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Abstract: The BREATH (Building Retrofit for Efficiency, Air quality, Thermal comfort and Health) project was a research pilot led by the City of Melbourne in partnership with Cbus Property, the University of Melbourne, AG Coombs, SEED engineering, AURECON and Westaflex. It was a rapid retrofit project that tested various air conditioning and ventilation retrofit options with the express purpose of reducing airborne particulates and infection transmission, but also considering the energy and cost consequences. The work was undertaken within an existing building. Open windows, conventional air conditioning, ceiling-mounted HEPA filters, and displacement ventilation were included in this initial pilot. Personal air was also showcased but not integrated into the overall research. Results indicate that some recommendations to reduce transmission may have impacts on power demand. Leaving the windows open on a floor of the 10-story test building led to an estimated 12% increase in air conditioning energy consumption. The best option for reducing transmission risk and improving energy consumption appeared to be a low-level displacement supply air system; provided the workers exercised social distancing and the stratified room temperature profile was maintained. The lower energy consumption of displacement ventilation was estimated to increase the NABERS rating of the building by 0.5 stars. The most cost effective and simplest approach to improvement was in-ceiling fan filtration units, these reduced transmission risk with minor increases in energy consumption if appropriately dimensioned. This paper looks at what these possible interventions mean for office buildings retrofit improvement.

Keywords: Air Quality, HVAC, Energy and cost.

1. Introduction

The primary objective of this pilot study project was to examine, for the first time, the impacts of the energy demand of various building ventilation retrofit options that could be used to reduce the risk of aerosolised viral spread. Particular attention was 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).

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This paper details the results from the experiments, summarises the insights gained, and provides recommendations for what this could mean for building retrofit and future research. Before presenting the results and conclusions, the paper outlines the approach, assumptions, and data models that used.

The literature and experience have shown that how a buildings air-conditioning works is a significant contributor to the spread of aerosolised viruses (see review of all paper written since 2007 in Thornton *et al*., 2022; and from a medical perspective Correia e*t al.,* 2020).

A recent paper looking at the impact of the ASHRAE recommendations to minimise COVID-19 transmission looked at the recommendations of increased air rate changes, flushing buildings, no recirculation and HEPA filter machines, showed a potential jump of 30-50% in energy consumption (Aviv *et al*. 2021). For Melbourne for all the metropolitan office buildings this would mean a potential increase of up to 420Gwh of energy and 419,022tonnes CO2e (11% increase) (City of Melbourne, 2020).

For well insulated buildings, it has been established in the literature that for well insulated buildings, ventilation loses are the main cause of energy loss (Stabile *et al.*, 2019). Thus, one would expect for a given building configuration (in terms of insulation), a ventilation retrofit would provide the largest remaining energy savings.

For residential buildings, Kang *et al.* 2022 found that ventilation retrofits can improve indoor air quality by a statistically significant amount, for a relatively minimal upfront cost (maximum of US$4222, with an average total cost of US$2,346). This study was conducted over two years, with one year as a baseline and one year in the retrofit configuration. While the energy analysis from that study is forthcoming, it does highlight that relatively cheap ventilation retrofits can lead to large improvements in indoor air quality.

There are options for healthy retrofits though that can turn this increased impact into a decreased outcome. Using available technology it is possible to rapidly retrofit commercial buildings to use the displacement and radiant thermal comfort options. This could reduce energy consumption but significant amounts, improve comfort, productivity and a sense of safety (Aviv *et al.* 2021). Meanwhile providing jobs for installing the systems and further economic activity around the production of the technology.

In the review of the literature there were no papers of experiments that looked at COVID-19 transmission, clean air provision and energy use for commercial buildings. Given the urgency of this problem, it was a pilot study was proposed examining one floor of a building in Melbourne.

