MINISTRY OF EDUCATION
TE TĀHUHU O TE MĀTAURANGA

The Effectiveness of Natural Ventilation

A Case Study of a Typical New Zealand Classroom with Simulated Occupation

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Foreword

The New Zealand Ministry of Education's approach to addressing ventilation in schools, as part of its response to the COVID-19 pandemic, has been informed by an evidence-based approach which includes this study's report.

In November 2021, the Ministry, in collaboration with the National Institute of Water and Atmospheric Research (NIWA) carried out a ventilation study, which confirmed that an efficient way of achieving good ventilation and reducing the transmission risk of COVID-19 is by opening doors and windows (i.e., natural ventilation).

In March 2022, the Ministry's Ventilation Programme in collaboration with the research institutes above carried out the next phase of targeted studies which were performed in an unoccupied classroom at Epuni School in Hutt City, Wellington. This study was used to corroborate a subset of the NIWA study findings by more closely studying the impacts of lower outdoor temperatures, and the effectiveness/impact of in room features including portable air cleaners as well as ceiling, extract, and supply fans.

The findings from these studies have informed our approach on managing ventilation improvements in schools.

Sam Fowler

Associate Deputy Secretary - Property Delivery

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Executive Summary

In November 2021, the New Zealand Ministry of Education, in collaboration with the National Institute of Water and Atmospheric Research (NIWA) carried out a rapid observational study on ventilation and air quality in 18 classrooms at three New Zealand schools. This study confirmed that an efficient way of achieving good ventilation and reducing the transmission risk of COVID-19 is by opening doors and windows (natural ventilation). With winter approaching (June – August in the southern hemisphere), there is a concern that fully opening windows and doors to achieve good ventilation may not be desirable or possible without excessive thermal discomfort.

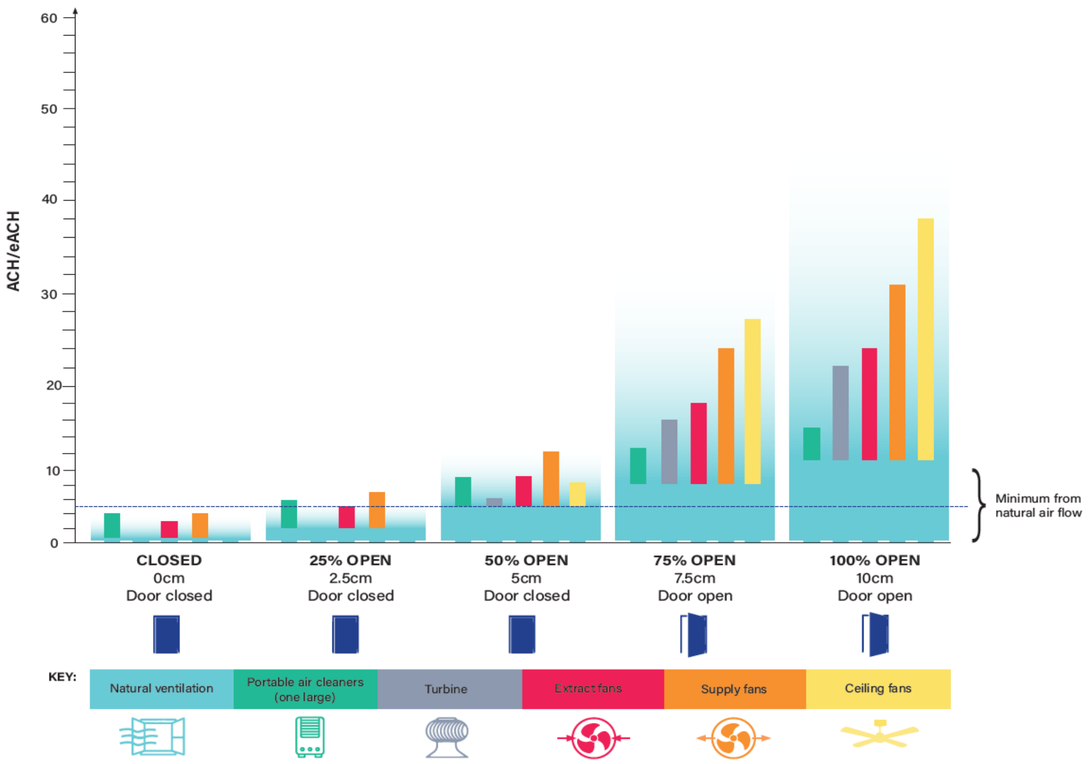
Building on the approach and findings from the rapid ventilation study, a further study was carried out in an ‘unoccupied’, typical naturally ventilated New Zealand classroom (75m^2 floor area) with simulated occupation. The aims were to assess how the ventilation was impacted by different opening areas, by differing indoor versus outdoor temperatures, and by supplementary measures such as portable air cleaners and fans. This was an urgent follow-up study conducted over a two week period to inform the winter ventilation guidance to be provided by the Ministry to New Zealand schools.

To simulate occupation, a gas cylinder was used to release CO_2 (i.e., the gas tracer method), while smouldering incense sticks were used to generate aerosols (airborne particles). The decay in concentration was observed as the gas and particles were removed from the space by the various ventilation methods being tested. Tests were then repeated on different days. From this, the actual and effective Air Changes Per Hour (ACH and eACH) were calculated for different window and door opening percentages, and for the supplementary measures.

As shown in the chart below, the study’s findings indicate that:

- In a typical classroom with an openable window area to net floor area ratio of ~10%, opening windows by 5 cm (50%) can readily achieve the preferred 5 ACH.

Impact of window opening area and the role of supplementary ventilation measures



- Ceiling fans and a turbine increased ventilation when natural ventilation was already effective (i.e., >50% of maximum openings were open) but had neither a stable nor significant impact on ventilation when only limited opening area was available.
- An exhaust fan provided about 3 – 5 additional ACH at minimal opening area.
- A supply fan had the largest effect in boosting ventilation. Although only tested on one day, it provided at least an additional 5 ACH regardless of the opening area.
- The extract and supply fans had a flow rate of 297L/s (1070m^3/hr), with variations in wind speed and direction resulting in different flow rates in practice.
- Portable HEPA Air Cleaners (PAC) provided a consistent improvement in particle removal, regardless of ventilation rate.
- A single larger PAC operating at maximum speed provided 4 effective air changes per hour (i.e., eACH), and a medium PAC provided 2.7 effective eACH.
- With the door shut, and the upper north and south windows (on both sides) opened by 50%, approximately 5 ACH was achieved.
- At 50% window opening, and with a ±10 ^{o}C temperature difference, a 6 kW heating power is adequate to maintain the temperature. During an occupied class, this 6 kW of heating would be supplied by the installed heaters (e.g., heat pump) plus body heat of the occupants (typically 2 kW for a class of 32 people with minimal physical activity) and heat-emitting equipment such as computers and projectors.

Summarily, the findings indicate that typical, naturally ventilated New Zealand classrooms can achieve good ventilation through partially opened windows, which in some cases can be assisted by supplementary measures such as fans and portable air cleaners. Though noting the study was limited in its scope due to urgency, the tests conducted suggest that achieving this level of ventilation should not significantly reduce thermal comfort.

The 'unoccupied' classroom windows had restrictors limiting the capacity of window opening and subsequential natural ventilation rates. However, if there were no window restrictors, opening the windows wider could greatly exceed the ACH rate found in this study. The results affirm the findings of the previous study (NIWA, 2022), that natural ventilation provides a wide range of air change rates, and depending on the wind speed, rates up to 60 ACH could be achieved.

