BREATH (Building Retrofit for Efficiency, Air Quality, Thermal Comfort and Health) Research Project: Deliverable # 2

Grant Skidmore,[1, a)] Liam McGregor,[1, b)] Max Rounds,[1, c)] Kevin,[1, d)] and Jason Monty[1, e)]

University of Melbourne
Department of Mechanical Engineering
4th Floor Grattan Street
Parkville, VIC 3010, Australia

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This document, Deliverable #2, summarizes our experimental findings, details the final research approach, and provides our recommendations. In addition to this, we have provided a digital copy of our raw data and have provided a user-guide to the data set as an Appendix.

[a)]Electronic mail: grant.m.skidmore@gmail.com
[b)]Electronic mail: liam.mcgregor@unimelb.edu.au
[c)]Electronic mail: max.rounds@unimelb.edu.au
[d)]Electronic mail: kevin.kevin@unimelb.edu.au
[e)]Electronic mail: montyjp@unimelb.edu.au

I Objectives

Long-Term Goals

The primary objective of this pilot study project is to examine, for the first time, the impacts of the energy demand of various building ventilation retrofit options that are used to reduced the risk of aerosolised viral spread. Particular attention will be paid to the potential health implications and energy usage for each option, while considering the level of comfort of the occupants (to the best of our ability without human subjects).

A. Deliverable #2 Goals and Intended Outcomes

The primary objectives for this deliverable are to detail the results from the experiments, summarize the insights gained, and provide recommendations for others.

It is our aim that this document thoroughly summarizes our approach, assumptions, and data models that we used for both our Results and Conclusions.

II Experimental Details

Overview

As detailed in Deliverable #1 (D1), we have considered four conditions in the first-floor of 423 Bourke Street:

- baseline vacant operation
- open-window operation
- in-ceiling HEPA filtered operation
- displacement ventilation operation

Baseline Vacant Operation: was used to determine the baseline power usage of the vacant space as well as the equivalent-air-change-per-hour, ACH_e, value of the space before retrofit modifications were made. We were able to use our numerous days in the baseline conditions to determine a correlation between chiller power usage and average high temperature, which we will detail below.

Open-Window Operation: examined the impact of opening windows while leaving the HVAC running in its standard operating mode (19-21% outdoor air and the remainder recycled indoor air). This configuration (with upgraded filters installed, which we are assuming will not impact performance) would follow the ASHRAE recommendations for the space. Please note that due to the high percentage of wall space being operable windows, only every-other-window on East-facing wall was opened (resulting in eight 1.0-m by 1.6-m windows being opened). This was to both prevent cross-flow and minimize the chance for incoming wind to affect the measurements (recall that to the East there is another high-rise building that would shield 423 Bourke from easterlies, so there should be little, if any, wind coming from that direction). We also note that while it was possible in this space to open windows, operable windows are not available for all high rise offices. Herein we are portraying opening the operable windows as a "free" upfront cost option for increasing the ACH_e of a space. That is not to say that the findings detailed are not applicable to spaces where windows are not operable; more that for spaces that can open windows, we have detailed findings for them, for the spaces without operable windows the other two controls would remain practical options for increasing the ACH_e.

For this measurement, and the measurements listed below, we placed 1600-Watts of heaters in buckets of water distributed throughout the space (on chairs to simulate seated person height). This is done to replicate the heat load modelled by A.G. Coombs with their displacement ventilation system (100-Watts for a person with 60-Watts worth of laptop/monitor setup for 10 people). Specifically, the 1600-W of heat was generated through two-300-Watt and five-200-Watt aquarium heaters. These heaters were set to their maximum temperature setting which they were not able to achieve with the volume of water they were submerged in, hence we assume they were constantly outputting their rated maximum wattage.

In-Ceiling Filtered Operation: We initially planned to use five fan-driven HEPA filter equipped, locally made Westaflex ceiling mounted units to filter the air. However, because these tests ended up being concurrent with the displacement ventilation tests, we instead focused on three units of the same make and model in half the space. Figure 1 shows the breakdown of the space for the In-Ceiling Filtered and Displacement Ventilation sub-spaces. From the figure, it can be seen that there is not an even distribution of supplies, nor is the space set to keep the ACH value constant across the sub-spaces.

The in-ceiling HEPA units are low power devices (measured at 60-Watts), equivalent to the fan/filter power of a portable HEPA filters but they allow for BMS integration, making them an industrial solution to the problem of increasing the ACH_e.

Displacement Ventilation Operation: A.G. Coombs used nine columns to retrofit slightly less than half the space for displacement ventilation. The floor was divided with floor-to-ceiling construction plastic. After some testing it was determined that we needed the air exiting the displacement column to be 20°C, which is 2°C higher than the standard mixing operating temperature observed of 18°C.

Experimental Approach

Air Changeover Measurements: ideally the first period of measurements (where the building is not isolated) consisted of approximately four days of experimentation with three readings per day. Again, this was our intended test plan, but as we will detail below, some deviations from this had to be taken. In these ideal conditions, the readings are taken in the nominal morning, mid-day, and close-of-business (understanding that these times are nominal and can shift depending on the day). During these readings we were taking an effective-air-changes-per hour reading as well as temperature readings of the space. The purpose of these three readings were to capture any changes in the space as the outside temperature changes. Due to the short duration of the experimental campaign, we were hoping to capture different weather conditions over the four days. We have used meteorological measurements of temperature (rather than the BMS captured values, due to gaps in the data) as the source of "true" outdoor conditions.

However, the reality of the full scale tests and the problems associated with both supply

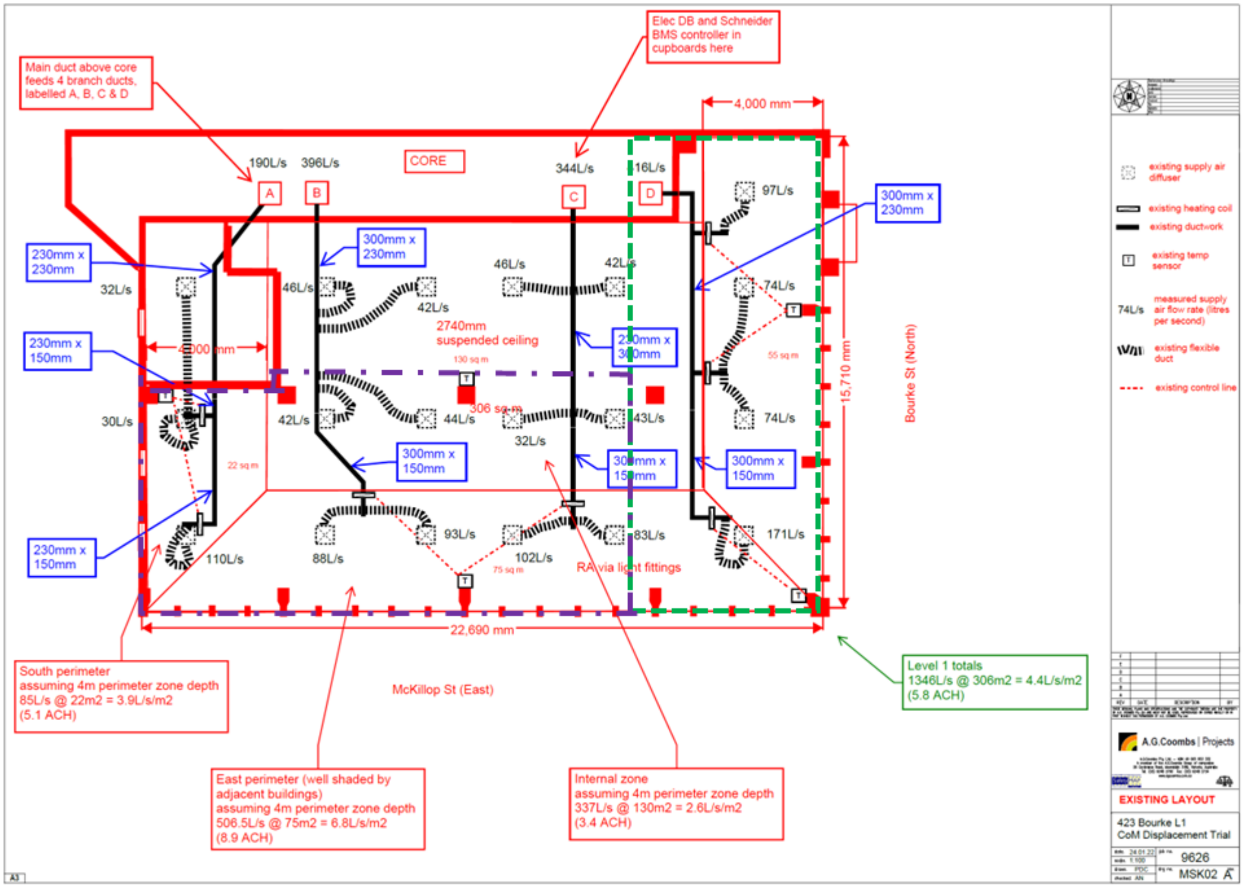

FIG. 1. How the floor was subdivided for the Displacement Ventilation (shown in purple) and In-Ceiling Filtered (shown in green) cases. The strength of supplies for the space, as measured by A.G. Coombs, is provided in L/s on the figure.

chain constraints, and HVAC shutdowns following fire alarms, meant that only the Open-Window and Baseline measurements were taken sequentially over four days. The other conditions, Displacement Ventilation and In-Ceiling HEPA were taken as the space was available/possible. For the Displacement Ventilation, this meant conducting experiments early in the morning (between 0700 and 0900) as the supply air temperature had to be increased; thus to avoid negative impact of other building tenants we conducted these tests on the mornings of 07Apr22, 08Apr22, and 19Apr22. The In-Ceiling HEPA measurements were as the space was available and free. These results should have limited impact on the air changeover measurements, but they did have a bit of an effect on power use. We have corrected for this; scaling our results up to have a full floor's worth of In-Ceiling HEPA and Displacement Ventilation units in both costing and power analyses.

To measure the ACH_e we used an ultra-low-volume (ULV) fogger to generate 0.1-10-μm diameter aerosols (with a mean diameter of approximately 5-μm). The testing aerosol fluid for most of these measurements is salt-water (with the highest concentration of salt we were able to dissolve in the room-temperature water of the device). For some measurements on isolated days (mostly for photographs of the tests), we also employed propylene-glycol based theatrical-fog as an aerosol.

For the ACH_e measurements, we used a TSI DustTrak DRX aerosol monitor to measure the mass density of aerosol in the space. We begin with a zero measurement (before aerosols filled the room). We then use the ULV fogger to fill the space with saline aerosols as we walk around the test space (to ensure uniform seeding density). This leads to a large aerosol density reading on the DRX device. We then allow the measurement to run until the device reads 99% of the peak reading value (or lower). We can then use the following equation:

$$ACH_e = \frac{-\ln(0.01)}{\text{Time for 99\% clearance (hours)}}$$

to calculate the effective air-changes-per-hour of the space. We prefer this metric over a more standard ACH value, because it allows us to directly measure the impact devices such as filters and open windows have on changing the baseline ACH (i.e. standard air-changes-per-hour).

For the In-Ceiling HEPA and Displacement ventilation tests, we also added a second TSI device, the DustTrak II aerosol monitor. This device also measured the mass density of aerosol, but we were focused on measuring ACH_e of the space at both seated and standing height of a simulated office worker (whom is 1.1-m tall when seated and 1.7-m tall when standing). We used a shelving unit, with shelves at both of these heights for the devices to be placed upon, to ensure uniformity of testing heights for these experiments.

Initially we used a thermal imaging camera to take a vertical temperature profile of a column in the space (for the Baseline and Open-Window tests). We found no discernible temperature profile and found the thermal imaging camera compared well with with the BMS temperatures of the space (that is we found that the maximum for both tends to agree quite well). Hence, for the period of time without BMS data we were able to use our IR camera and vice-versa.

For the displacement ventilation testing, we constructed a vertical array of Protech QM1601 thermocouples. This was built because the accurate measurement of the thermal profile was a critical piece of information and the IR camera employed only featured a 1°C of resolution in their measurement, which was too coarse for this purpose.

Power Usage Measurements: in order to estimate power for the space, we had a series of observations and assumptions. First, we observed that the supply fan is always running (except when the system is in an error-state). Because of this, we can assume constant power from the supply fan, and hence ignore it. We also noticed that, because we were testing in summer and late autumn; the heater was rarely called. Hence we decided to ignore the impacts of heating the building (and moreover, we would need to test in the winter to determine the impact of the ventilation systems on heating power costs). From these two observations/simplifications, we were able to determine that the building power use for our case, is driven by the chiller.

423 Bourke Street employs a Turbocor TT300W-100-H6 using R22 as coolant for a chiller. This chiller has had its power assessed as part of the "Danfoss Turbocor Compressors Retrofit Performance Data Worksheet 2005-08". The power output values given by the literature are: 92.0, 46.9, and 28.8 kW of power input for running at 100, 75, and 50 percent capacity, respectively. We were able to use these values to generate an exponential power curve to these points, with the following equation:

$$P[kW] = 8.7403 * \exp\left(0.0232 * \text{CapacityValue}[\%]\right) \tag{1}$$

Our measurements generally agreed with the curve; as we were able to time our amperage measurements with the BMS chiller load value. We would simply total the measured amperage between and use a value of 0.7-kV for the system voltage (the voltage of the chiller).

Now that we were able to estimate the power for the building (or more precisely, the power value that would change throughout the measurement), we first went about estimating the power usage for the baseline case. We had a series of days where the system operated normally without intervention. For these days we correlated meteorological conditions with chiller usage and found the best correlation was with the three day running high temperature (that is, the running average of the high temperature). The correlation plot is reproduced in Figure 2. In this figure, you can also see that we have plotted our power usage and line of best fit from days where we were running in the Open-Window configuration.

It may seem odd at first glance to use external building parameters to determine chiller usage, however, we are having to extrapolate for many days where we do not have building data. Hence, using external variables was preferred for internal building variables, despite the fact that they may have been more accurate.

Now that we have the two lines of best fit for the Baseline and Open-Window power estimates, we are able provide curves for all cases. Recall that the In-Ceiling HEPA units each draw 60 Watts, hence for an entire floor's worth, 300 Watts of power are required. This correlates to an increase in 7.2-kW-hr a day from the baseline state. For Displacement Ventilation, we merely shift our baseline power usage left by 2°C. That is, our system can run two degrees warmer with displacement ventilation, hence we are cooling the building as though it was 2 degrees colder outside, but still using the same chiller. These curves together are plotted in Figure 3.