2. Methods

2.1 Experimental Details

The building was 423 Bourke Street, owned by Cbus Property, the project team where given access to the building early in February 2022, a short-term peppercorn lease was agreed on with all the usual tenant requirements. Two floors were used for the study, the tenth floor to test the real-world context of how air moves in a space based on the existing HVAC system. The space has office spaces, meeting rooms, desks, partitions, and all the normal office furniture. The first floor was vacant of furniture and a last 356m^2 space where four conditions could be tested:

- baseline vacant operation (full floor)
- open window operation (full floor)
- in-ceiling HEPA filtered operation (1/2 floor north section)
- column based displacement ventilation operation (1/3 floor south-east section)

2.1.1. Baseline Vacant Operation (full floor)

To start with, the experiment determined the baseline power usage of the vacant space as well as the equivalent-air-change-per-hour (ACHe), value of the space before retrofit modifications were made. The research methods used in this pilot were to collect data on air changes using the aerosol clearance method (*Lee et al.* 2022) and directly measure energy consumption of the chiller with a non-contact ammeter. The aim was to enable a determination of the correlation between chiller power usage and air-conditioning power needs in response to space needs.

The existing HVAC system included a Turbocor TT300W-100-H6 using R22 as coolant for the chiller, air provided through constant delivery, through a standard ceiling duct lay out with supply diffusers in the ceiling and extraction through the ceiling cavity. The weather for the site for Feb-May 2022 was moderate for a South-Eastern Australian summer; with daily high-temperatures for those days experiencing a maximum-high of 38°C, minimum-low of 11°C, average of 22.4°C, and standard deviation of 4.9°C.

The space was vacant, so the energy contribution of people and equipment was created through discrete heat sources. The discrete heat sources were large buckets of water, with commercial aquarium water heaters. The heat load added to the space was a total of 1600Watts evenly distributed throughout the space (on chairs to simulate seated person height). This was determined as a good proxy for the heat emitted by 10 people; each person emitting approximately 80-100 Watts and an additional 60-80 Watts per person for IT equipment.

Specifically, the 1600Watts of heat was generated through two 300Watt and five 200Watt 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 constantly outputting their rated maximum heat.

2.1.2. Open Window Operation (full floor)

The project was specifically interested in the ASHRAE and other recommendations around opening windows, increasing air changes and flushing the building. Given the pilot nature of the research, the fact that building was being demolished within three months of the research starting. Further, that there were still tenants on some floors of the building and there was a limited budget, the research team determined that the recommendation that has the highest correlation between energy and infection transmission risk was opening the windows. Therefore, the component investigated was opening windows and running the HVAC system to meet comfort conditions. The data gathered allowed the impact of opening windows to be examined while leaving the HVAC running in its standard operating mode, in this case 19-21% outdoor air and the remainder recycled indoor air.

The building had a more than typical percentage of wall space of operable windows. As such every-other-window on East-facing wall was opened (resulting in eight 1.0-m by 1.6-m windows being opened) to meet the ~4% floor area window-opening guideline. Windows were opened on only one side of the building prevented crossflow, which is known to markedly increase air exchanges, but is rare in commercial buildings. Further, to the east of the building, there is another building less than 10 meters away sheltering the research building from easterly winds.

Part of the research intent was to be realistic and effective for industry decision making, the research team calculated preliminary high-level costs and pay back calculations based on capital, operational and maintenance expenditure and energy use. Factors not considered were health, absenteeism, productivity, and other associated savings from improved indoor air quality. For the case of opening the windows the

assumption was that there were no upfront costs, acknowledging that if a building without operable windows wanted to consider this option there would be significant costs in retrofitting the façade.

2.1.3. In-Ceiling Filtered Operation (1/2 floor)

The research design initially aimed to install five locally made fan-driven HEPA filter units mounted into the ceiling to filter the air. However, because of the realities of running a real-world experiment in a working building it became necessary to run the displacement and the in-ceiling experiment concurrently. This resulted in three units being used. The spaces were divided by floor-to-ceiling construction plastic.