Future studies could explore various ventilation technologies with natural ventilation on the same day (ideally simultaneously in near-identical control and intervention rooms), as well as under the range of wind and thermal conditions over a typical winter school day. However, the study results provide insightful findings and can, in principle, be transferred to similar situations in rooms without good natural ventilation that are occupied by more than a single occupant, such as conference rooms, waiting rooms and shared offices.

1.0 Introduction

A high proportion of buildings in New Zealand, including schools, rely on natural ventilation achieved by opening windows and doors for good ventilation. The COVID-19 pandemic has resulted in increased attention on how, through everyday actions and practices, the effectiveness of natural ventilation can be improved in indoor spaces without converting these spaces to more controlled mechanically ventilated spaces. The aim during New Zealand's pandemic response has been to maximise natural ventilation.

Achieving good levels of ventilation performance in naturally ventilated buildings will require changes to occupant behaviours, as well as an increased appreciation for what enables and what impedes good ventilation. It also requires exploring the use of supplementary technologies to understand how these work alongside or as an alternative to natural ventilation methods.

The ventilation performance achieved from opening windows (and doors) can fluctuate in real-time depending on ambient conditions including wind velocity and indoor versus outdoor temperature differences. This means that the appropriate opening of windows throughout the day is the primary determinant of how effective natural ventilation is in classrooms and other spaces.

In November 2021, the New Zealand Ministry of Education, in collaboration with NIWA, carried out a rapid observational study on ventilation and air quality in 18 classrooms at three New Zealand schools (NIWA, 2022). This study confirmed that the most efficient way of achieving good ventilation and reducing the transmission risk of COVID-19 is by opening doors and windows (natural ventilation).

However, with winter approaching, it might seem that fully opening windows and doors to achieve good ventilation may not be desirable or possible without excessive thermal discomfort. This informed the need to explore the impact of different window opening areas on the effectiveness of natural ventilation and temperature differential, and the role of supplementary ventilation technologies.

Building on the rapid classroom ventilation study, a follow up study was carried out in a typical New Zealand classroom with simulated occupation. The impact of natural ventilation was analysed as follows:

1. Quantify the effectiveness of natural ventilation by using different window/door opening percentages and ventilation methods (i.e., cross- and single-sided ventilation).
2. Identify the role of supplementary ventilation technologies (i.e., portable air cleaners, ceiling, supply and extract fans, and turbine) at different window opening percentages.
3. Assess the impact of indoor vs outdoor temperature levels at different window opening percentages.

Quantifying COVID-19 infection probability and ranking the various ventilation technologies was not within the scope of this study. Another limitation was the urgency to inform winter ventilation approaches, which restricted the study to a single classroom for a total duration of two weeks.

2.0 Methodology

2.1 Experimental Design

Carbon dioxide occurs naturally, it is non-hazardous in low concentrations, and is commonly used as a proxy for ventilation effectiveness. However, the natural concentration varies throughout the day. The measurement of high levels of CO_2 is a reliable indicator of a poorly ventilated indoor environment. However, the opposite is not true, because a low CO_2 level does not indicate clean air. This is because particulate matter and other pollutants may be present in the air even at atmospheric CO_2 concentrations.

In this study we measured both CO_2 and particulate matter in a 'Control Room' for two weeks from 28th February (late summer) to 11 March (autumn), 2022. A gas cylinder was used to release CO_2, while smouldering incense sticks were used to generate aerosols in the vacant classroom. The decay in concentration was measured as the gas and aerosols were removed from the space by tested ventilation methods. From this, the 'air changes per hour' (both ACH and eACH) were calculated for different window opening percentages, including repeats on other days. The role of supplementary technologies (i.e., portable air cleaners, fans, and turbine) in improving ventilation was also explored.

As shown in Table 1 below, four test scenarios annotated as A1–4, were carried out exploring different window opening percentages from 25% to a 100% window opening as shown in Table 1 below.

Table 1: Summary of control study test scenarios

Test Scenarios	Description	Experimental Week
A1 (Natural Ventilation)	This test explored ventilation rates with doors and windows opened to varying extents (0% – 100%), windows opened, and doors shut, cross-ventilation, and single-sided ventilation, respectively.	Week one and two
A2 (Augmented Ventilation – Fans)	At different window opening percentages, this test explored the impact of ceiling fans (bi-directional – winter and summer mode), extract fans, turbine (Roofquip whirly vent), and supply fans in improving ventilation.	Week two
A3 (Air Cleaners)	At different window opening percentages, this test explored ventilation rates and noise levels with one and four air cleaners, respectively.	Week one
A4 (Temperature Differential)	At different window opening percentages, this test simulated winter conditions to assess ventilation rates and temperature differentials.	Week one and two

2.2 Building Design and Characteristics

The study was conducted in Room One at Epuni School (the 'control room'), illustrated in Figure 1 below. The length and width of the room is 10 m by 7.5 m and is a typical purpose-built "Open Air" classroom building type. This type of block was mainly constructed between 1930 and 1965 and can be found in many schools across the country. The building is a single storey structure that is characterised by near full height and width windows (Figures 2 below).

Room Floor Plan

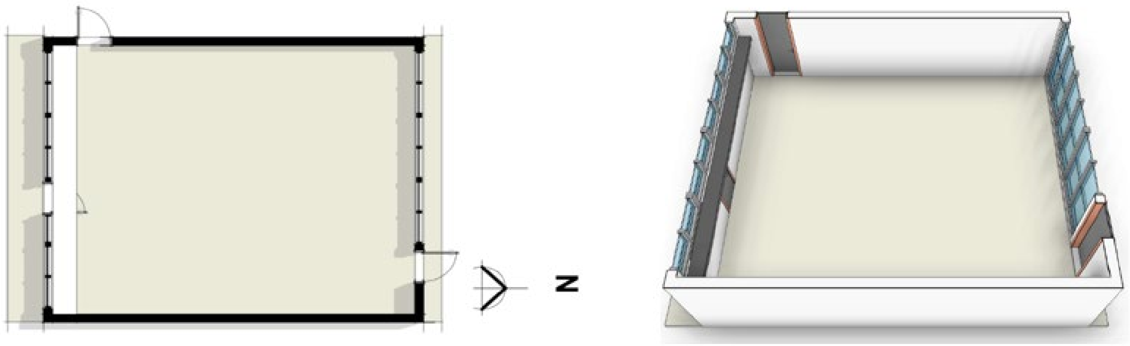


Figure 1: Plan sketches of the control room

Room Interior and Exterior Images

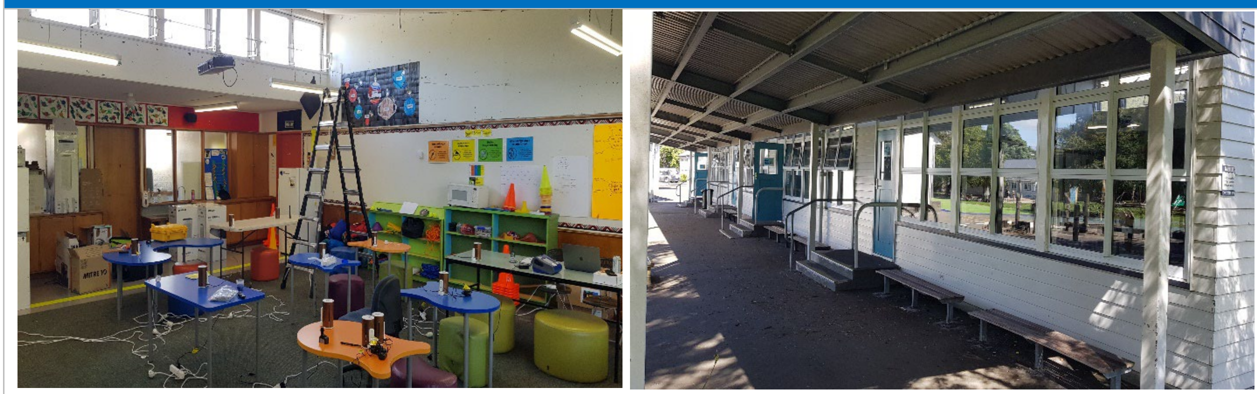


Figure 2: Images of the control room

The walls of the classroom are made of light timber framing, lined externally with timber weatherboards, and internally with plasterboard. The classroom has a covered veranda on the north elevation for solar control. The form and orientation of the classroom are arranged to allow effective crossflow ventilation with a good mix of high and low windows on the north facade, and a high-level clerestory window on the south facade.