The step required to turn these kW-hr values into an AU$ value was to find an appropriate power rate. There are numerous websites claiming to have rates that business pay, however, we felt it was best to use the Australian Energy Regulator's November 2021 report (https://www.aer.gov.au/system/files/Annual%20Retail%20Markets%20Report%202020-21.pdf), as it is a government written report on what is paid for power, despite the fact it was written about residential customers. In this report, we can see that the median power

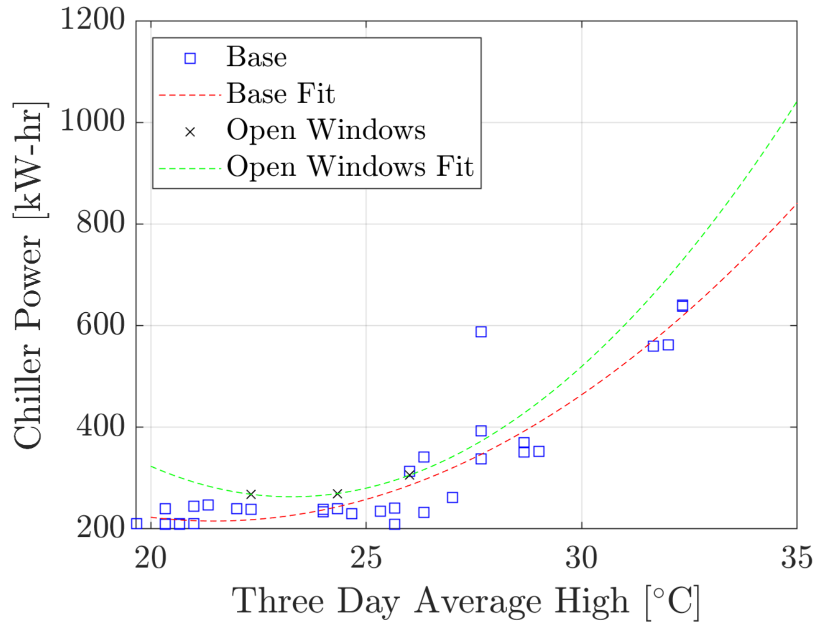

FIG. 2. Correlation between average high temperature and kW-hr used by the chiller.

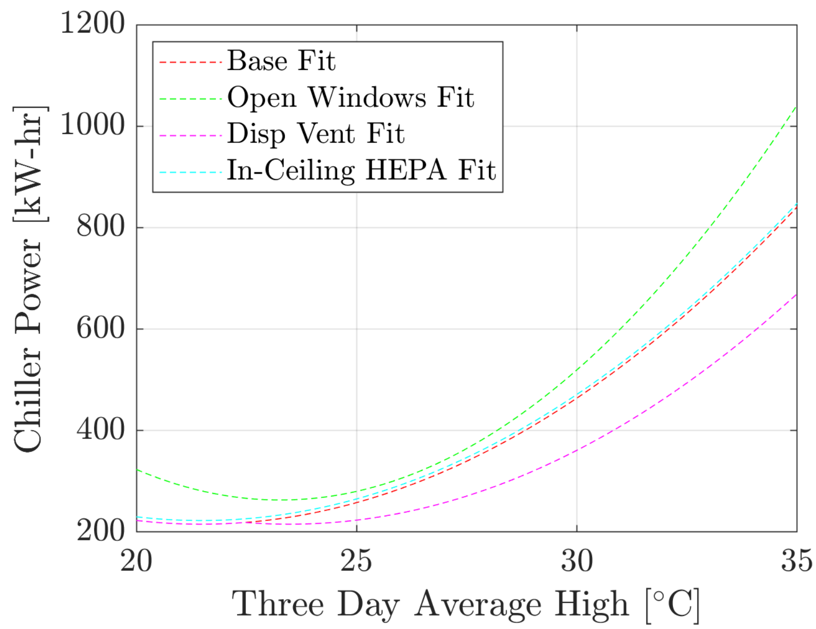

FIG. 3. kW-hr used by the chiller versus average high temperature curves for all cases considered herein.

price paid by Victorians for 2020-2021 was $0.28/kW-hr (i.e. the cost of CitiPower); hence we will use this value to estimate the energy costs for these options. This value was also confirmed to be within the price range paid by Cbus for similar properties in the area of 423 Bourke Street. However, please refer to Section VIII for differing power price values within the range provided.

Variable	Value
Average 99% Clearance Time	31.47 minutes
Standard Deviation	3.82 minutes
Average ACH_e	8.8
Minimum ACH_e	6.7
Maximum ACH_e	10.0

TABLE I. Details of all baseline clearance tests.

Variable	Value
Average 99% Clearance Time	30.40 minutes
Standard Deviation	0.58 minutes
Average ACH_e	9.1
Minimum ACH_e	8.9
Maximum ACH_e	9.3

TABLE II. Details of median baseline clearance tests.

III Experimental Results

A. Experimental Results: Equivalent Air Changes per Hour

The primary measurement was clearance for the spaces with each of these controls. In this section we will detail those measurements.

1. Baseline

The clearance plots for all baseline cases performed is shown in Figure 4. In this figure, it can be seen that there is some variation from run to run. The details of these runs are provided in Table I.

If we remove the outliers from these runs so that only the median cases remain, the result is shown in Figure 5. These runs are similar enough that we can average them together so we have a sense of what a typical run looks like. We have generated this “average” run in Figure 6. The details of these median cases are given in Table II. Considering how many runs repeated within this range, we are treating the median set of runs (and the average of their output) as the “true” baseline. That is, we are saying that the ACH_e of the first floor of 423 Bourke St is 9.1.

However, the variability of these runs does highlight an important point, despite the nearly identical conditions in the space, we can measure quite a bit of scatter for each run. In order to avoid biased results, we are best served (and continue to do so throughout this report) to exclude both the fastest and slowest runs, and focus on the median tests for a given condition.

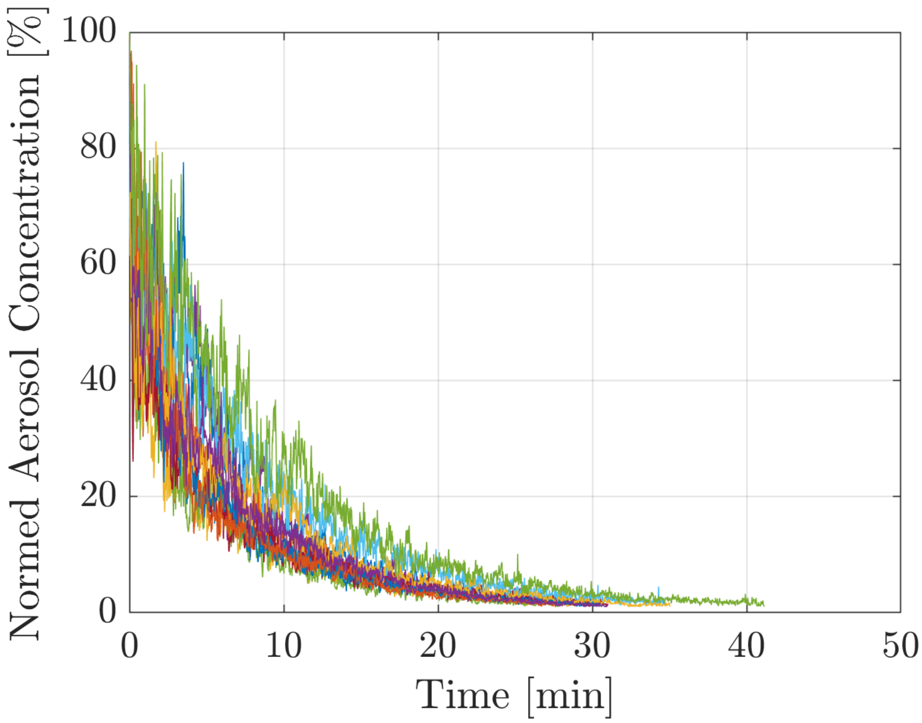

FIG. 4. Normalised aerosol concentration versus time for clearance for all baseline tests.

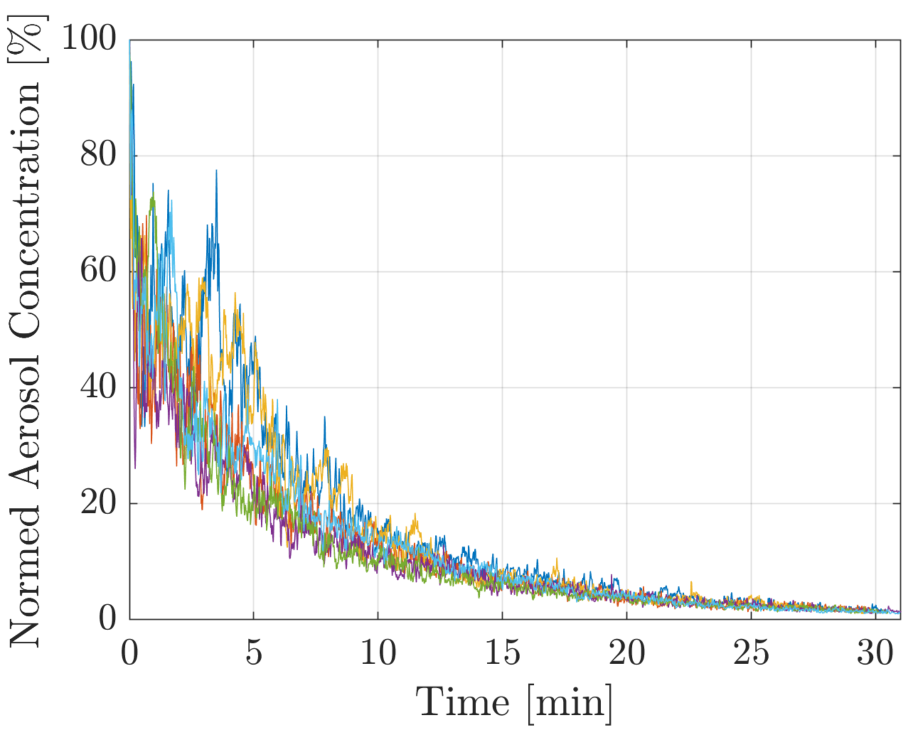

FIG. 5. Normalised aerosol concentration versus time for clearance for median baseline tests.

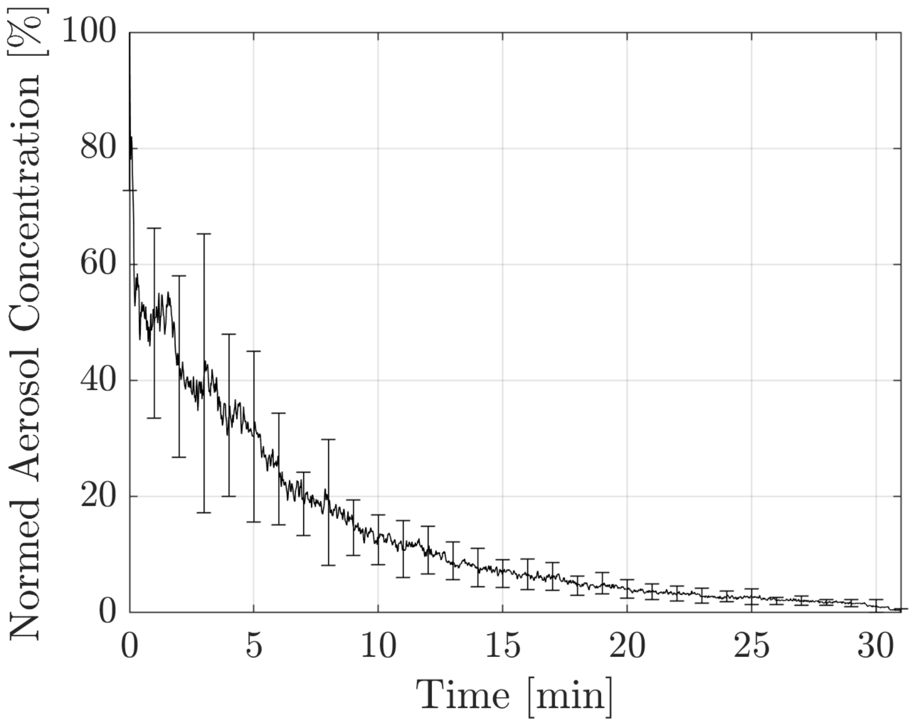

FIG. 6. Normalised aerosol concentration versus time for clearance for "average" baseline test.

2. Open-Window

From Section III A 1 we know that the first floor has a base ACH_e of 9.1; we now look at how opening windows in the space will impact the effective clearance rate. First we plot all Open-Window tests examined in Figure 7. As expected, there is much more deviation in these runs than the baseline. The most likely explanation for this is differing outdoor conditions (wind direction, wind speed, pressure, etc.) from run to run. This scatter is also tabulated in Table III, where we can see that the ACH_e ranged from 12.8 to 77.5.

Clearly, we need to reduce these down to a median set of runs to make more sense of our data, and we have done just that in Figures 8 and 9 as well as Table IV. We can see in our average run and median table data that our standard deviation has decreased and our ACH_e range has reduced.

From the figures and tables presented in this section, we have shown that opening windows is an effective way of increasing the ACH_e of a space. This change is great from an infection reduction standpoint. It is likely for this reason that the increasing natural ventilation recommendation was given by ASHRAE. However, as we will highlight later, there may be some negative thermal and power implications associated with this control.

