. (2012). Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance. *Environmental Health Perspectives*, 120(12), 1671–1677.

Viitanen, H. A., Ritschkoff, A. C. (1991). Mould growth in pine and spruce sapwood in relation to air humidity and temperature. *Scandinavian Journal of Forest Research*, 6(1–4), 481–497.

WHO. (2009). WHO Guidelines for Indoor Air Quality: Dampness and Mould. Geneva: WHO Press. https://www.who.int/publications/i/item/9789289041683

Zedan, S., Ma, Y., Liu, A., Miller, W., Chambers, P., Murphy, A., Garbett, W., Lansell-Kenny, D., Leb, C., Armstrong, S., *LLHC 5 Net Zero Emissions and Resilient Hospitals – considerations of future climate, pandemics, and demand management*, 2022