The openable area and effective window opening area of the control room was calculated before and after temporary modifications (installed for the purpose of the study) were carried out to the windows. Table 2 below shows the modifications carried out in the second week of the study to investigate the various test scenarios.

Figure 3 below shows the classroom colour coded and annotated as A–C to illustrate the various modifications that were carried out. A bi-directional ceiling fan was used. It could be operated counterclockwise in summer to help create a downdraft, which creates a direct cooling breeze. In winter, it can be operated clockwise to create an updraft and circulate warm air around the room. The turbine was installed vertically on the clerestory window on the south facade wall with a ducted connection, clearing the ridgeline.

Table 2: Specification of fan unit modifications, size, flow rate and cost

Location	Description	Size	Flow Rate	Cost (NZD)
A	Smooth Air VEOV1250	250mm	297L/s (1070m^3/hr)	$371
B	Roofquip Straight Vane Whirly Vent (Turbine)	300mm	100L/s (At 5-degree temperature difference, 1m/s wind speed and 6m roof height)	$549
C	HPM Ceiling Sweep Fan, Summer and Winter, 3 Blade, 3 Speed Control	1200mm	2917L/s	$129

Figure 3: Control room with modifications

2.3 Window Opening Methodology

The New Zealand Building Code's Clause G4 requires that "natural ventilation of occupied spaces must be achieved by providing a net openable area of windows or other openings to the outside of no less than 5% of the floor area". As shown in Table 3, the control room study met the building code requirements with or without the window modifications. Clause G4 requires that openable window area be calculated from the face dimensions of the window, rather than from the aperture dimensions. This method differs from that used to calculate the effective window opening areas (Tables 4 – 6) in this study, which are a more realistic indication of airflow potential.

Table 3: Net floor area to openable window area ratio

NZ Building Code Requirement	Control Room (Without Modification)	Control Room (With Modification)
≥5%	14.35%	10%

In addition, the New Zealand Building Code's Clause F4 requires "areas of buildings likely to be frequented by children to have a restrictor fitted to limit the maximum opening, so that a 100 mm diameter sphere cannot pass through it". The control room window opening complies with the building code. The maximum opening of the north façade windows was restricted to 100 mm. The clerestory centre-pivot windows on the south façade, at both top and bottom opened to 220 mm.

Tables 4 and 5 and Figures 4 and 5 below show the window opening conditions and schematic window diagrams of the control room. This includes the window restrictor opening diameter, the corresponding net openable area, and the effective window opening area. The maximum opening allowed by the restrictor is categorised as 100% open. A window opened to 25% of the restrictor length is characterised as 25% open.

In this study, the 'effective window opening area' has been calculated as per Jones et al., (2016a, 2016b), which is defined as the product of the opening's free area and its discharge coefficient, taking into account the restrictor width/angle (Figures 4 and 5).

Typical discharge coefficients are around 0.60 – 0.65 for large external openings. However, there are many uncertainties when it comes to calculation of effective window opening area. This is because it is dependent on window configuration, local geometry, opening area, pressure and temperature differences (Heiselberg & Sandberg, 2006). A discharge coefficient (C_d) of 0.05 – 0.37 was used in this study to represent the ratio of effective airflow. This is notably lower than the typical discharge coefficient for large external openings because of the difference in window configuration and opening area.

Table 4: North elevation window restrictor opening diameter and corresponding effective window opening area without modifications

North Elevation Windows (Double Row)					
Description of window opening	**Restrictor opening length**	**Effective window opening area (one window)**	**Effective window opening area (twelve windows)**	**Door opening area (always at 100%)**	**Total effective window opening area (twelve windows & door)**
25%	25mm	$0.023m^2$	$0.28m^2$	$1.8m^2$	$2.08m^2$
50%	50mm	$0.044m^2$	$0.53m^2$	$1.8m^2$	$2.33m^2$
75%	75mm	$0.064m^2$	$0.77m^2$	$1.8m^2$	$2.57m^2$
100%	100mm	$0.084m^2$	$1.00m^2$	$1.8m^2$	$2.8m^2$

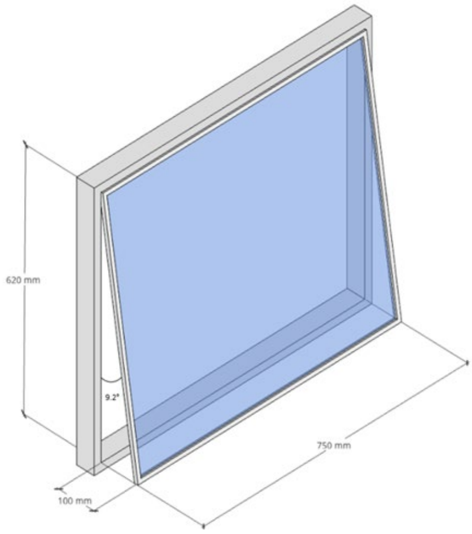


Figure 4: North elevation window design and opening ratio illustration

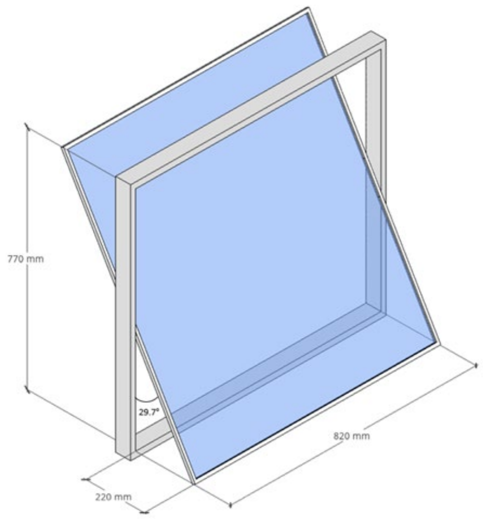


Figure 5: South elevation window design and opening ratio illustration

Table 5: South elevation window restrictor opening diameter and corresponding effective window opening area without modifications

South Elevation Windows			
Description of window opening	**Restrictor opening length**	**Effective window opening area (one window)**	**Effective window opening area (eight windows)**
25%	55mm	$0.10m^2$	$0.80m^2$
50%	110mm	$0.16m^2$	$1.28m^2$
75%	165mm	$0.20m^2$	$1.60m^2$
100%	220mm	$0.24m^2$	$1.92m^2$

Augmented ventilation equipment (extract and supply fans, turbine) was installed in place of three south façade windows for the week two test. This reduced the corresponding effective opening area as shown in Table 6.