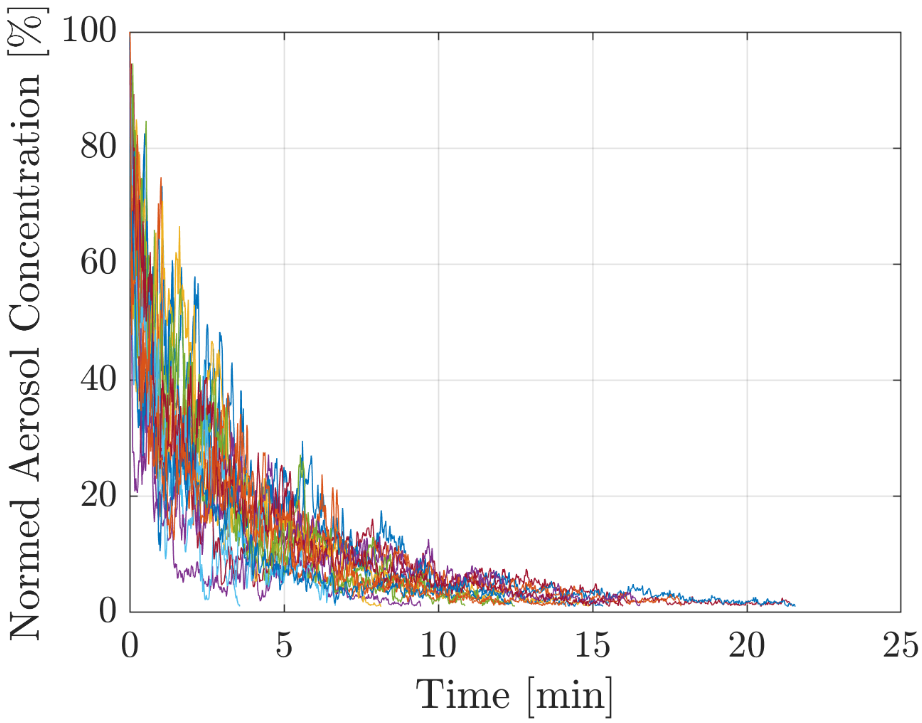

FIG. 7. Normalised aerosol concentration versus time for clearance for all Open-Window tests.

Variable	Value
Average 99% Clearance Time	13.34 minutes
Standard Deviation	4.96 minutes
Average ACH_e	20.7
Minimum ACH_e	12.8
Maximum ACH_e	77.5

TABLE III. Details of all Open-Window clearance tests.

Variable	Value
Average 99% Clearance Time	13.57 minutes
Standard Deviation	1.40 minutes
Average ACH_e	20.4
Minimum ACH_e	18.0
Maximum ACH_e	22.7

TABLE IV. Details of median Open-Window clearance tests.

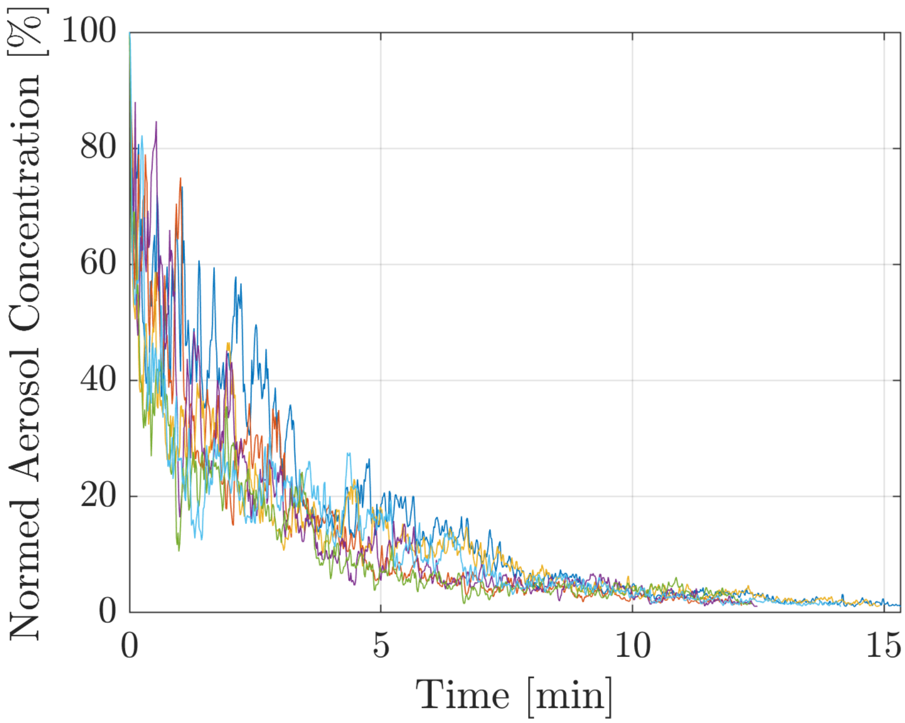

FIG. 8. Normalised aerosol concentration versus time for clearance for median Open-Window tests.

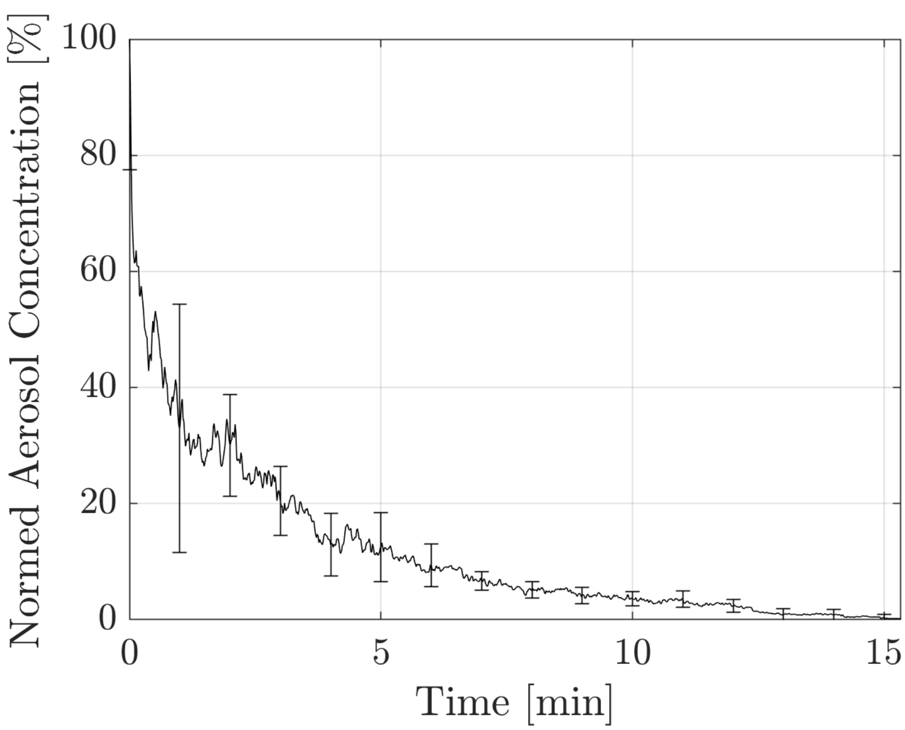

FIG. 9. Normalised aerosol concentration versus time for clearance for "average" Open-Window test.

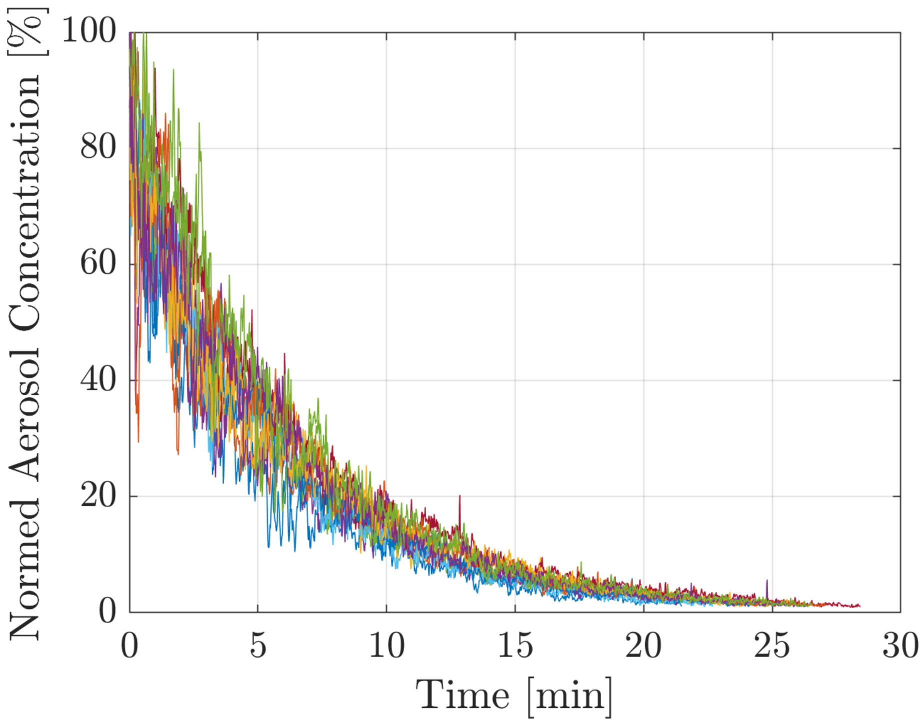

FIG. 10. Normalised aerosol concentration versus time for clearance for all In-Ceiling HEPA tests.

3. In-Ceiling HEPA

For the In-Ceiling HEPA cases, where the space was subdivided we first went about measuring the baseline ACH of the space (recall the division of the space is shown in Figure 1). Note that for the In-Ceiling HEPA and Displacement Ventilation systems, we elected to use the volumetric flow rates for each of the sub-spaces rather than directly measuring the clearance time. This decision was largely due to the fact that with Displacement Ventilation we did not have the ability to measure the base airflow rate of the subspace until after the retrofit had occurred. To calculate the ACH we merely divided the volumetric flow rate of the room (in m^3/hr) by the sub-space volume. For the In-Ceiling HEPA half of the room, we found that the base ACH value was 5.0. Note that this value differs from both the Displacement Ventilation and Baseline room ACH due to the uneven distribution of both supplies and supply strengths where the plastic barriers were placed.

For the reader's reference we have plotted all In-Ceiling HEPA cases in Figure 10, the median cases in Figure 11, and the average case in Figure 12. In addition to this we have summarized our findings for all cases in Table V and the median cases in Table VI.

From these tests we can see that there was a considerable increase in ACH_e due to these three units in half the space. We do remind the reader, that three units were used in approximately half the room volume. Had we run these tests in the full space, we would have spaced five units throughout it.

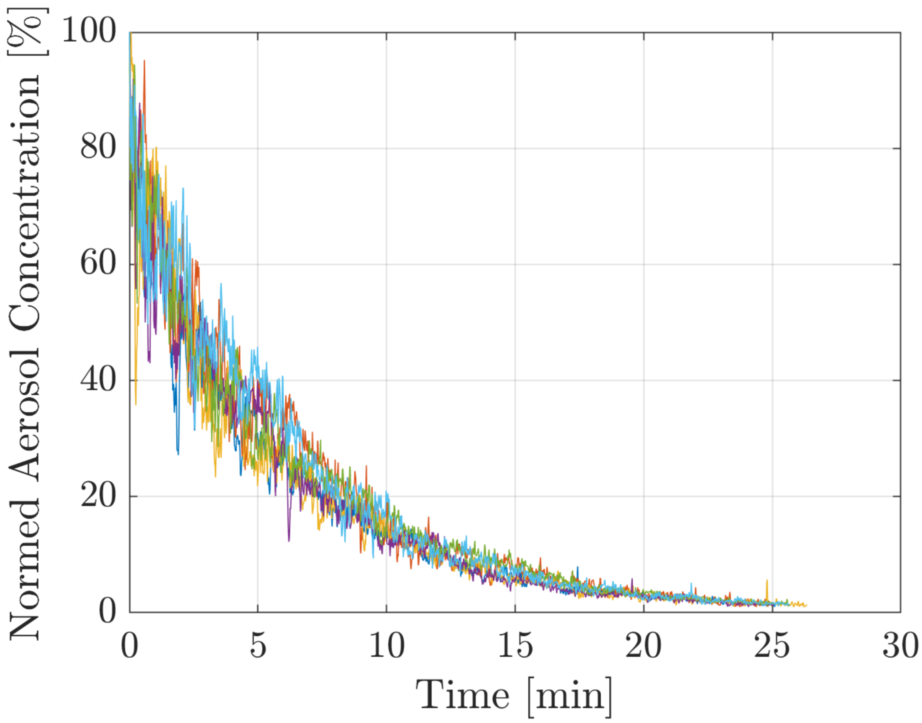

FIG. 11. Normalised aerosol concentration versus time for clearance for median In-Ceiling HEPA tests.

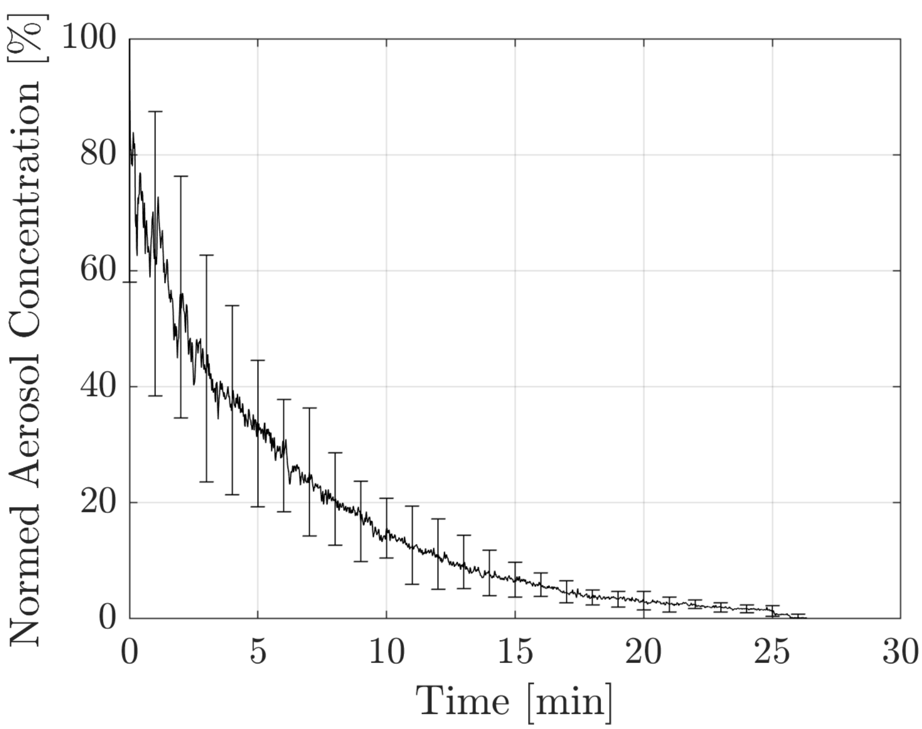

FIG. 12. Normalised aerosol concentration versus time for clearance for “average” In-Ceiling HEPA test.

Variable	Value
Average 99% Clearance Time	25.30 minutes
Standard Deviation	1.85 minutes
Average ACH_e	10.9
Minimum ACH_e	9.7
Maximum ACH_e	12.9

TABLE V. Details of all In-Ceiling HEPA clearance tests.