In assessing the existing ducting and HVAC system it was found that there was not an even distribution of air supply. The implications, therefore, for splitting the experiment was that air change rates in each of the sections were different, requiring the researchers to collect data on the air changes for each sub-space. Direct comparison of the three conditions was not possible for this reason, so linear scaling for each condition was employed.

The in-ceiling HEPA units were low power devices (measured at 60-Watts), equivalent to the fan/filter power of a portable HEPA filters but allowing BMS integration, making them a more commercial and generally applicable solution to the problem of increasing the ACHe. The filters in the in-ceiling HEPA units need ongoing replacement to ensure their effectiveness and this was taken into account in the calculations of the cost of this option.

2.1.4. Displacement Ventilation Operation (1/3 floor)

The air-conditioning partner for the research was A.G. Coombs. They conducted HVAC system measurements and designed and installed the displacement units. Displacement systems do not require air to be supplied at the same temperature as mixed ventilation systems. For this reason the air was introduced at 20◦C at floor level. The air coming from the mixed system at the ceiling level was measured at 18◦C, this is higher than usual mixed ventilation supply air which is usually 14-16◦C depending on system design, ceiling height, etc.

2.2. Experimental Approach

The baseline air changes per hour measurements were carried out over four days taking three measurements a day. The intention was to take these readings consistently in the morning, mid-day, and close-of-business. During these readings the research team recorded 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, the intention of this period was to capture different weather conditions over the four days. For outdoor ambient air temperature the research team used meteorological data, external conditions were reported in the building management system, but the data was incomplete.

2.3. Limitations of the study

There were many elements of this pilot project which need to be considered in reviewing the results. Below each of the elements is discussed and how the research team worked to still ensure outcomes have validity and reliability. In summary this was a pilot project intended to inform industry, working in a real building, with the limitations of non-laboratory and controllable variables.

One of the main limiting factors was that the building was still occupied on several floors. This meant that altering the air handing and comfort systems of the buildings was limited. For the displacement ventilation component the supply air needed to be increased, but as this would increase the (centrally controlled) supply air for all tenants, measurements could only be taken in the mornings before tenants arrived. The tenants also worked across some of the weekends, eliminating the option of weekend 9am-5pm testing.

The second limiting factor was the research was being conducted during the first months of 2022 where COVID-19 was still having significant disruptive impacts on part of the experiment. This added to the need to be agile in research adaptation to whatever problem arose. The hard deadline of the building being demolished did not change, so any COVID induced delay potentially limited data collection. Key problems were supply shortages of the in-ceiling system which meant that the suppliers and researchers had to create an adapted version that was not able to sit flush with the ceiling as was intended.

The third aspect that is of note is that as the building was being decommissioned, so management response was at times not conducive to timely data collection. Several times fire alarms were triggered shutting down the HVAC systems at critical research times and taking significant time to be reset.

All of these impacted the ability to be consistent in the research design realisation of 4 days of measurements of each condition, three times per day. The research team adapted the research so that the other conditions, Displacement Ventilation and In-Ceiling HEPA data readings were taken as the space was available/possible:

- For the displacement ventilation, as the supply air temperature had to be increased, the measurements were taken early in the morning (between 0700 and 0900) on the mornings of 07Apr22, 08Apr22, and 19Apr22.
- For the in-ceiling HEPA measurements, these were taken when the space was available and free.

The implications were that there was limited impact on the air changeover measurements, but they did have an effect on power use. The strategy applied to correct for this was scaling the results up to have a full floor's worth of in-ceiling HEPA and displacement ventilation units in both costing and power.

2.4. Measuring air change rates

To measure the ACHe the experiments 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 was salt-water. In order to prepare the aerosol, the salt was dissolved into room-temperature water until the water was not able to absorb any further salt. The salt water was then spread throughout the space using a Longray Electric Portable ULV 3600E. For some measurements, the research team employed propylene-glycol based theatrical-fog as the aerosol where the intention was to capture explanatory photos or to demonstrate to the partners. Critically, for these tests the building needed to be isolated, that is the building manager needed to turn off the smoke sensors and the Melbourne Fire Brigade needed to be notified.