Table 6: South elevation window restrictor opening diameter and corresponding effective window opening area with temporary modifications

South Elevation Windows			
Description of window opening	Restrictor opening length	Effective window opening area (one window)	Effective window opening area (five windows)
25%	55mm	0.10m^2	0.50m^2
50%	110mm	0.16m^2	0.80m^2
75%	165mm	0.20m^2	1.00m^2
100%	220mm	0.24m^2	1.20m^2

Before the augmented ventilation modifications, the total effective window opening area (north and south openings combined) was 2.92 m^2 (with door closed), and 4.72 m^2 (when the door was open). Cross-ventilation is where both the north and south façade windows were open. Single-sided ventilation is where the windows on the south façade were closed, and only the windows on the north façade were open.

2.4 Measurement Protocol

Measurements were conducted using using Hau-Hau™ smart air quality monitors, which measure carbon dioxide, particulate matter ($PM_{2.5}$ and PM_{10}), temperature and relative humidity. The devices are mains powered, record measurements at a user-defined rate and sends data to a cloud server using a 3G USB modem dongle. Although the device does not have any data display, an online dashboard is used to view and download both live and stored data.

As shown in Figures 6 and 7 below, nine Hau-Hau monitors were deployed in the control room in a rectangular grid pattern. This arrangement was chosen to enable the pattern of air mixing in the room to be understood, and particularly the time required for CO_2 or particulates to mix evenly throughout the air volume. All Hau-Hau monitors were deployed at approximately table height, and recorded data every five seconds. An external sensor was also placed outside in a covered veranda to record outdoor CO_2 and temperature levels, and a weather station was placed on the school site, within 100m of the control room.

Although the floor plan shows three doors, only the door in the north façade, which opens to the outside, was used to explore the ventilation rate with the door open. The door on the western side of the building opened into a breakout space and was always shut during the test. The door in the south façade opened into an adjoining corridor and was also kept closed during the test.

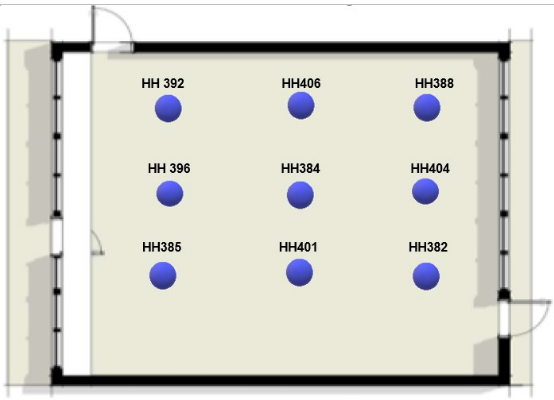


Figure 6: Plan of control room showing Hau-Hau monitor locations

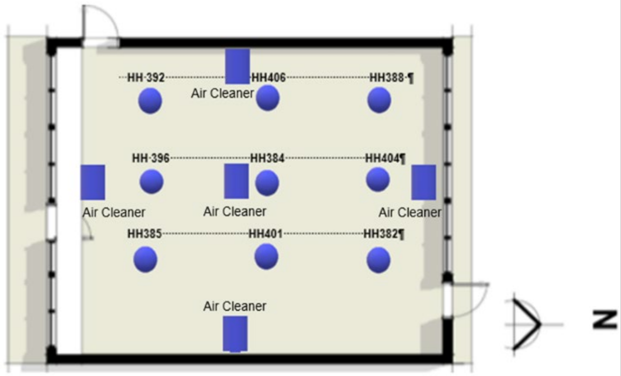


Figure 7: Plan of control room showing Hau-Hau monitor locations, the location of the three medium and one large air cleaners around the periphery, and the location of the single large air cleaner at the centre of the room.

Figure 8: Interior image of control room showing Hau-Hau monitor's location

For each test scenario, the following process was followed:

- The window and door configuration were set according to the window opening percentage in Tables 4, 5 and 6.
- CO_2 was released from a gas cylinder and incense sticks were lit to create particulates within the space.
- An approximately 6-minute period was allowed for CO_2 and particulates to evenly mix within the room.
- CO_2 decay was observed, and the room configuration was held constant for a further 10 – 15 minutes, after which the configuration was changed for the next test.
- The method was repeated for test scenarios A1 – A4.
- Across the two weeks of the study, each test was repeated at least twice on different days, to reflect changes in meteorological conditions.

In the earlier classroom study (NIWA, (2022), it was ascertained that by having the "Hau-Haus set in a grid pattern across the room, it was possible to observe the mixing time of air in the room, and hence, the consistency of each monitor". It was also shown that within six minutes, the standard deviation of CO_2 measurements across all monitors converged on a minimum value.

2.5 Reliability and Validity of Data

The CO_2 sensor in the Hau-Hau monitor had a measurement range of 0–5000 ppm, a resolution of 1 ppm and an accuracy of ±30 ppm. The $PM_{2.5}$ sensor had a measurement range of 0–1000 μg m^{-3}, a resolution of 1 μg m^{-3} and an accuracy of ±15 %. The temperature sensor had a measurement range of -40 to 85 °C, a resolution of 0.001°C and an accuracy of ±0.5 °C. Calibration was carried out before and immediately after deployment of the Hau-Hau monitors. The base CO_2 level used in this study was 420 ppm and the base $PM_{2.5}$ was 0 μg m^{-3}.

2.6 Method of Data Analysis

A Microsoft Excel workbook was used to collate the manual records of test start and end times and to align step-changes in the CO_2 and $PM_{2.5}$ data for each test scenario. The background concentration of 420 ppm was subtracted from each measurement and the adjusted data was averaged to generate a single representative measure of excess CO_2 in the room.

Hau-Hau monitors where readings substantially deviated from the others were excluded from the analysis. For each test scenario, ACH rate was calculated as the gradient of the straight line through the natural logarithm of room-excess CO_2 and $PM_{2.5}$ concentration plotted against time in hours.

Studies suggest that in a well-ventilated classroom, there should be 5–6 ACH to minimise the build-up of pathogens (Burridge et al., 2021; Dai & Zhao, 2020; McNeill et al., 2022; NIWA, 2022; Nourmohammadi et al., 2020; Park et al., 2021). Although this will not eliminate the pathogens from the air volume (pathogens will be continually emitted by the occupants, i.e., the students and the teachers), it can greatly reduce the risk of cross infection.

Classrooms that achieve more than 5–6 ACH will typically have CO_2 levels less than 800 ppm. A concentration of less than 800 ppm is “widely used as an imprecise but easily measured indicator of good ventilation” (NIWA, 2022). Hence, 5 ACH was used as the target for good ventilation, and the impact of augmented ventilation and supplementary technologies in achieving this target was assessed with different window opening areas.