Variable	Value
Average 99% Clearance Time	25.45 minutes
Standard Deviation	0.55 minutes
Average ACH_e	10.9
Minimum ACH_e	10.5
Maximum ACH_e	11.1

TABLE VI. Details of median In-Ceiling HEPA clearance tests.

4. Displacement Ventilation

After consultation with CBus, Teska Carson, The City of Melbourne, and Airmaster; it was decided that we were best served to limit our impact on other building occupants and conduct the Displacement Ventilation tests between 0700 - 0900 for three mornings. These tests were conducted on 07Apr22, 08Apr22, and 19Apr22. Unfortunately, due to these time constraints, we were only able to conduct 6 tests fully, with one test that occurred such that the building ventilation switched to normal operation midway through the run. When this occurred we lost the ideal temperature profile and the clearance rate of the space changed dramatically. Before further analysis, we thought we'd show you just how dramatic the change can be. Figure 13 shows all the Displacement Ventilation cases taken at seated height plotted together. In the figure it can be seen that there are two cases which clear much more slowly than the remaining cases. These two cases have the do not have the correct temperature profile, and the details of their clearance will be given in Section III A 4 b. For the remainder of the cases that tend to clear quickly, the correct temperature profile was implemented and we will detail their characteristics in Section III A 4 a.

We also note that throughout this section we will split the results into tests at seated height (1.1 metres above the ground) and head height (1.7 metres above the ground). These heights were selected as they matched the height of one our experimentalists.

As with the In-Ceiling HEPA tests, we used the measured airflow rate data to estimate our base ACH for this space. Based on the rate of air flow into this part of the space, we calculated an ACH of 7.4 for this portion of the room.

a. Displacement Ventilation With Correct Temperature Profile

When the temperature profile was correctly implemented, Displacement Ventilation was quite efficient at improving the ACH_e of the space at both seated and head height. We first begin by presenting all the seated height results in Figure 14 and Table VII. When we perform our typical median and average analysis, the plots become those that can be seen in Figures 15 and 16 as well as Table VII.

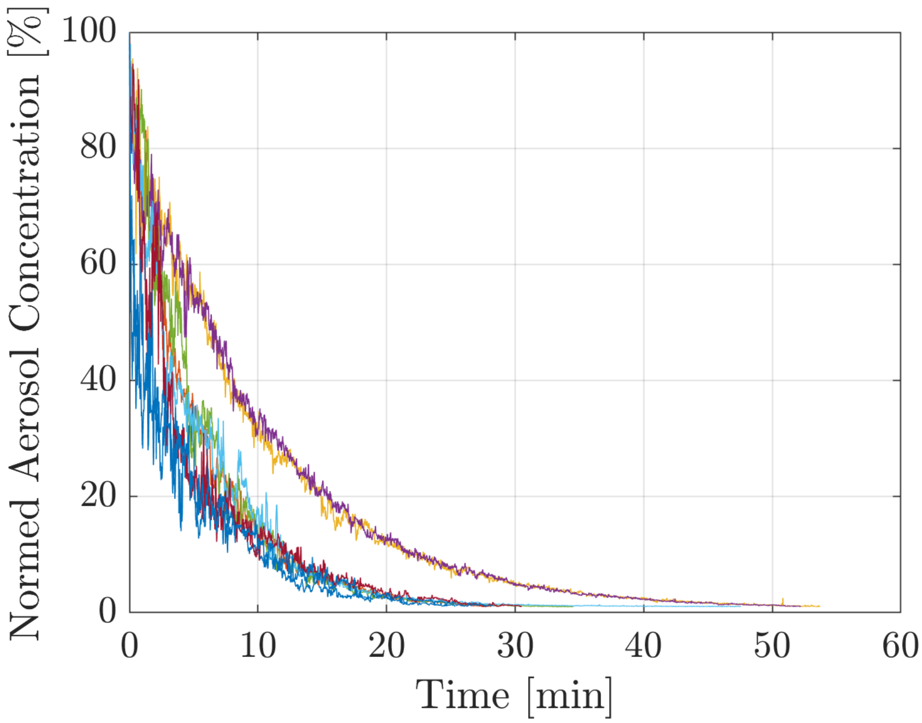

FIG. 13. Normalised aerosol concentration versus time for clearance for all Displacement Ventilation tests.

Variable	Value
Average 99% Clearance Time	23.76 minutes
Standard Deviation	2.45 minutes
Average ACH_e	11.7
Minimum ACH_e	10.1
Maximum ACH_e	13.2

TABLE VII. Details of all Displacement Ventilation clearance tests at seated height.

We contrast this with the median results at head height, presented in Table IX. Here it can be seen that the ACH_e has decreased as time to clear has increased. This finding is supported by the literature, Displacement Ventilation clears quickly at low to moderate heights, and leaves aerosol stranded high in the room. It is for this reason that it is favoured in spaces with high ceilings such that the aerosols are not encountered when standing, however for the moderate ceiling height of 423 Bourke street, we do observe a difference in clearance rate.

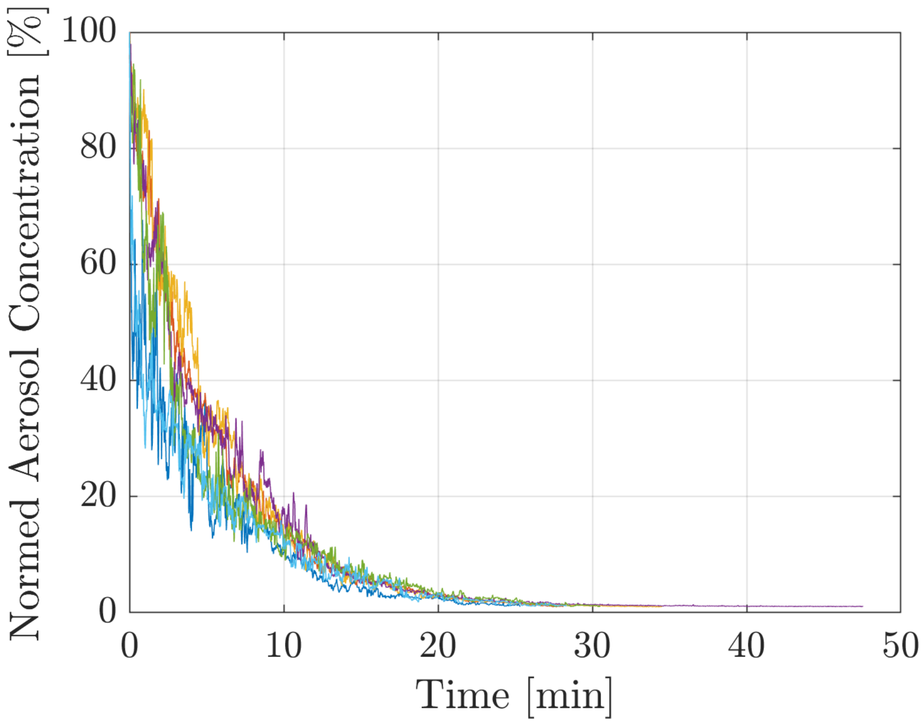

FIG. 14. Normalised aerosol concentration versus time for clearance for the correct temperature profile Displacement Ventilation tests.

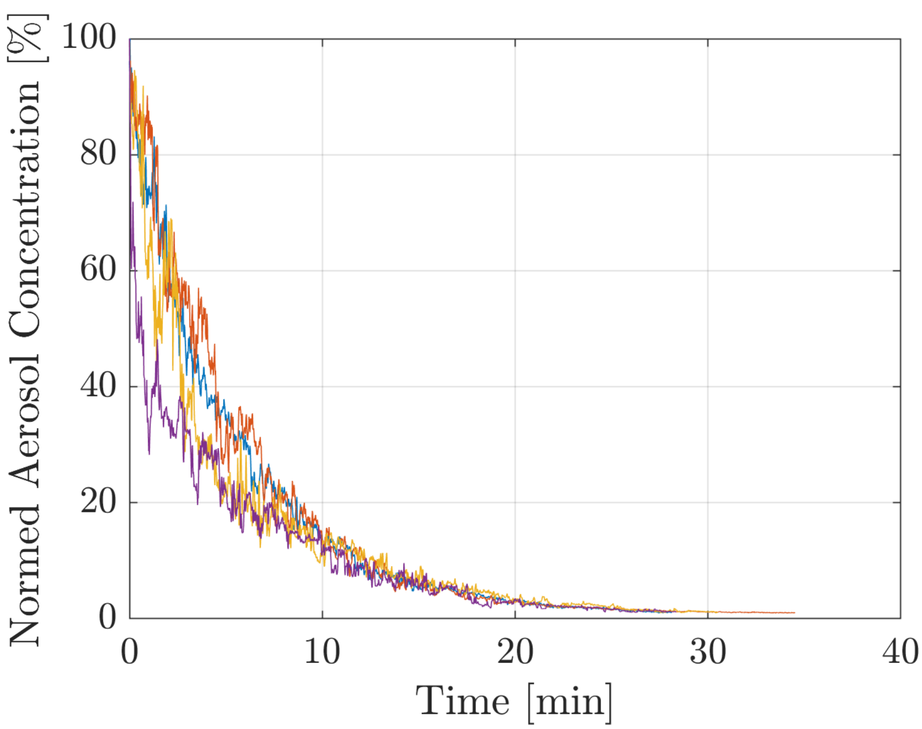

FIG. 15. Normalised aerosol concentration versus time for clearance for median Displacement Ventilation tests at seated height.

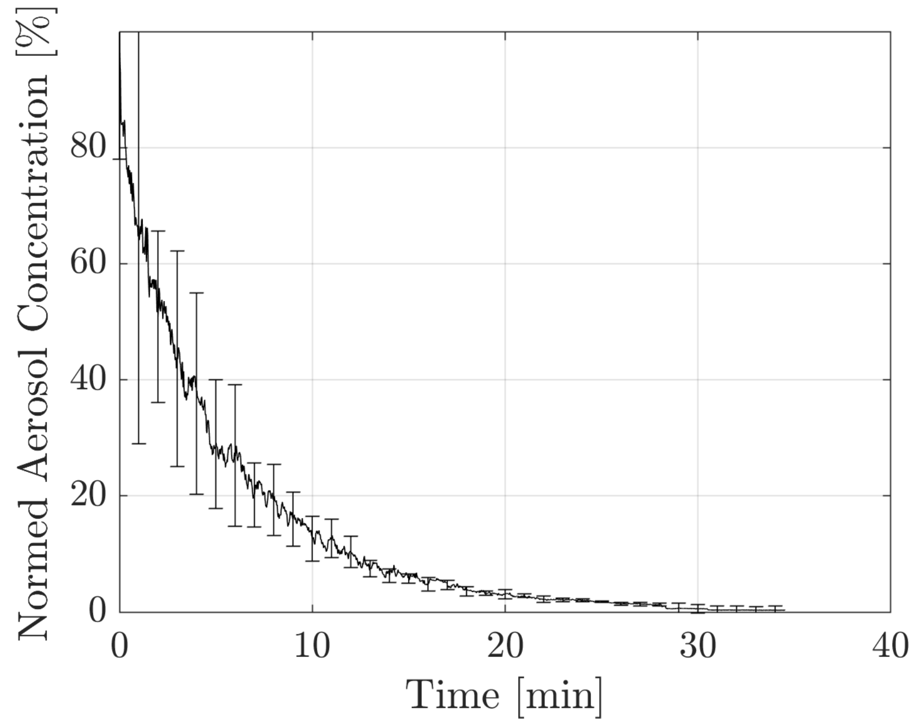

FIG. 16. Normalised aerosol concentration versus time for clearance for "average" Displacement Ventilation test at seated height.

Variable	Value
Average 99% Clearance Time	23.53 minutes
Standard Deviation	1.65 minutes
Average ACH_e	11.8
Minimum ACH_e	11.1
Maximum ACH_e	13.1

TABLE VIII. Details of median Displacement Ventilation clearance tests at seated height.

Variable	Value
Average 99% Clearance Time	30.36 minutes
Standard Deviation	2.98 minutes
Average ACH_e	9.2
Minimum ACH_e	8.0
Maximum ACH_e	9.8

TABLE IX. Details of median Displacement Ventilation clearance tests at head height.

b. Displacement Ventilation Without Correct Temperature Profile

One potential downside of retrofitted displacement ventilation is that it requires a carefully constructed temperature profile to work effectively. That is, in the absence of true underfloor ventilation, we rely on thermal load and plumes to move the air upwards. We stress to the reader that these thermal plumes existed for all cases that the heat loads were present in. However, we believe that when the supply temperature decreased to its standard operation, 18°C value, our heat load was not sufficient to drive the requisite upwards motion for a temperature that low. We do not believe there was a change in supply air volume, however, we are not able to rule out a slight change in supply volume simultaneously occurring. In this section, we detail exactly what that looks like in terms of clearance and temperature profile.

A curious reader might wonder how different these temperature profiles are to explain the difference in clearance. Figure 17 shows all temperature profiles taken over the three testing dates. Please refer to Table X for a guide between number and date and time of the profile. In the figure, it can be seen that ones taken after 09:00 are dashed as the ideal temperature profile was either already lost or in the process of being lost. This figure has a bit too much going on to clearly see what is happening when the profile is lost, so we have generated Figures 18 to 20 to show the temperature profiles from each testing day. Figure 18 in particular highlights the much flatter temperature profile in the cases after 09:00 than the cases before.

As we have shown in Figure 13, this can have quite a considerable impact on the clearance time. Figure 21 shows that these profiles do collapse upon one another, suggesting that neither was a one-off freak occurrence. For these two cases, we have an average ACH_e of 6.15. Further backing this up was one case that finished seeding at 08:45 on 07Apr22. Please note this run was not shown on our previous plots as it is a bit of an anomaly for reasons we are about to discuss. The clearance from this run is shown in Figure 22. In the clearance we appear to have a moment in time where the HVAC appeared to switch operation. This is seen most clearly in Figure 23 which focuses on where we believe the switch occurred. It is also worth noting that DT1 is the one placed at standing-height whereas DT2 is placed at seated-height. If there were to be a change in the HVAC we would expect it to first appear on the lower DT before propagating upwards, which we see in the data. For this run in particular, if we split the analysis to before and after the data points called out, we find estimated ACH_e values 11.8 and 5.9, before and after this point, respectively (at seated height) and values of 10.5 and 5.3, before and after this point, respectively (at standing height). These values are close to those measured in the correct and incorrect temperature profile scenarios, so we believe that the HVAC change occurred as programmed around 08:50 that morning.