To carry out the ACHe measurements, a TSI DustTrak DRX aerosol monitor was used. This measured the mass density of aerosol in the space. This started at zero then the ULV fogger was used to fill the space with saline aerosols as the researchers walked around the test space ensuring uniform seeding density. This led to a large aerosol density reading on the DRX device. The measurements then continued to run

until the device read 99% of the peak reading value (or lower). This was then used with the following equation (1):

$$ACHe = -ln\,(0.01) \,/\, Time\ for\ 99\%\ of\ clearance\ (hrs) \qquad (1)$$

For the in-ceiling HEPA and displacement ventilation tests, a second TSI device was added, the DustTrak II aerosol monitor. This device also measured the mass density of aerosol. For these two conditions results were measured for both seated and standing height of a simulated office worker, 1.1-m tall when seated and 1.7-m when standing.

Initially, to look at the thermal profile and stratification of the space, the researchers used a thermal imaging camera to take a vertical temperature profile of a column (for the Baseline and Open-Window tests). It was found that there was no discernible temperature profile and found the thermal imaging camera compared well with the BMS temperatures of the space. This has the benefit that at one of the shutdown periods where there was no BMS data the IR camera was able to provide the needed data.

For the displacement ventilation testing, the researchers constructed a vertical array of Protech QM1601 thermocouples. This was built because the accuracy of the thermal profile was a critical piece of information for the displacement ventilation research.

2.5. Power Usage Assumptions and Measurements

In order for the researchers to estimate power for the space, a series of observations and assumptions were made. First, it was observed that the supply fan was always running (except when the system is in an error-state). Because of this, an assumption was made that there was a constant power draw from the supply fan, enabling it to be left of the calculations as it was constant. Secondly, because the testing occurred during summer and late autumn, heating did not impact energy consumption. From these two observations/simplifications, the power usage for the case study was determined and that this power was driven by the chiller.

As mentioned above the building had 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 were: 92.0, 46.9, and 28.8 kW of power input for running at 100, 75, and 50 percent capacity, respectively. This data was used to generate an exponential power curve with the following equation (2):

$$P[kW] = 8.7403 * exp\,(0.0232 * CapacityValue\,[\%]) \qquad (2)$$

The measurements taken by the researchers generally agreed with the curve as they were able to time amperage measurements with the BMS chiller load value. They were able to perform a sanity check on these values using a clip-on amperage meter and assuming a constant 0.7-kV voltage for the device to calculate power experimentally. For a few instances where this was checked, the measured power roughly matched the value from the literature; hence considering the greater accuracy for the literature, the literature values were used. This enabled the researchers to estimate power usage across the experiments.

Firstly, they measured the first floor while the system operated normally without intervention. For these days they correlated meteorological conditions with chiller usage and found the best correlation was with the three-day running high temperature (Figure 1). This figure also shows a plotted line of best fit for power usage for days the Open-Window configuration. Using external conditions to estimate chiller usage enabled the research to extrapolate for the days where building data was missing.

Building on Figure 1a for energy use the researchers added the energy implications of the In-Ceiling HEPA units at 60 Watts each or 300 Watts for the floor adding 7.2-kW-hr a day to the baseline state. For Displacement Ventilation, the BMS set point for air coming from the diffusers was increased from 18◦C to 20◦C that is, running the systems at 2◦C warmer. These curves together are plotted in Figure 1b.