3.0 Results

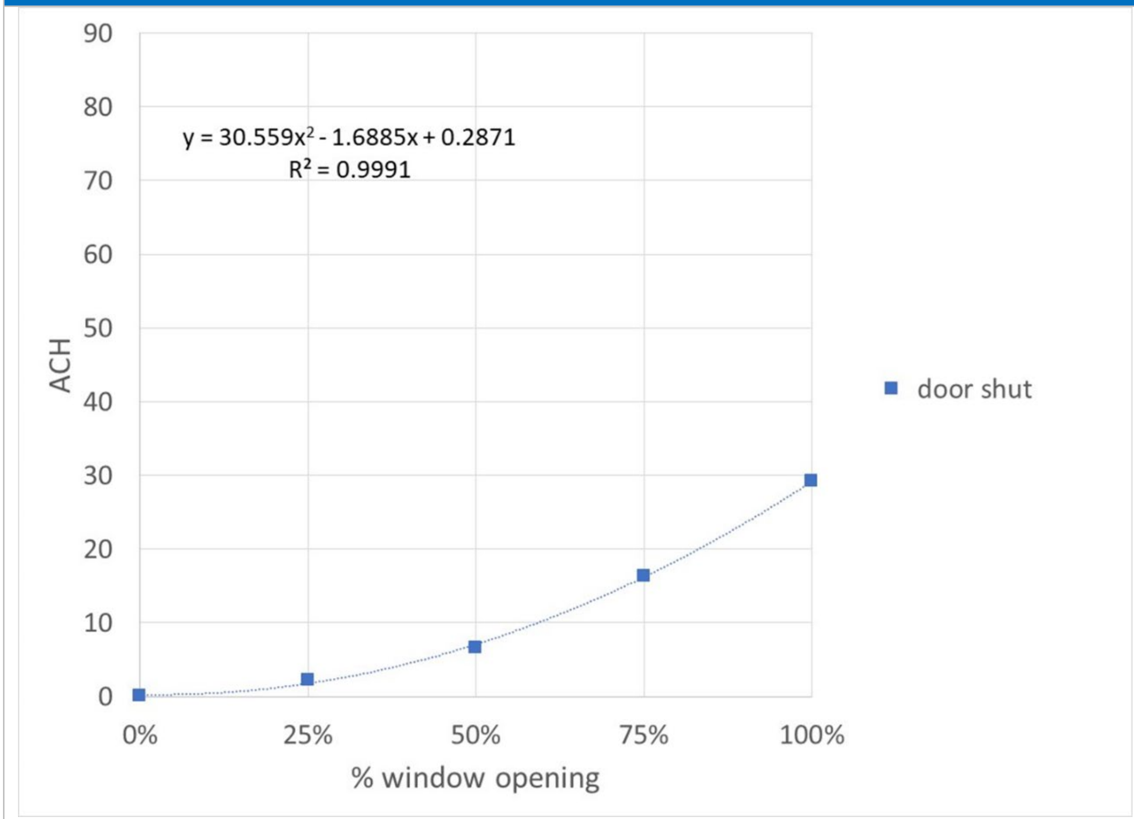
3.1 Natural Ventilation (Test Scenario A1)

3.1.1 Natural Ventilation with Crossflow

The impact of natural ventilation (i.e., with the north and south façade windows open) on the ACH rate was explored at different window opening percentages. Over the two-week period, this test was carried out on 4 separate days (1, 7, 8 and 11 March), with different control room configurations.

Figure 9 shows that, while there was generally a relationship between the ACH rate and the opening area that was best approximated by a polynomial expression, the slope of the curve (expressed by the polynomial parameters) varied from day to day. For this reason, the study results were analysed initially for individual days, and results over multiple days were then combined.

1 March



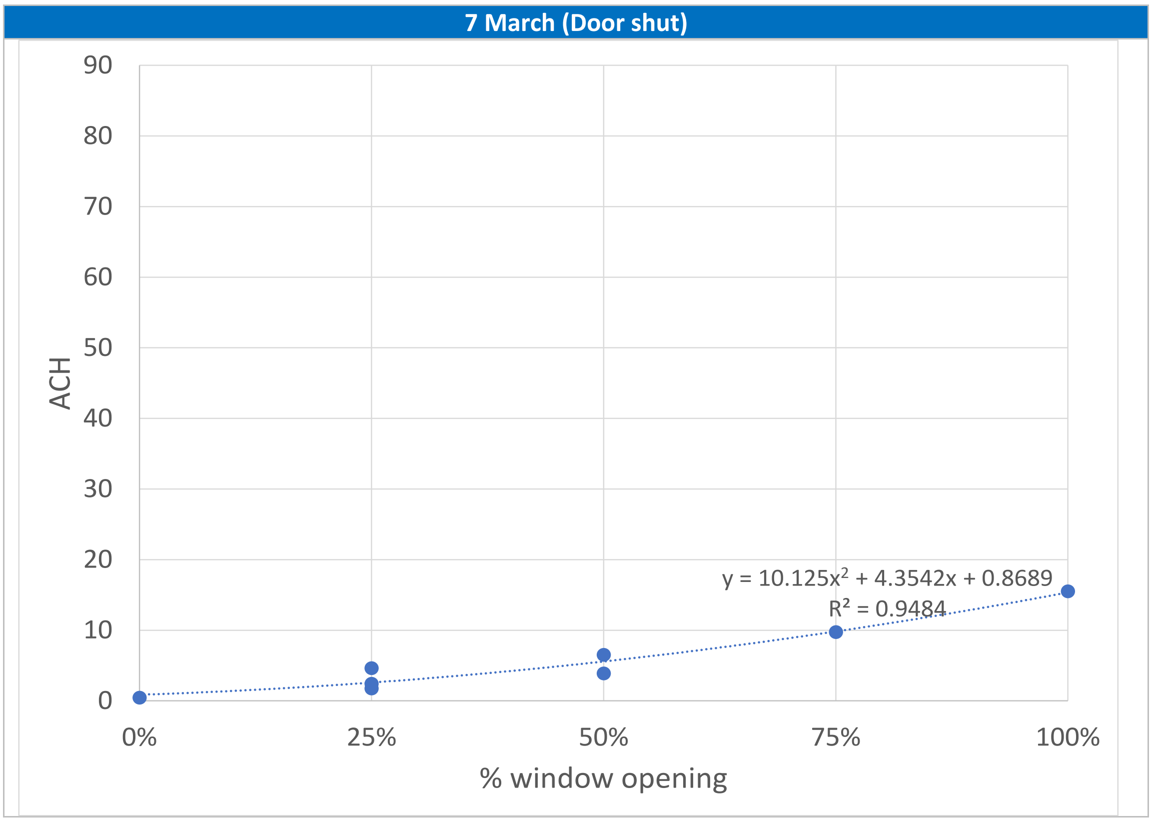


Figure 9: ACH in cross flow configuration

Figure 10 shows the polynomial best fit curves for the three days on which natural ventilation tests were conducted. There was substantial variation in the ventilation performance for the same opening configurations between the different days.

Exploratory analysis has indicated a relationship with wind speed. As shown in Figure 12 below, 11 March was the windiest day in the study with a mean wind speed of 3.5 m s^{-1} during test hours, and 7 March was the least windy of these four test days (mean wind speed of 1.2 m s^{-1}). The ACH rate was typically 2.7 times higher on the 11^{th} than on the 7^{th} for the same opening area.

Although this analysis has been unable to derive a practical mathematical expression for the modifying effect of wind, the results indicate that ventilation rate varies with wind speed, even under the same ventilation method. However, changes in both indoor and outdoor temperature may also modify the relationship between the ACH rate and opening area.