While it could be argued that this analysis was not necessary, we felt it was worth highlighting the discrepancy in clearance rate for the correct and incorrect temperature profiles when a retrofit was performed. That is, an *ad hoc* floor-by-floor approach likely would not work with displacement ventilation as the temperatures both on the floor and for the building would have to be closely monitored for effective clearance. However, if the entire building were to take this approach and change the set-point temperature of the chiller (especially if the building had taller ceilings), displacement ventilation can be and is an extremely effective way further increase safety from aerosols in an office setting.

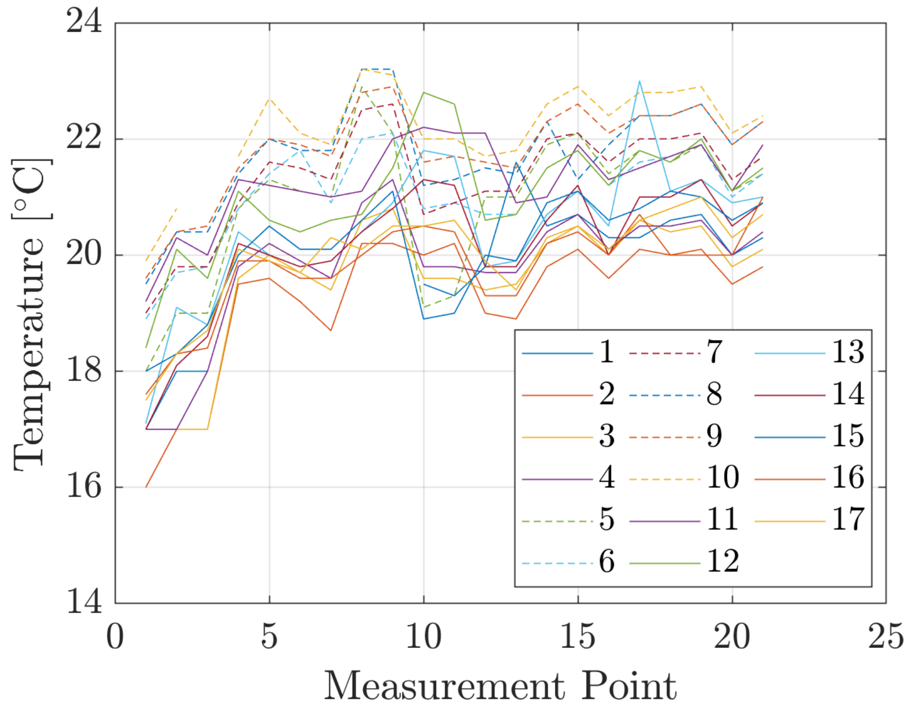

FIG. 17. All temperature profiles taken during displacement ventilation tests.

#	Date and Time
1	07Apr22 06:04
2	07Apr22 07:20
3	07Apr22 08:36
4	07Apr22 08:53
5	07Apr22 09:12
6	07Apr22 09:51
7	07Apr22 10:30
8	07Apr22 11:52
9	07Apr22 13:02
10	07Apr22 14:00
11	08Apr22 06:11
12	08Apr22 06:17
13	08Apr22 07:07
14	08Apr22 08:07
15	19Apr22 06:58
16	19Apr22 07:59
17	19Apr22 08:58

TABLE X. Dates and Times for Displacement Temperature Profiles.

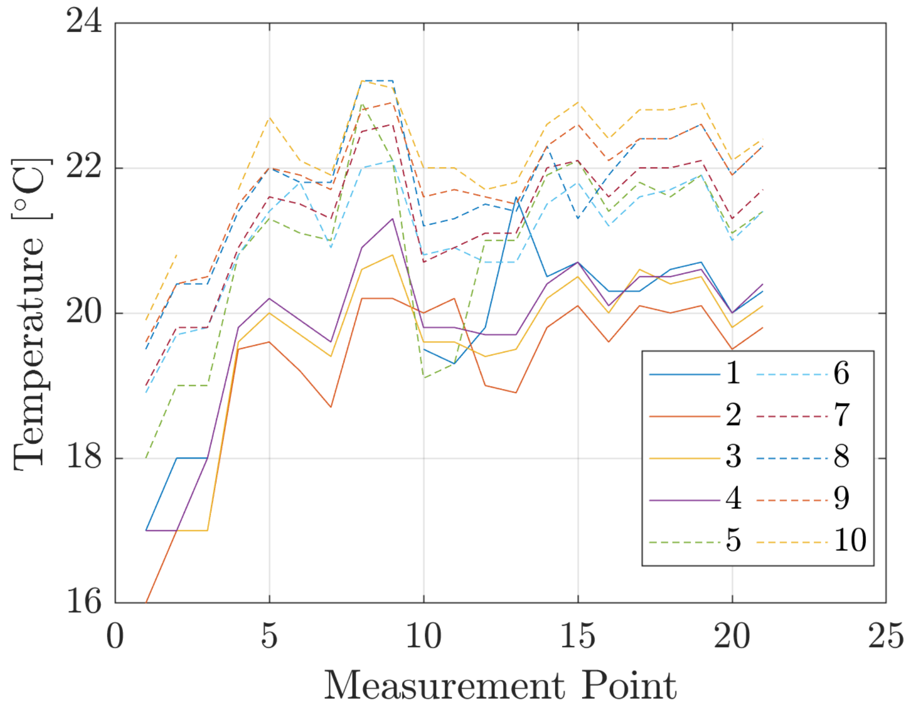

FIG. 18. All temperature profiles taken on 07Apr22.

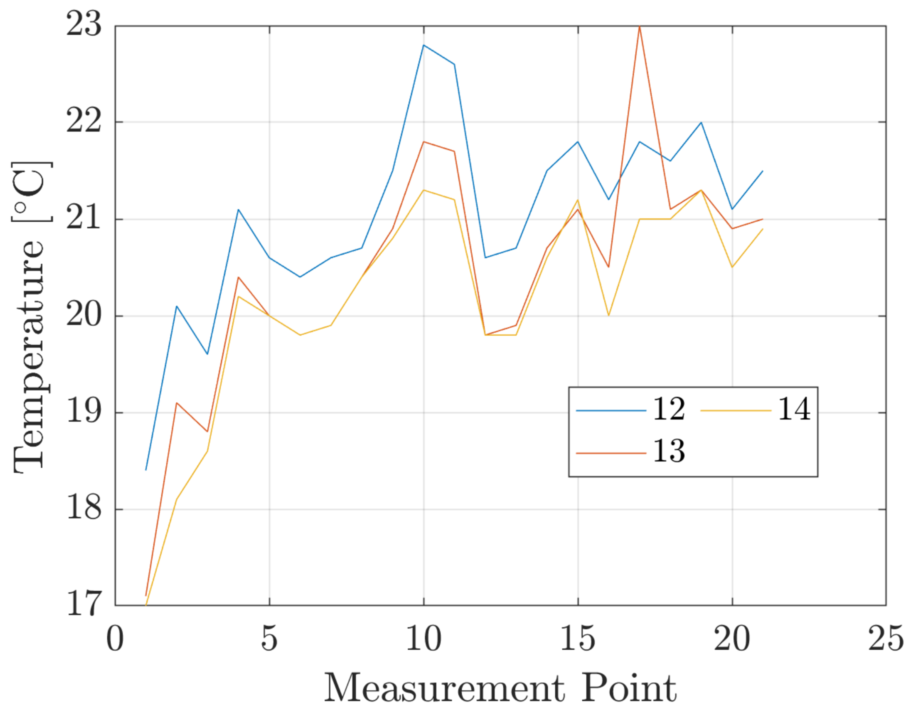

FIG. 19. All temperature profiles taken on 08Apr22.

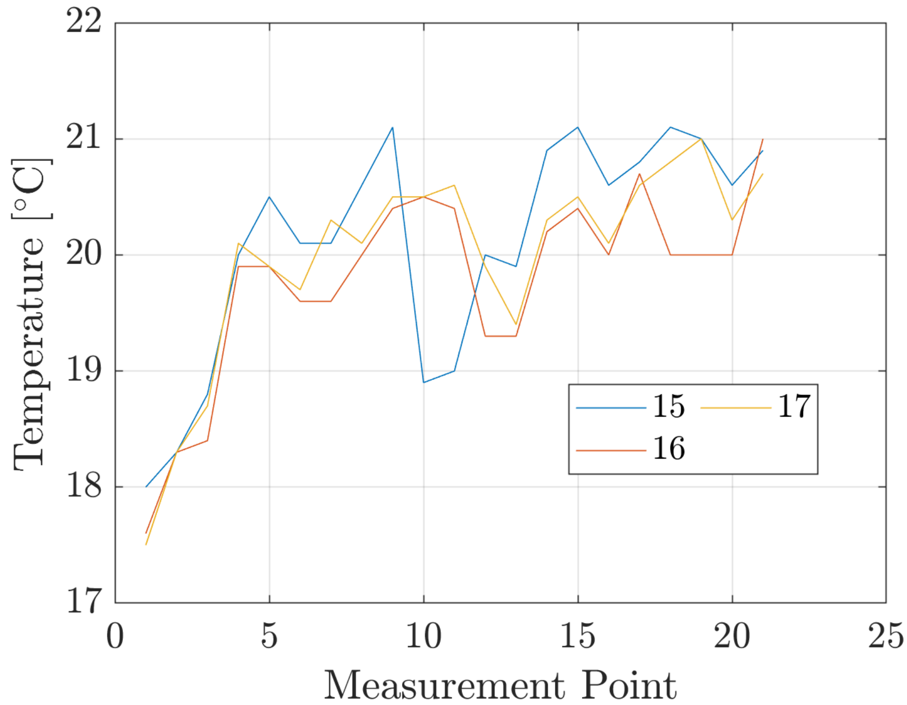

FIG. 20. All temperature profiles taken on 19Apr22.

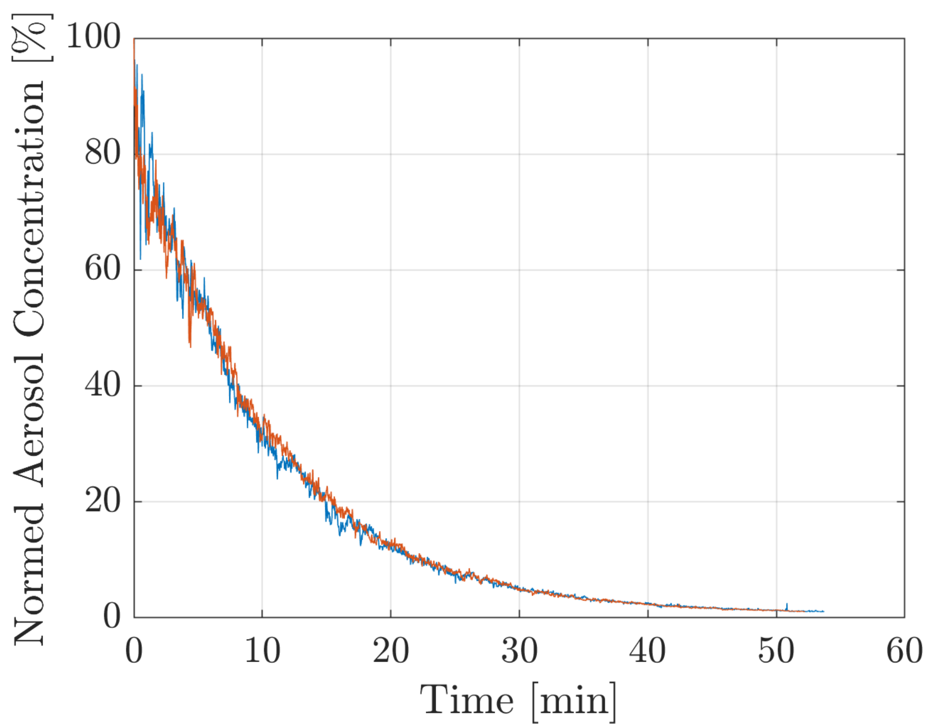

FIG. 21. Normalised aerosol concentration versus time for clearance for the incorrect temperature profile Displacement Ventilation tests.

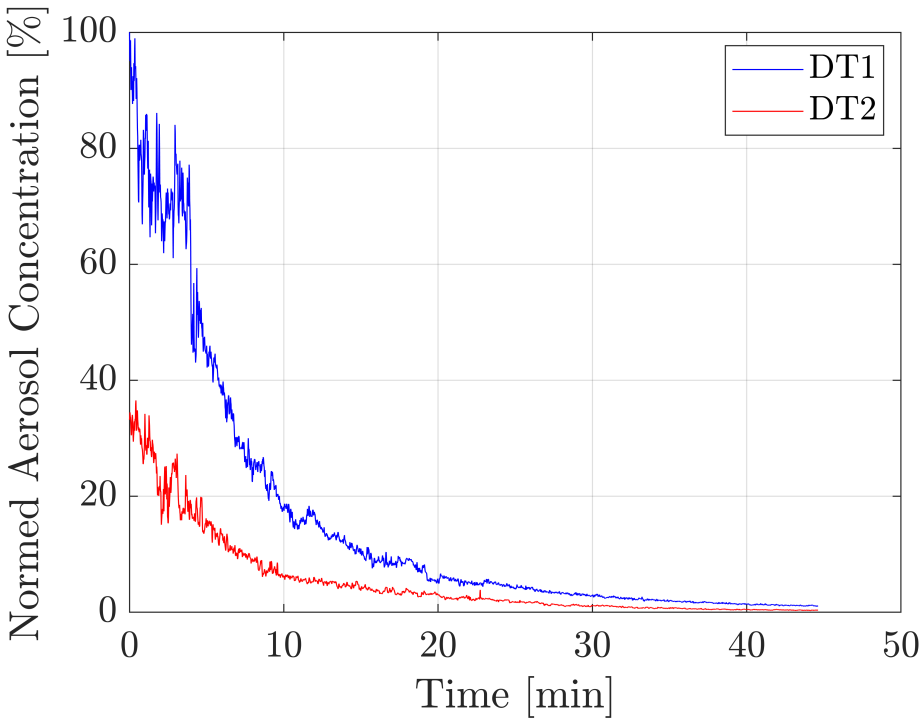

FIG. 22. Clearance for case where temperature profile was lost mid-run.