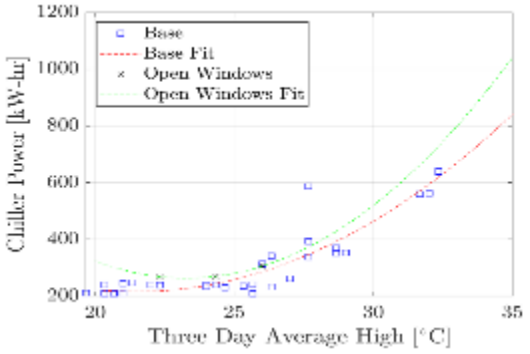

Figure 1a: Correlation between average high temperature and kW-hr used by the chiller

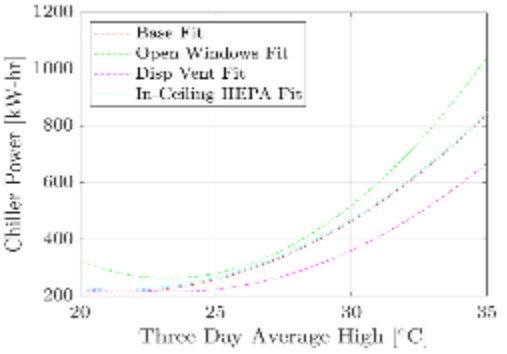

Figure 1b: kW-hr used by the chiller versus average high temperature curves for all cases considered

2.6. Cost Assumptions

To develop the simple cost benefits aspects of the research reporting, the researchers used the Australian Energy Regulator's November 2021 report on energy costs $0.28/kW-hr (AER 2021). Though the AER report speaks to residential prices, in checking with Cbus Property they reported it was at the high end of what they pay, a sensitivity was done to see impact of this on the pay back values.

Costs for the various retrofit options where: for the in-ceiling filtration, $1000 per system (x5) with a $500-$1000 a year maintenance cost to replace the filters ($500 with assumption of in-house installer and $1000 for contracted installer); and the costs for the column-based displacement retrofit was $60,000.

3. Experimental results and discussion

3.1. Equivalent Air Changes per Hour

3.1.1. Base line

The clearance plots for all baseline cases performed had some variation from run to run. Removing the outliers from these runs left the median cases that were similar enough that they could be averaged to get a sense of what a typical run looks like. Considering how many runs repeated within this range, this set of runs (and the average of their output) is considered the "true" baseline. That is, the average ACHe of the first floor of the test building is 9.1.

However, the variability of these runs does highlight an important point, despite the nearly identical conditions in the space, there was quite a bit of scatter for each run. In order to avoid biased results, the researchers excluded both the fastest and slowest runs and focus on the median tests for a given condition.

3.1.2. Open Window

For the open windows measurements there was more deviation in these runs than the baseline. The reason for this was the differing outdoor conditions (wind direction, wind speed, pressure, etc.) from run to run. The ACHe ranged from 12.8 to 77.5. Using the same approach as above the average ACHe was determined to be 20.4.

That is opening windows is an effective way of increasing the air changes (ACHe) in a space, impacting infection transmission by reducing aerosols as they are removed from the space. This is why organisations such as ASHRAE recommend opening windows. Yet as an option, this has implications on energy consumption, thermal comfort and may not be practical.

3.1.3. In-ceiling HEPA

For the In-Ceiling HEPA experiment, where the space was subdivided the first task was to measure a new baseline ACH of the space. Note that for the In-ceiling HEPA and Displacement Ventilation systems, volumetric flow rates were used rather than directly measuring the clearance time. This was because for the Displacement Ventilation option it was not possible to measure the base airflow rate of the subspace until after the retrofit had occurred. For the In-Ceiling HEPA half of the room, ACH value was 5.0 and with the in-ceiling HEPA filtration increased the average ACHe to 10.9.

3.1.4. Displacement ventilation

As mentioned, these tests required changing set points which would have impacted existing tenants in discussion with all involved it was decided to run the Displacement Ventilation tests between 0700 - 0900 on 07Apr22, 08Apr22, and 19Apr22. Enabling six full tests to be carried out.