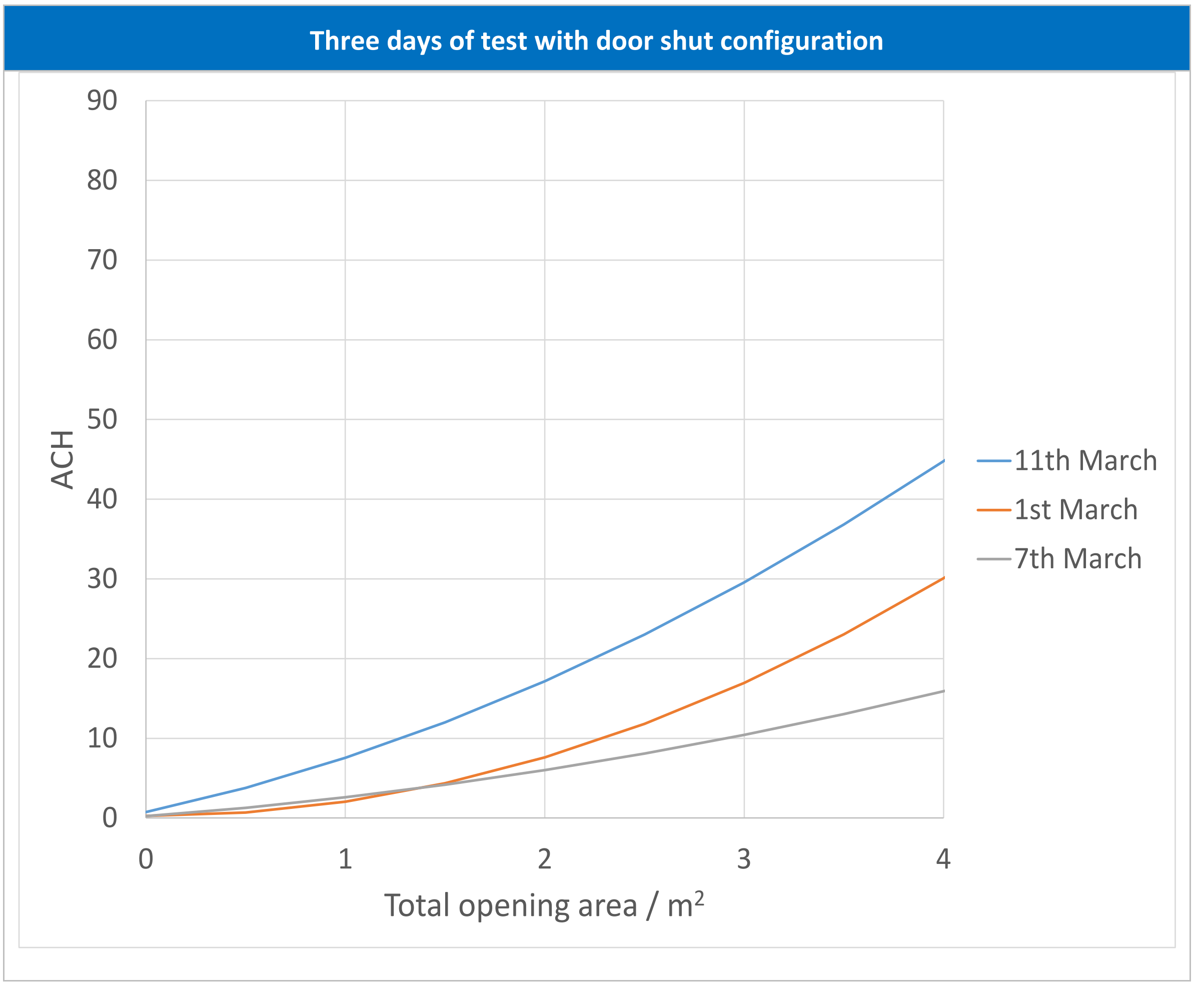


Figure 10: ACH comparing patterns between days

In Figure 11 below, all data points are approximately contained between values described by these two equations:

$$\text{Maximum } ACH = 2.18\,A^2 + 2.39A + 3.0$$
$$\text{Minimum } ACH = 0.076\,A^2 + 2.34A + 0.02$$

Whereas the mean ACH is described by:

$$\text{Mean } ACH = 2.52\,A^2 - 2.27A + 2.15$$

A simpler approximation shows that the minimum ACH rate is numerically equal to 2.5 times the total effective opening area (i.e., 1 m^2 = 2.5 ACH minimum).

Figure 11 also indicates observations of natural ventilation in the 5–51 ACH range depending on wind conditions and window and door openings. With all windows and the door opened at 100%, the highest ACH of 51 was achieved on 11 March. This was the windiest day (mean wind speed of 3.5 m s^{-1}) in the study. Given that the classroom windows had restrictors (even at 100% window opening), this suggests that if the windows are opened wider, the ventilation rate in certain conditions could be up to 60 ACH. Also, higher wind speeds than those observed during the study could lead to ACH of 60 or above.