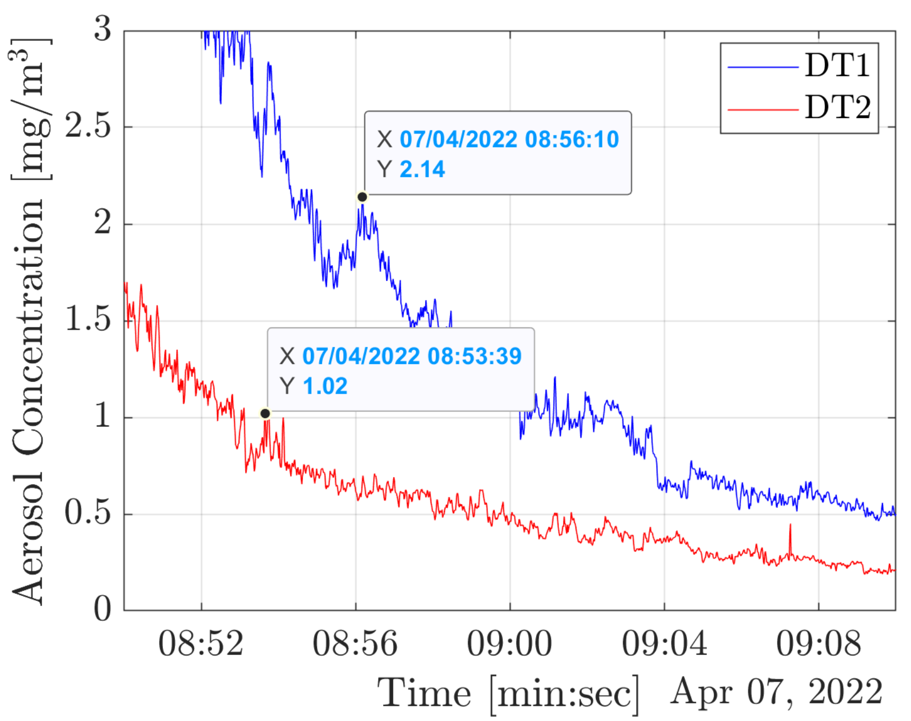

FIG. 23. Clearance for case where temperature profile was lost mid-run.

B. Quantifying Infection Risk

We begin this section by stressing, the results presented herein are estimates. There is a certain human element to these estimates that make them somewhat of a guess. An example of this for Open-Window controls, is if someone were to be next to a single open window that would be a much different factor than multiple open windows with people sitting next to them. We cannot estimate the risk for every possible permutation, so instead we will list our assumptions and estimate the risks. The calculator we are using for these risks is available online at https://cires.colorado.edu/news/covid-19-airborne-transmission-tool-available. The details of the analysis are conducted in the accompanying spreadsheet entitled "COVID-19 Aerosol Transmission Estimator BREATH".

Our assumptions for our infection risk are:

- **Baseline:** Our assumed population for the space is 100 people, which is held for all future cases except where noted otherwise. This assumption gives 3.56-m^2 per person for the area. We are assuming the space is occupied 8-hours a day for a single day. Also no one is assumed to be wearing a mask. Finally, we modelling Omicron BA.1 and assuming that the vaccine does not reduce infection risk (we are not commenting on severity, just that the vaccine does not reduce chances of catching this strain of COVID). This is to avoid any further modelling regarding asymptomatic cases of Omicron BA.1. Should the reader disagree with any of these assumptions, they are invited and encouraged to modify the spreadsheet values to see how it impacts the H value (which informs the number of secondary cases).
  - We note that this level of personnel loading would be extreme, however, we are using it because the calculator appears to do some internal rounding based on the number of people present. Please refer to the supplementary analysis in Section VIII where we detail how scaling the number of personnel down to 32 (11.13-m^2 per person), yields the same relative change percents for the controls, with some slight rounding adjustments.
- **Open-Window:** We are assuming there is no inherent loading that increases risk. That is, we make no assumptions about people working close to or far away from the windows. For this analysis we are merely looking at the combination of displacement and natural ventilation of the space, with uniform mixing of the air in the space.
- **In-Ceiling HEPA:** We are assuming that the extra ACH_e of the HEPA filters acts to assist our mixing ventilation. In reality, this is a bit of a conservative estimate, as we have a series of sinks for our aerosols; which can be strategically placed over places people tend to congregate and spend extended periods of time (e.g. a meeting room), however we are ignoring that for this analysis.

Control Name	Baseline ACH_e	Control ACH_e
Open-Window	9.1	20.4
Disp Vent (seated)	7.4	11.8
Disp Vent (standing)	7.4	9.1
In-Ceiling HEPA	5.0	10.9
In-Ceiling HEPA (no HVAC)	N/A	6.6

TABLE XI. ACH_e improvements for each control. Note that the baseline values for Displacement Ventilation and In-Ceiling HEPA controls are different from Open-Window and each other because the space was subdivided in a way that did not keep the ACH constant for all sub-spaces.

- **Displacement Ventilation:** We have the most assumptions for this control, the reasons being 1) we have two different ventilation rates for a seated and standing worker and 2) we have to try to deal with the lack of mixed ventilation in the space. To deal with this we are assuming for this control:
  - The risk of being in the space is a hybrid of sitting and standing risks. We are assuming that each worker spends 1/4 of their day standing and the rest seated. Specifically, this means we will perform a weighted average of the seated and standing configurations, with the aforementioned weighting.
  - Because we are no longer dealing with a situation where infected aerosol is easily mixed throughout the space, we are treating the space as though its density has been cut in half. That is, we are cutting the population for this analysis from 100 to 50. There can be arguments made for reducing this even further, however, we felt as though it was best to be conservative and that people would not effectively socially distance at all times (alternatively, people need to be in different parts of the office so they would still be walking through other's local aerosol space). Furthermore, we have not studied the impact confined space nor furniture in the space on the effectiveness of Displacement Ventilation.

These results from the spreadsheet were then used to generate Table XII. Our results suggest that all three controls are able to effectively reduce the average risk that a person would catch the Omicron variant of COVID-19 seen via the drop in estimated number of secondary cases. Our calculations highlight that these controls would lead to at least a 50% reduction in the number of secondary cases per day when an infectious person is present. For Displacement Ventilation this reduction increases to approximately 80%, with a reminder to the reader that there were several assumptions taken to account for the change from mixing ventilation risk to Displacement Ventilation risk. In short, all three of these options appear viable from a reduction of risk standpoint.

Control Name	Baseline	Control	Change	Reduction %
Open-Window	0.49	0.25	0.26	53
In-Ceiling HEPA	0.8	0.41	0.39	49
Displacement Ventilation	0.58	0.10	0.48	83

TABLE XII. Number of secondary infections based on COVID estimator tables. Please note, had we not assumed the drop to half loading for Displacement Ventilation, then the change value would be 0.17 (a 29% reduction).

C. Experimental Results: Power Usage

Please note that the details and raw calculations from this analysis are provided in the accompanying spreadsheet in the "$ from c/kW-hr" and "Cost Recovery Estimate" tabs.

In our introduction we covered how we determined our curves for estimating power usage from external three-day average high temperatures. Next we gathered all the high temperature data (with 2 days of prior data for a sufficient moving average for the first day) for the interval of 01Sep21 to 20Apr22. Using our curves, we estimate the power usage for this spring/summer/autumn period (which we will term "cooling season").

Once we have our estimated kW-hr values for the cooling season, we multiply by our c/kW-hr value to estimate the cost of running each option. From this, we have estimated that the baseline chiller costs (again assuming consumer electricity rates) were $17,489.20. For Open-Window this increases to $19,546.00. For an entire floor's worth (5 units) of In-Ceiling HEPA filters this value is $17,956.91. Finally, for the Displacement Ventilation system, this value is $15,631.58. The key values for this analysis are summarized in Table XIII.

Control Name	MW-hr of Power	Estimated Cost AU$	kg of CO_2
Baseline	63.1	17,489.20	27046
Open-Window	70.4	19,546.00	30226
In-Ceiling HEPA	64.8	17,956.91	27769
Disp Vent	56.5	15,631.58	24173

TABLE XIII. Estimated power usage, costs, and CO_2 produced for the chiller for one cooling season. Note the CO_2 estimates were based on the calculator available online at: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

Next we used the Open-Window control as our cost-base. That is, we are assuming someone would be using the open window control and we're attempting to demonstrate how long the other controls would take to pay for themselves relative to the Open-Window control. For this analysis we are assuming that:

† (Reiterating) we are only looking at the cooling season and ignoring the costs associated with heating due to lack of data during this time of the year.

† The cost per cooling season remains fixed, year-to-year, for the prices listed above.

- In order to assess this, we also ran the numbers for the 2020/2021 summer. We found that the costs of cooling for the previous summer were very similar (\$16,655.50; \$18,830.04; \$16,936.13; and \$15,141.70, for Baseline, Open-Window, In-Ceiling HEPA, and Displacement Ventilation, respectively).

† The Open-Window choice would be taken, hence we are looking at repayment relative to the power costs of Open-Window.

† The baseline choice would not be taken due to the fact it does not improve worker safety.

† Costs of setting up spaces scale linearly.

- The cost of setting up Displacement Ventilation was approximately \$30,000 for half the floor, hence \$60,000 for the entire floor
- The cost of 5 In-Ceiling HEPA units was \$7,500 for the entire floor. On top of this there was a \$2,500 installation cost; hence \$10,000 for the entire space.

† Displacement Ventilation has no ongoing costs.

† We looked into three sets of ongoing In-Ceiling HEPA costs: a cheaper \$500 a year option where an already employed building engineer would service the units (check and/or change the filters) and a more expensive \$1,000 a year option where an external contractor would be hired to service the units. Finally, for a direct cost recovery comparison, we are looking at no ongoing costs for these units.

With these assumptions in mind, Table XIV shows how long it takes for each system to pay for itself relative to the Open-Window control. As the table shows, it could take 11 cooling seasons for the In-Ceiling HEPA system to get "out of the red" with a moderate service cost per year. Similarly, a Displacement Ventilation system may take 17 cooling seasons to get "out of the red". While this seems like quite a long time, it is well within the expected lifespan of an office space, and hence there is considerable financial incentive to invest in one of these options versus simply opening the windows.

It is worth mentioning that while the system paying for itself is a benefit, the safety increases, and hence, increase of potential tenant occupancy will far outweigh the financial benefit that these systems offer. That is, any of these systems paying for themselves should be viewed as a secondary benefit. The primary benefit would be in increasing the safety of, and ability to fill, a tenancy of a building.

# Cooling Season	In-Ceiling HEPA (without Service) $	In-Ceiling HEPA ($500 service) $	In-Ceiling HEPA ($1,000 service) $	Displacement Ventilation
1	-10,000.00	-10,000.00	-10,000.00	-60,000.00
2	-8,410.91	-8,910.91	-9,410.91	-56,085.58
3	-6,821.81	-7,821.81	-8,821.81	-52,171.16
4	-5,232.72	-6,732.72	-8,232.72	-48,256.74
5	-3,643.62	-5,643.62	-7,643.62	-44,342.32
6	-2,054.53	-4,554.53	-7,054.53	-40,427.90
7	-465.43	-3,465.43	-6,465.43	-36,513.48
8	1,123.66	-2,376.34	-5,876.34	-32,599.06
9	2,712.76	-1,287.24	-5,287.24	-28,684.64
10	4,301.85	-198.15	-4,698.15	-24,770.22
11	5,890.95	890.95	-4,109.05	-20,855.80
12	7,480.04	1,980.04	-3,519.96	-16,941.38
13	9,069.14	3,069.14	-2,930.86	-13,026.96
14	10,658.23	4,158.23	-2,341.77	-9,112.54
15	12,247.33	5,247.33	-1,752.67	-5,198.12
16	13,836.42	6,336.42	-1,163.58	-1,283.70
17	15,425.52	7,425.52	-574.48	2,630.72
18	17,014.61	8,514.61	14.61	6,545.14

TABLE XIV. Estimated financial balance relative to Open-Window for chiller power usage for each control system.

IV Temperature/Comfort Results

Before discussing, summarizing, and concluding on these retrofit options, we thought it was best to address the thermal comfort that each of these retrofitting options would provide. For the baseline and In-Ceiling HEPA options, the thermal comfort is the same. That is, the existing building thermal settings were maintained, and have been set to maintain comfort throughout the building.

For Displacement Ventilation, we have plotted the thermal profile from floor to ceiling in Figure 17 and shown that when the correct temperature profile was maintained the space ranged from approximately 17 to 22°C.

For the Open-Window condition, thermal comfort is a large concern. Unfortunately, throughout these tests we were not able to experience an extreme heat day, to directly measure what the effect of open windows would be on the temperature of this floor, however, we do have a few days worth of data that we can consider. Going through the data, we did not observe a day where the temperature inside the space exceeded what the baseline thermal range was (approximately 18 to 23°C).

Instead we will do our best to estimate what the temperature of the space could be if inside was 20°C with an 18°C supply. Finally let's assume outside was 40°C when the windows were opened. For this assumption let's also fix the chiller to be running at maximum capacity for simplicity. Recall that the ACH_e of the space during baseline is 9.1 and the ACH_e of the space with open windows is 20.4. This suggests *at least* an additional 11.3

room volumes worth of air has to enter the space from outside in order for that much to exit. If we assume uniform mixing of the air, we achieve a temperature equilibrium at 30.2°C.

Clearly this is an extreme example but it does highlight the possible high temperatures that can happen when we open windows in an environment that gets as warm as Australia does.

V Discussion

Herein we address some additional benefits for the controls that are worth discussing for completeness, but not appropriate in a Results section.

- **Open-Window:** While we have highlighted the issues of open windows on extreme/inclement weather days; depending on the climate and attire of those in an office, open windows may be comfortable for staff for a majority of the year. Additionally, depending on the building location, there may be (and likely are) benefits to fresh air that the other options do not offer.