The results showed that importance of having the right temperature profile. When this was not present the air clearance was severely impacted. Of the experiments, two did not have the correct temperature profile (top lines) because the HVAC had switched to standard operation earlier than anticipated. When this occurred, the air was cooled to a point where the installed heat load was not able to generate the requisite thermal gradient for Displacement Ventilation to operate as designed for this retrofit. These were not included in the generalised results.

The second was the impact of seated versus standing height. Based on the rate of airflow into this part of the space, we calculated an ACH of 7.4 for this portion of the room, average ACHe for seated height is 11.8 minutes and for standing 9.2. The reason for this difference is that the air is entering the space from the floor level of the room and moving up, losing momentum as it spreads and exits the room.

3.2. Quantifying Infection Risk

Infection risk is impacted by many factors, beyond what can be captured by an equation, for example, where one sits in an office, how often one walks around, how many people are in a space, and many factors that cannot be accounted for in an experiment as outlined in this paper. The calculator used came from the work of Jimenez and Peng (2022) based on the transmission of COVID19-Omicron B1.

In addition to the above limitations, the most pertinent limitation of this calculator is that it was designed for standard mixed ventilation; therefore, assumptions were needed to ensure it aligned with this real world application. For clarity and reliability, assumptions were discussed in the full report of the research (Skidmore et al. 2022), and were sense tested with the industry reference group involved in the project. Further, this was peer reviewed by AURECON. Table 1 summarises the ACHe improvements, Table 2 the transmission reduction results.

Table 26: ACHe improvements for each control. Baseline is the measured clearance rate in the space before the intervention (control). ACHe different for each, as space were different sizes

Control Name	Baseline *ACHe*	Control *ACHe*
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 2: Number of secondary infections based on COVID estimator tables

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 Vent	0.58	0.1	0.48	83

3.3. Summary of all the results

Bringing all the results together (table 3), each option reduces transmission risk. If an organisation is aiming to reduce energy, improve occupant wellbeing and reduce transmission then the displacement ventilation retrofit presents the best options. There are significant benefits and limitations to this option though which is beyond the scope of this paper to discuss. The in-ceiling filtration gives a good balance between providing reduced transmission and practicality, with its integration in to the BMS offering the ability to manage it centrally, increase and decrease as needed and cost. It's only downside being an ongoing maintenance cost.

Table 3: Summary of the results for the three tested options.

System	Impact on transmission	Cost be m2 (AUD)	Energy use – $/m2/yr	Energy
Open windows with standard HVAC operations	~53% less infections	Nil (however few office spaces have openable windows)	Costs $6/m2 per year	10-20% increase
In-ceiling air cleaner HEPA Filtration units	~49% less infections	$28m2 + $1.5-3/m2/yr maintenance costs	Saves $4.21/m2 per year	2% increase
Displacement Ventilation air conditioning	~83% less infections	$170m2 – no additional ongoing maintenance costs	Saves $10.67/m2 per year	10-20% decrease

4. Conclusion

This was a rapid research project that was enabled by the critical need for information to support building owner decision-making around building retrofit, transmission of COVID-19 and energy costs. With the limitations of the time, funding, the use of a real-world context, COVID-19 interruptions and so forth, this research aimed to give a sense of existing building options in regard to air provision in terms of COVID-19 transmission, energy use and cost of implementation. Providing safe places for people to live and work is critical, and this does not necessarily have to come at the cost of energy consumption and associated carbon legacy - this is missing from the current literature.

This paper shows that all options examined will improve 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. Though air changes is a good surrogate, in the case of displacement ventilation that provides a different type of ventilation, the benefits are not directly attributed to air changes, but as related to the physics of warm air rising reducing the distance aerosolised viruses travel. Thus, in terms of the decreased risk of modelled infection, displacement ventilation was most effective with open-window and in-ceiling HEPA options approximately equally effective at reducing modelled infection risk.

For architects the current market is shifting from new buildings to reusing existing buildings, there are a great deal of design challenges associated with this, and providing an effective design that works with the options provided in this paper is a critical part of the tool kit.

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