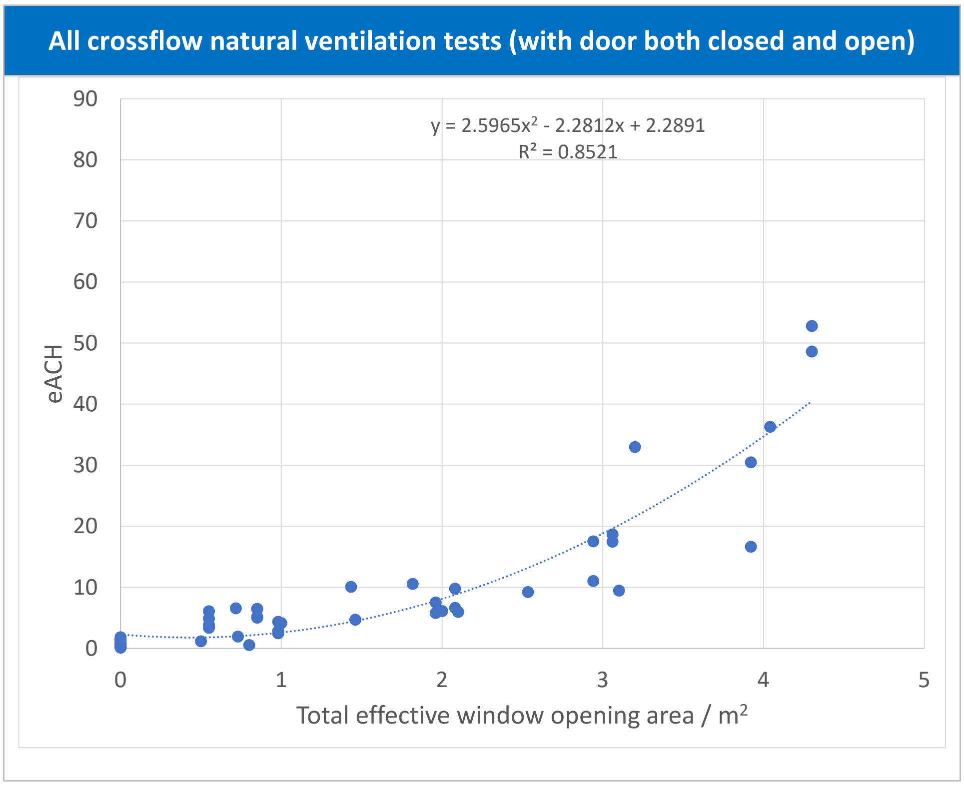


Figure 11: Combination of data from all natural ventilation tests

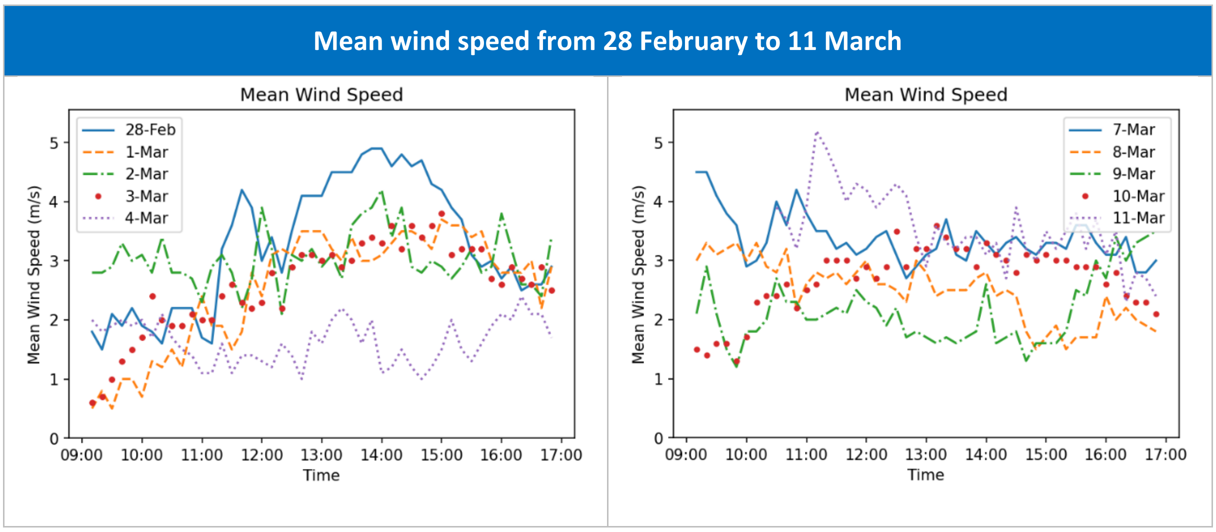


Figure 12: Mean wind speed over the two weeks of the study

3.1.2 *Natural Ventilation with Single-Sided Flow*

The impact of natural ventilation with openings on one façade only (i.e., with the north façade windows open) was also explored. In Figure 13, the results for single-sided ventilation are consistent with the relationship between the minimum ACH rate and opening area for double-sided ventilation. The wind speed during this test was 2.3 m s^{-1}, which is approximately equal to the mean wind speed during the crossflow ventilation tests. A comparison of Figures 11 and 13 shows that with the same window opening area and at comparable mean wind speeds, crossflow ventilation is significantly more effective than single-sided ventilation.

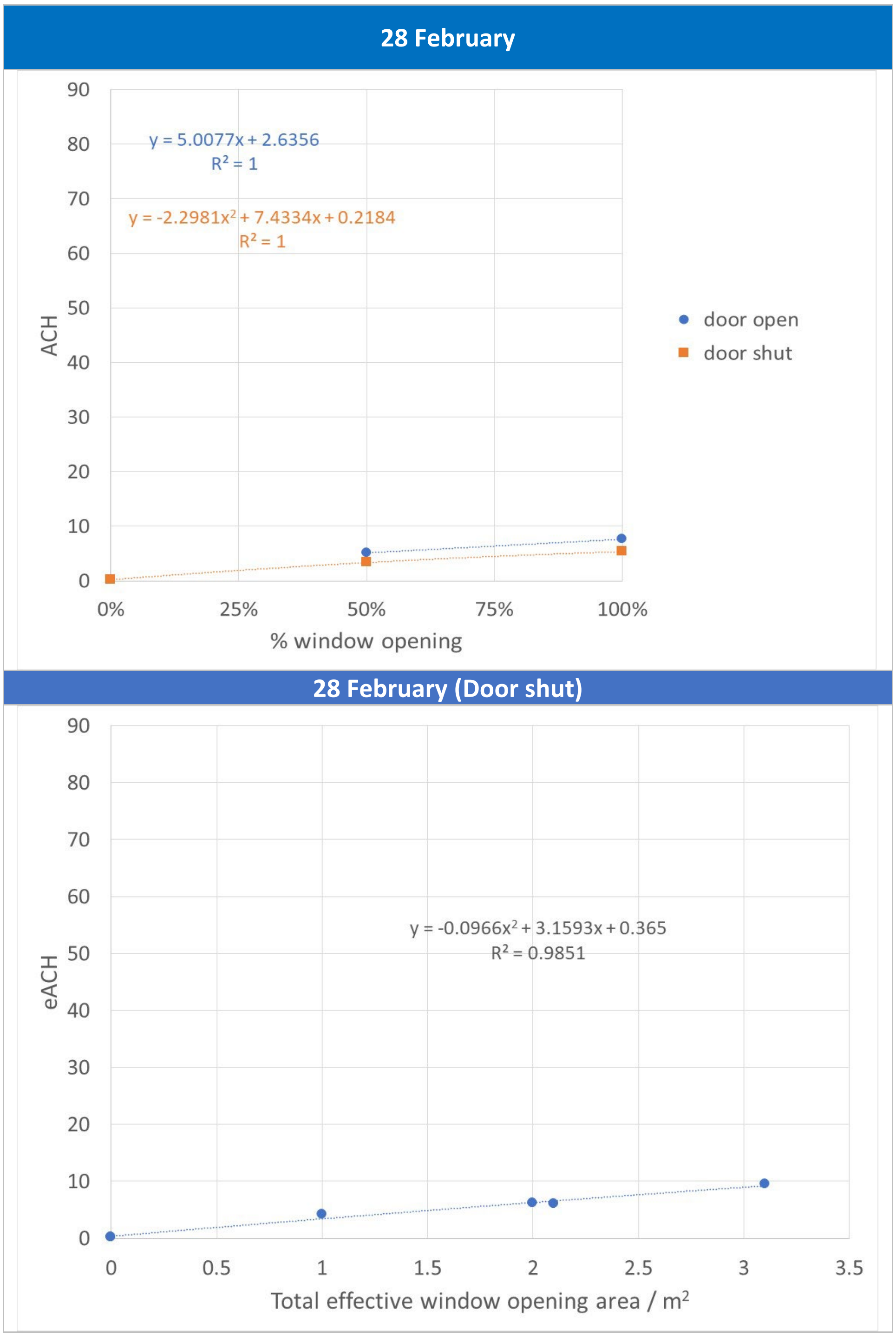


Figure 13: ACH in single-sided configuration

3.1.3 *Summary of Natural Ventilation Test Scenario A1 – Impacts on Ventilation*

The results presented above indicate that a minimum total effective opening area of around 2 m^2 was required to achieve 5 ACH in low wind conditions using single-sided natural ventilation alone (1.5 m^2 opening area achieved 5 ACH with cross-flow ventilation). In the classroom used in this study, this equates to all windows opened 50% with the door closed, or 32% with the door opened. The same opening provided up to 15 ACH on the windier days.

2^{nd} order polynomial functions have been fitted to most of the test series due to a relatively good fit in many, but not all cases. The plausibility of a polynomial expression representing the physical processes was not further investigated, so we cannot verify that a non-linear relationship between ACH rates and area is 'correct'.

However, the findings generally show that the air change rate is broadly proportional to the total door/window opening area.

The results also agree with the previous study (NIWA, 2022), that natural ventilation provides a wide range of air change rates, depending on the wind speed. In some cases, this could be up to 60 ACH.

3.2 Augmented Ventilation (Test Scenario A2)

As shown in Figure 14, and with different window opening areas:

- A supply fan (nominal flow rate 297 L/s) added 4 – 7 ACH at <50% opening area, and more at larger opening areas.
- The ceiling fans and turbine (working independently) provided more than an additional 5 ACH at larger opening areas.
- However, with openings below 25%, the ceiling fans and the turbine (working independently) added no more than 0.5 ACH and had neither a stable nor significant impact on ventilation (refer to appendices for more results).
- An extractor fan (nominal flow rate 297 L/s) added 3 – 5 additional ACH at a low opening area.