- **In-Ceiling HEPA Filters:** The added benefit of In-Ceiling HEPA units (and all HEPA filters) is that they serve a purpose outside of the potential reduction of aerosolised viral spread and increasing ACH_e. These same units can also be used to increase worker comfort when there is an excess quantity of allergens in the air (e.g. dust and pollen) or when there are nearby industrial or wildfires, removing excess soot and smoke aerosols from the air (something the other methods are unable to do). That is, if there is high pollen or smoke due to a nearby bush/industrial-fire, these filters would actively remove those irritants from the air in the office space. In addition to this, these units were operated at a medium fan speed to keep the noise they produce to approximately 60-dBA, which is typical of an office. However, should these units be installed somewhere without people, like a meeting room after it has emptied; they can be run on high speed to clear the space quickly before the next meeting room use. Their largest benefit relative to the other controls is ease of installation and integration with an existing setup, but their largest downside is the requisite filter maintenance and associated costs. Our analysis assumes quite a high level of attention, and additional testing should be able to determine how frequently these filters need to be serviced or changed.

- **Displacement Ventilation:** The benefits to Displacement Ventilation are largely the reduction in lateral movement of air throughout the space. That is, the air is no longer uniformly mixed and instead stays confined to isolated regions, which it is still able to diffuse over. We do remind the reader that this is typically employed in spaces with ceilings that are 2.7-m (9-feet) or larger, so it is slightly off-design for the space considered herein. However, in the correct space Displacement Ventilation offers benefits beyond the aerosolized spread of illnesses. These include, but are not limited to, improved air quality of the space and reduced background HVAC noise levels.

- **How Simulated Coughs Move with these Controls:** We have conducted some supplementary measurements to highlight the reduced horizontal movements of aerosol with Displacement Ventilation via a simulated cough. What we found was that for

FIG. 24. Simulated cough in Displacement Ventilation. Note that the smoke here extended approximately 2 metres from the source location.

all systems that rely on mixing (i.e. Baseline and In-Ceiling HEPA) the cough would mix and spread throughout the room. However, for a simulated cough in displacement ventilation, shown in Figure 24, the cough mostly stays within approximately 2 metres of the test subject. Open-Window simulated coughs, are somewhat more complex; and we have attempted to highlight these for the on-site demos. In that situation, the location of the cough and window both matter, when a subject is close to an open window, the cough will travel out the window (even if it has to reverse direction to do so, as seen in Figure 25)). However, far from the window it will mix into the room before either entering the HVAC return or exiting the space via the window. It is for this reason it is easiest and safest to assume that with open windows, the air is still mixed inside the space.

While the above images can help demonstrate what is happening, we have added a computational fluid dynamics (CFD) component of this project to provide additional insight. In these simulations, the ventilation scenarios we described had an infected person placed in the centre coughing "infected" air. The simulations were able to demonstrate the effectiveness of different kinds of ventilation in terms of their ability to keep aerosols isolated to a smaller region (or for some control cases their inability to keep these isolated). More information on those simulations is provided in Appendix A.

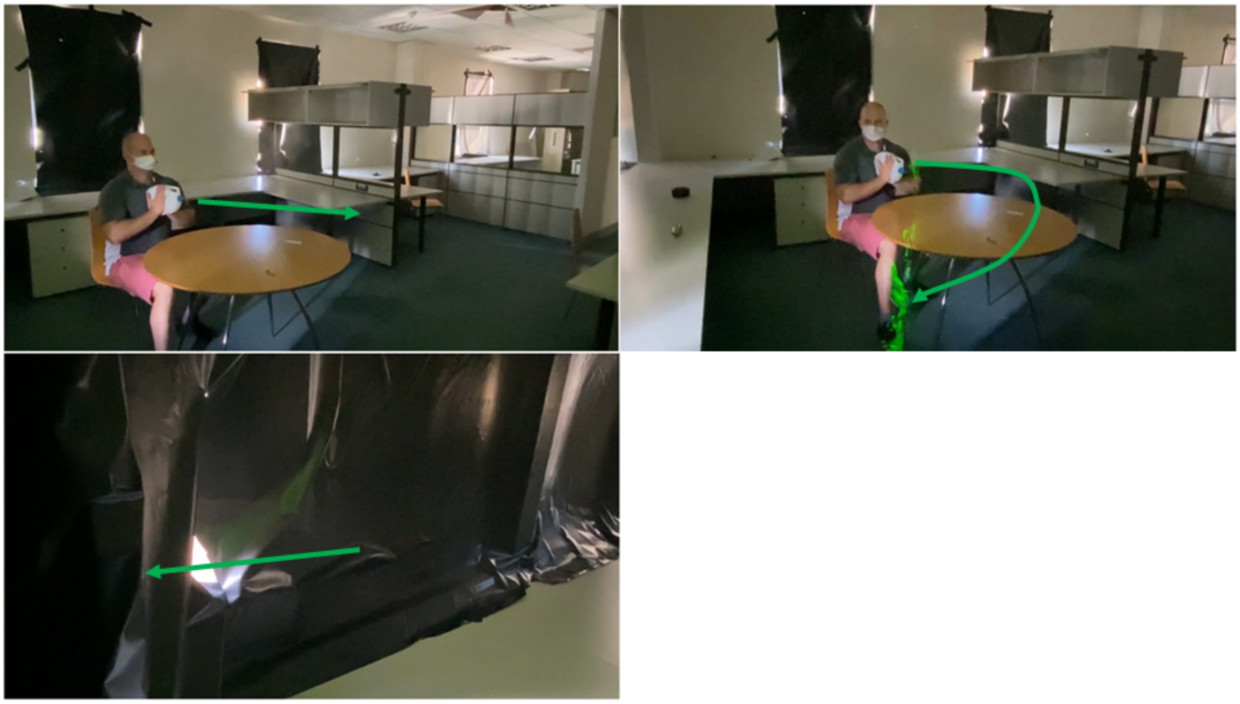

FIG. 25. Simulated cough near window. Upper left panel: a milk container is used to simulated a cough; upper right panel: the smoke takes a bend and passes through a laser sheet; and lower left panel: smoke exits the nearest window.

VI Impact/Applications

We hope that this work may be used for two primary purposes. The first of which is to inform building managers of the trade-offs between up-front and on-going costs for ventilation retrofits. That is, we have tried to show that over time, all of the up-front-costing retrofit options will pay for themselves relative to the Open-Window configuration (due to the expected increase in power usage for summer measurements in a warm climate). We have tried to provide a rough guide of how long it could take for these other retrofit options to pay for themselves relative to the no-up-front-cost but increased on-going-cost option.

The second use for this work, would be to develop a business case for outside investors or other interested parties. While we are attempting to do the best work we can in such a short time-frame, with additional funding it will be possible to do a longer duration measurement to give a more comprehensive/systematic set of answers to these questions. Minimally, we'd like to repeat this project in the winter to see the energy impacts during heating. Looking at the larger picture, we'd also like to answer further questions regarding worker comfort in all of these controls (e.g. while open windows may be inefficient power usage wise, the fresh air may be greatly enjoyed by workers and hence be desirable). We also have great interest in repeating these measurements in spaces with larger ceilings. Here, Displacement Ventilation should perform much better, and HEPA filters tend to have issues with the increased room volumes, so it may change the upfront costs.

VII Conclusions

While this project has been short in duration, it has not been short in findings (nor have the reports been short). We believe the key takeaways from this project are:

★ All controls examined could be able to increase worker safety from aerosolised viruses.

★ In terms of increasing the effective air-changes-per-hour (as a surrogate for safety) the control order from best to least effective was: Open-Window, In-Ceiling HEPA, and Displacement Ventilation.

★ In terms of decreased risk of modelled infection the control: Displacement Ventilation was most effective when a reduction in effective population was assumed (and we have argued that this assumption is justified). Open-Window and In-Ceiling HEPA approximately equally effective at reducing modelled infection risk.

★ In terms of upfront cost, the order of controls from least to most expensive is: Open-Window, In-Ceiling HEPA, and Displacement Ventilation

★ In terms of power use, the order of controls from least to most expensive are: Displacement Ventilation, In-Ceiling HEPA, and Open-Window.

  ⋆ The level of reduced cost was sufficient for the In-Ceiling HEPA system was able to pay for itself with chiller power savings in 8 cooling seasons from Open-Window. When ongoing filter maintenance is included, this can increase to 10 or 18 cooling seasons, depending if the maintenance per annum costs are $500 or $1,000, respectively.

  ⋆ The Displacement Ventilation system was able to pay for itself with chiller power savings in 17 cooling seasons from Open-Window.

In short, there is no objective best control that we observed. In terms of power usage, opening windows was not the best option, but in terms of worker safety (with effective air-changes-per hour as the informative measurement) it was. It is worth mentioning that while this control was possible in this space, for buildings that lack operable windows, it would not be a possible strategy. For buildings without operable windows, In-Ceiling HEPA HEPA filters were the cheapest up-front control and were able to increase the effective air-changes-per-hour reasonably well. However, this system has a potential downside in that the filters need to be monitored and serviced, unlike the other controls. The Displacement Ventilation system was the most expensive control upfront, offered the smallest increase in effective air-changes-per-hour, but had the lowest modelled power costs of all controls. The In-Ceiling HEPA and Displacement Ventilation systems were able to pay for themselves within 20 years, just due to reduced chiller power costs in the spring/summer/autumn, when compared to the high power costs of leaving the windows open.

VIII Additional Analysis

After presenting our results to the partners and community of practice, several sensitivity analysis requests were made. That is, there were questions on how robust these findings were and how sensitive they are to slight to moderate changes in the data or assumptions. In this section, we will provide some text to accompanying the "Sensitivity_Analysis.xlsx" spreadsheet, so that the results of the sensitivity analyses can be understood and appreciated. We will go through the sheets of the spreadsheet in order.

- **20_cents_per_kWhr:** here we repeat the analysis for cost savings using $0.20/kW-hr rather than $0.28/kW-hr above. This value was provided to us by Cbus as the lower limit of industrial power rates in the area around 423 Bourke Street. This analysis reduced the estimated chiller power costs to $12,492.29 for baseline, $13,961.43 for Open-Window, $12,826.36 for In-Ceiling HEPA, and $11,165.42 for Displacement Ventilation. The result of this was increasing the time for repayment to 9 cooling seasons for In-Ceiling HEPA outright, 16 cooling seasons for In-Ceiling HEPA with $500 annual service charges, 22 cooling seasons for Displacement Ventilation, and 75 cooling seasons for In-Ceiling HEPA with $1000 annual service charges.

- **25_cents_per_kWhr:** here we repeat the analysis for cost savings using $0.25/kW-hr rather than $0.28/kW-hr above. This value was provided to us by Cbus as the middle value of industrial power rates in the area around 423 Bourke Street. This analysis reduced the estimated chiller power costs to $15,615.36 for baseline, $17,451.79 for Open-Window, $16,032.95 for In-Ceiling HEPA, and $13,956.77 for Displacement Ventilation. The result of this was increasing the time for repayment to 8 cooling seasons for In-Ceiling HEPA outright, 11 cooling seasons for In-Ceiling HEPA with $500 annual service charges, 24 cooling seasons for Displacement Ventilation, and 18 cooling seasons for In-Ceiling HEPA with $1000 annual service charges.

- **30_cents_per_kWhr:** here we repeat the analysis for cost savings using $0.30/kW-hr rather than $0.28/kW-hr above. This value was provided to us by Cbus as the upper limit of industrial power rates in the area around 423 Bourke Street. This analysis reduced the estimated chiller power costs to $18,738.43 for baseline, $20,942.14 for Open-Window, $19,239.54 for In-Ceiling HEPA, and $16,748.12 for Displacement Ventilation. The result of this was increasing the time for repayment to 6 cooling seasons for In-Ceiling HEPA outright, 9 cooling seasons for In-Ceiling HEPA with $500 annual service charges, 15 cooling seasons for Displacement Ventilation, and 15 cooling seasons for In-Ceiling HEPA with $1000 annual service charges.

- **3_degrees_DispVent:** here we look at what our savings would be for Displacement Ventilation if the system were more favourable for its use. That is, instead of being able to be run with a 2 degree reduction in temperature from baseline, we look at a 3 degree reduction in temperature from the baseline. The result of this analysis is:
  - Total power cost: $15,015.54
  - Savings relative to Open-Window: $4,530.46
  - Cooling seasons to be financially positive: 14

- **4_degrees_DispVent:** same as above but with a 4 degree reduction instead of 3. The result of this analysis is:
  - Total power cost: $14,578.76
  - Savings relative to Open-Window: $4,967.24
  - Cooling seasons to be financially positive: 13
- **5_degrees_DispVent:** same as above but with a 5 degree reduction instead of 3. The result of this analysis is:
  - Total power cost: $14,241.41
  - Savings relative to Open-Window: $5,304.59
  - Cooling seasons to be financially positive: 12
- **40%_E_inc_ASHRAE:** here we look at applying the results from Aviv et al. (2021) where a 30-50% increase in power usage is estimated for buildings following the ASHRAE recommendations. We implemented these by scaling up the baseline chiller power demand by 40%. The same analysis is repeated from here, and we find the estimated chiller power costs for Open-Window increased to $24,484.88. The result of this greatly decreased the time for repayment to 2 cooling seasons for In-Ceiling HEPA outright, 2 cooling seasons for In-Ceiling HEPA with $500 annual service charges, 7 cooling seasons for Displacement Ventilation, and 2 cooling seasons for In-Ceiling HEPA with $1000 annual service charges.
- **Vax_Rates:** here we are looking at how our expected secondary case results change with different assumed levels of vaccination. For each, we have computed the number of expected cases for both a single 8-hour day and a 5-day workweek's worth of 8-hour days. The analysis highlights that the result of assuming different vaccination rates, is merely a scaling (due to the reduction in the population that is capable of catching the virus). It also can be observed that the number of cases for one day versus a week is five times the individual day number of secondary cases. There are some slight differences in % values due to the fact that only 2 decimals are output by default for the calculator.
- **Diff_Num_of_People:** here we look at both different loading schemes to the space and different numbers of infectious attendants to the space. We examined the impact of placing 100, 40, and 32 people in the space with 1 and 10 infectious people in attendance. From the results, it can be seen that the output is merely scaled for the different populations, where again there is some slight percentage changes due to the 2 decimal output of the model. The most intriguing finding from this sheet is that when scaling from 1 to 10 infected people attending the space, the results are not scaled up (i.e. there were not simply 10 times the number of cases). The important finding from this, is that the controls continued to reduce the number of secondary cases by approximately the same percentage, again allowing for some variation with the 2 decimal output.
- **Westaflex_Doubled_Units:** here we provide the key analytical points if we had used twice the In-Ceiling HEPA units in the space. We estimate an ACH_e of 16.7, which

would reduce the model's 0.80 secondary cases to 0.20, a 75% reduction, putting it on par with Displacement Ventilation with the 50% reduction in population assumption. In terms of repayment, due to the doubled power and upfront cost, it would take 33 cooling seasons with a $500 per year service and 165 cooling seasons with $1,000 per year service fee. The doubled In-Ceiling HEPA unit case would be the highest increase in ACH_e and the greatest reduction in percent of secondary cases from baseline.

- **West_Doubled_Power:** here we provide the energy cost calculation for the "Westaflex_Doubled_Units" sheet.

- **C02:** here we provide the details for our kg of CO_2 production calculation that was added into Table XIII.

- **HPC_Output, HPC_Power_Curve, and HPC_Calculation:** here we provide the analysis requested by Aurecon looking at a "humped power curve" for the chiller. The new power curve is provided in these sheets, as well as the updated relationship between moving three day high temperature and power. The updated power curve made the repayment period for In-Ceiling HEPA shorter (3-4 cooling seasons). For Displacement Ventilation repayment period was also shorted slightly (9 cooling seasons).

In summary, the sensitivity analysis highlights the importance of reasonable estimates throughout the document. That is, we have done our best to justify our decisions herein, but understand that other choices may have been made. However, we hope that with the accompanying spreadsheet and the explanations from this section, we have motivated that these changes would have lead to moderate alterations in results, but not drastically changed what we have detailed herein. We also would like to make a few comments that were brought up in discussion of the preliminary results:

† While our 2-degree reduction in temperature value may have been on the conservative side, due to the high cost of Displacement Ventilation, even if the reduced temperature output could have been driven to as low as 5 degrees, the repayment period will still take approximately 12 cooling seasons. We stress that this is modelling 12, identical, moderate cooling seasons. However, it is not very different from the output from our original report.

† If Open-Window were to increase the energy used by the building by roughly 40% as suggested by Aviv et al. (2021), then both Displacement Ventilation and In-Ceiling HEPA options are extremely compelling alternatives with very short repayment periods.

† To scale repeated exposure risks, simply multiple the number of projected cases by the number of times you would like the condition to repeat

† To scale with increased vaccination rate, scale the projected number of cases by the percentage immune to symptomatic exposure (this also keeps the percent change approximately constant, so that would be the take home parameter)

† The only non-intuitive result that came about from our sensitivity analysis was how to scale a change of % of working population infected. Instead it is best to repeat the calculations for the space modelling the conditions desired. We give this guidance

because as the number of people with the virus increases, the potential population that can catch the virus decreases, so there is a point where fewer secondary cases would arise but there would be more primary cases. These are strictly "worst case scenario" type estimates that are best done on a case-by-case basis.

† For the humped power curve, the estimated chiller power usage goes up for all cases. The new range of chiller power usage costs (assuming $0.28/kW-hr) are from $21,509 to $28,746 with the same ordering of costs (Open-Window most expensive and Displacement Ventilation the cheapest). While a change in costs of approximately 50% is slightly larger than what is expected in a sensitivity analysis, the fact that the results are similar to those of our primary analysis with the very different underlying power curve upon which all results are based, is an overall pleasing result; suggesting robust findings with these sorts of findings. However, we did find that a flat power curve on the low demand (i.e. one that does not tend towards zero as power usage falls below a given threshold, instead it flattens out and remains constant), was not one we could build a power-to-temperature relationship to. We were not able to perform a regression based on the power outputs that had an R^2 value above 0.25.

A Computational Results

The computational simulation videos referred to herein are available to view/download on OneDrive at: https://unimelbcloud-my.sharepoint.com/:f:/g/personal/grant_skidmore_unimelb_edu_au/Ejpik3UjeXpJhrOxJjzPNlsB1JQdaQQsza6_02rRbj1e3Q?e=Ar2noi.

The computational simulation videos demonstrate similar results to the experimental work, suggesting a robustness of these findings. Those key findings for each control are: for baseline case, aerosols spread uniformly throughout the space before slowly leaving through the air-return. For the Open Window case, both experiments and simulations found that aerosols still mixed throughout the space (owing to the mixing ventilation) but many aerosols quickly left through the windows due to the reduced pressure outside. For In-Ceiling HEPA filters, both experiments and simulations highlighted their efficacy but through different means. The experiments focused on their ability to clear a room of infected aerosols whereas the simulations showed how they were capable of ingesting most of the aerosols released by one infected person (some aerosols were mixed throughout the space due to the underlying mixing ventilation, but the quantity of aerosol was much less than the baseline case). Finally, both were able to demonstrate the efficiency of Displacement Ventilation. For the experiments we did this with a simulated cough, whereas the simulations highlighted how an infected person breathing would have their aerosols travelling almost vertically towards the ceiling.

Additional information on the computational setup, code, and underlying assumptions used to generate these simulation videos are provided on the following pages.

BREATH (Building Retrofit for Efficiency, Air Quality, Thermal Comfort and Health) Computational Research Project

Tony Zahtila,[1, a)] Zijin Cheng,[1, b)] and Andrew Ooi[1, c)]
University of Melbourne
Department of Mechanical Engineering
4th Floor Grattan Street
Parkville, VIC 3010, Australia

[a)]Electronic mail: tony.zahtila@unimelb.edu.au
[b)]Electronic mail: zijinc@student.unimelb.edu.au
[c)]Electronic mail: a.ooi@unimelb.edu.au

I Computational Setup

The results in this project were computed using the open-source software, OpenFOAM. This package allows trajectory-based prediction for indoor dispersion of contaminated particles expelled by either human coughs, sneezes or breathing. The flow field is realised by solving the incompressible Navier-Stokes equations, where buoyancy-driven flows induced by temperature gradients were included in the momentum equations via Boussinesq approximation. In this case, the governing equations are expressed as:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + Pr\nabla^2 \mathbf{u} - RaPr\Theta \mathbf{e_g} \tag{2}$$

$$\frac{\partial \Theta}{\partial t} + \mathbf{u} \cdot \nabla \Theta = \nabla^2 \Theta \tag{3}$$

where $\mathbf{u}$ is the three-dimensional velocity field vector and p is the pressure field. $\mathbf{e_g}$ is the unit gravitational vector. Ra, Pr, $\Theta = (T - T_0)/\nabla T$, denote Rayleigh number, Prandtl number, and the non-dimensional temperature, respectively; t and T are the dimensional time and temperature, respectively. A standard unsteady Reynolds-averaged Navier-Stokes equations (URANS) turbulence model was applied to predict the effect of turbulence, which is the tendency for air motion to be highly complicated and curvy, rather than linear.

The computational domain (see figure 1) was modelled based on one floor of a building on Bourke Street (see figure 2). Note that only half of the floor was modelled, and the computational domain is approximately cubic box with a size of 13m × 12m × 3.25m. Windows were on the front side of the room and the HVAC system was installed on the ceiling (see figure 1). Two columns (0.6m × 0.6m) were at the centre and the right side of the modelled domain in figure 1, respectively. The computational domain was discretised into a series of structured and unstructured 3-D elements using Finite Volume Method (FVM).

The flow generated by cough was modelled as a continuous jet at a constant flow rate, which lasted for approximately 3 to 5 seconds, and an average volumetric flow rate gathered from prior studies was applied. The diameter of the virus particles from the cough ranged

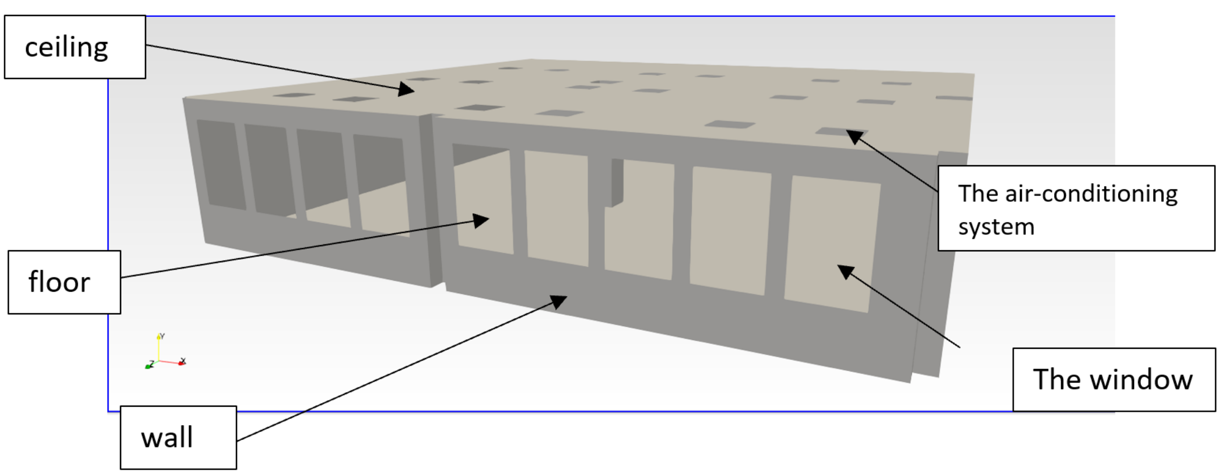

FIG. 1. The computational domain.

FIG. 2. The modelled floor of a building on Bourke Street.

from 2μm to 20μm, which is most of the respiratory size range. The trajectory of the particles was initially released at the person's mouth and driven by drag of the airflow and gravity forces. The particles were set to be sticky and massless so that there was no rebound when the particles hit any objects, rather they adhered to surfaces upon contact. As the computation domain did not include the area outside the floor, the trajectory of the particles stopped once it hit the boundaries of the room.

In this contamination study, the temperature field of the room was assumed to be affected by the heat released from the coughing person and the body temperature of other people in this floor. In this case, the heat released from the other people were simplified to be a lumped heat source of a higher-temperature floor. A constant surface temperature was applied to both the coughing person and the floor of the room. A constant inlet air temperature was also applied to the inlet duct of the ventilation system to simulate the cooled air. Temperature of the walls, ceiling and windows was set to be zero-gradient, $\nabla T = 0$.

In this study, four scenarios were considered. These scenarios are available online to view at , and will be kept online until the end of 2022. The details of the scenarios are: 0) In scenario 0, the baseline case was computed. The windows were assumed to be perfectly sealed and the mixing ventilation was employed. 1) In scenario 1 (Open-Window), the first altered condition was computed. The windows were assumed open, and a constant exit pressure was assumed. The HVAC system was ventilating the air in the room and the volumetric flow rate of each air duct was set to be approximately 400-CFM, which is an average flow rate for residential buildings. The geometry of the air ducts was simplified and the direction of the flow from the air ducts on the ceiling was assumed vertically towards the floor. 2) In scenario 2 (Displacement Ventilation), the windows were closed, and the air ducts were replaced by a set of vertical ventilation pipes (A volumetric flow rate of $130\text{m}^3/\text{h}$ approximately). In this case, the ventilation inlets were extended from the ceiling to 30cm above the floor. To observe mass conservation, the air was assumed to exit from the leakage on the ceiling. Note that to minimise the grid resolution sensitivity and mesh size gradient,

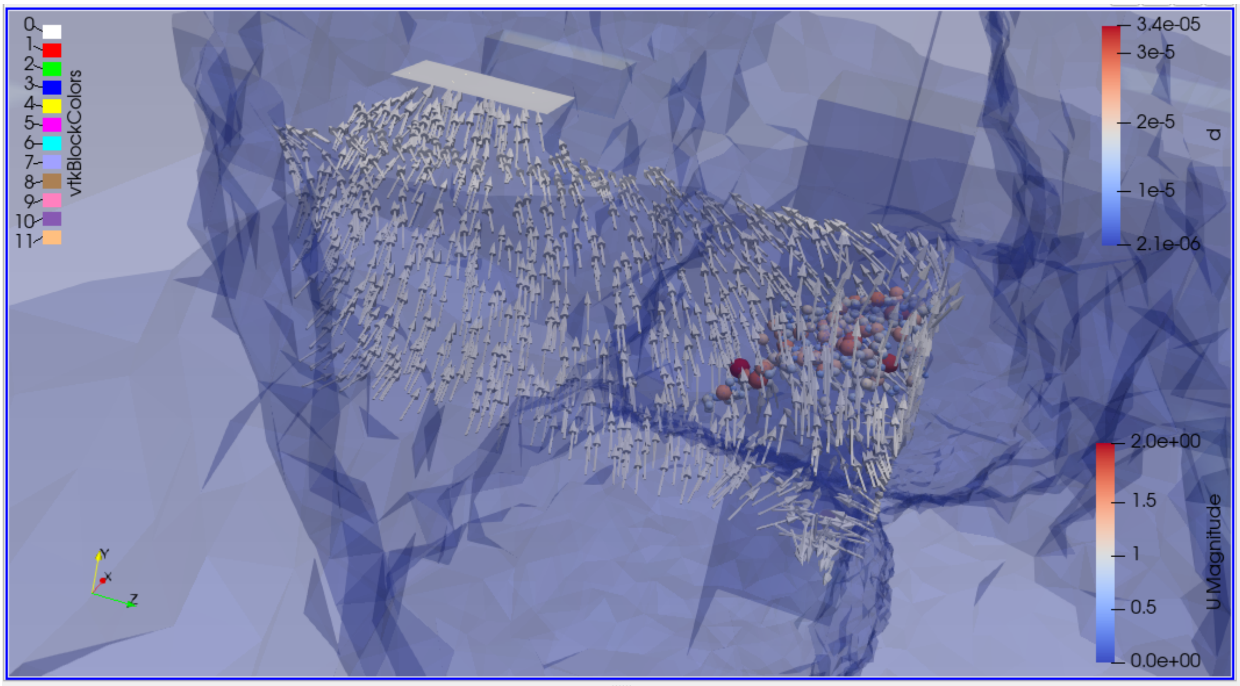

FIG. 3. Streamlines near the modelled purifier.

the leakage was combined into three outlets on the ceiling so that larger unstructured mesh elements and smaller mesh size gradients were able to be applied and a stabler simulation was achieved. 3) In scenario 3 (In-Ceiling HEPA), the boundary condition was developed from the baseline condition. In addition to the baseline scenario 0, extra five purifiers were installed on the ceiling and each of the purifier circulated at a constant volumetric flow rate of $500\mathrm{m}^3/\mathrm{h}$. The flow was sucked by the purifiers vertically and ejected at an angel of 45^o to the ceiling. In order to further highlight how wide of an area the purifiers are able to ingest aerosols from, we have generated streamlines in the vicinity around a purifier in figure 3. In the figure, it can be seen that the aerosols from the simulated cough are split between being heading towards the purifier and being mixed throughout the space.