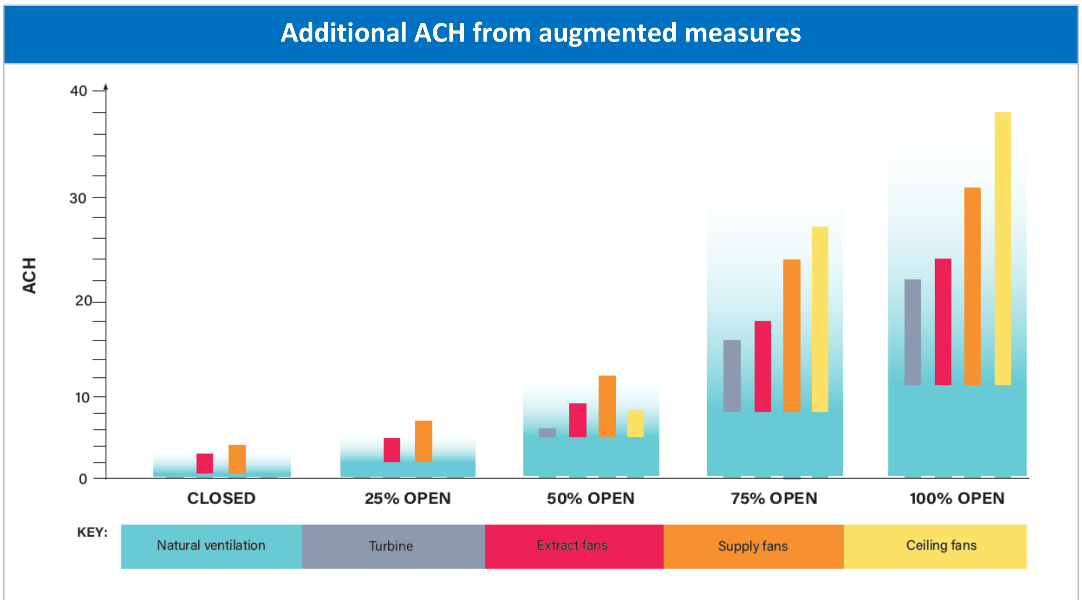


Figure 14: ACH added by different augmented ventilation methods

Figures 15, 16 and 17 show that with different window opening areas, a wide range of air change rates (from 3 to 29 ACH), straddling either side of the recommended goal of 5 ACH were achievable with different augmented ventilation methods.

The noise levels of the extract fan ranged from 59 to 60 dBA, while the noise levels of the supply fan ranged from 59 to 64 dBA, which exceed the recommended 45 dBA background noise levels (DQLS, 2020) for learning spaces. These fan selections were necessary for the test set-up, but quieter fans could be selected, with attenuation where required, for real-world applications.

10 March – Exploring different augmented ventilation methods

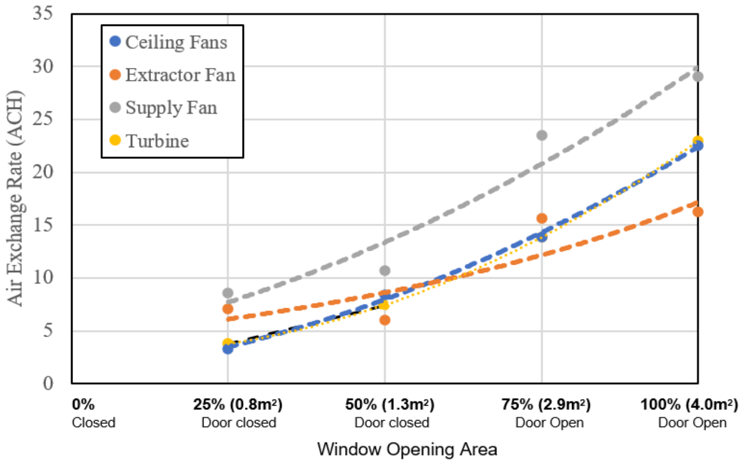


Figure 15: ACH at different augmented ventilation methods

11 March - Exploring two augmented ventilation methods

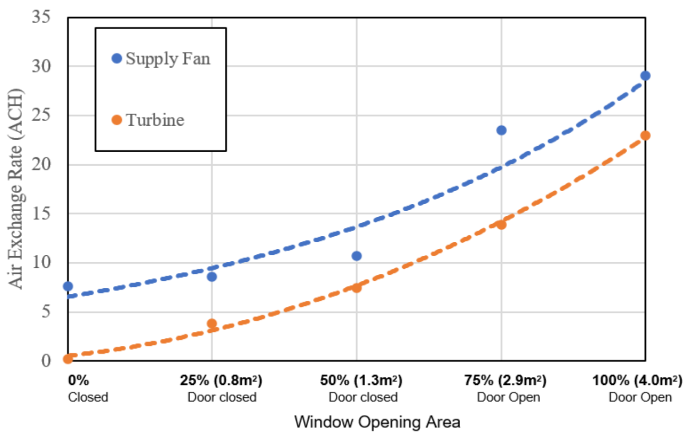


Figure 16: ACH comparison of supply fan with turbine

8 March – Exploring ceiling fans as an augmented ventilation method

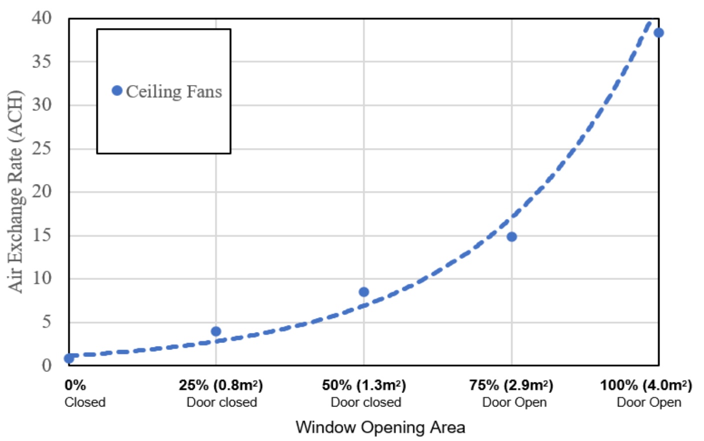


Figure 17: ACH comparison of ceiling fans

3.2.1 Summary of Augmented Ventilation Test Scenario A2 – Impacts on Ventilation

The data generally indicates that the ceiling fans and turbine tested delivered an increase in air change rate (e.g., fixed percentage improvement) which is proportional to the ACH rate, which itself is proportional to the opening area. This means that at a low degree of opening (e.g., 2.5 cm), the gain in ventilation was very small (~0.5 ACH).

However, the supply fan and the extractor fan supplied a constant absolute increase in air change rate. The extract fan provided about 3 – 5 additional ACH (relative to other tests) at low opening area. The supply fan appeared to have the largest effect in boosting ventilation. Although tested on only one day, it provided approximately 4 additional ACH at low opening area, increasing with opening area (refer to the appendices).

3.3 Additional Particle Removal (Test Scenario A3)

3.3.1 *Non-filtration Tests*

In principle, the removal of particles from the classroom air by processes other than ventilation and filtration (principally deposition to surfaces, but potentially also coagulation, evaporation, interception, and gas-particle conversion) should be revealed by a systematic difference between the concentration decay rate calculated for CO_2 (i.e., air changes per hour, ACH) and for PM (i.e., effective air changes per hour, eACH). However, in this study the average difference between ACH and eACH in tests not involving filtration was approximately zero. This suggests that the impact of non-filtration removal processes was smaller than the measurement uncertainty and that such processes were effectively negligible.

3.3.2 *Portable (HEPA) Air Cleaners (PACs)*

Two sets of tests were conducted. The first test was with a single large PAC with a manufacturer's stated Clean Air Delivery Rate (CADR) of 701 m^3 h^{-1}, giving a nominal 3 eACH in a 230 m^3 room. The second test was with three medium sized PACs giving a combined CADR of 2102 m^3 h^{-1}, and 9 eACH in a 230 m^3 room and one large PAC. All PACs were operated at maximum fan speed.

Figures 18 and 19 show that the observed particle removal rate slightly exceeded these ratings by approximately one third, providing 4 and 12 eACH respectively.

There was a very small reduction in additional particle removal at very high air change rates, but the magnitude was effectively negligible (and noting PACs are less likely to be used if high air change rates can be achieved through ventilation).

The noise levels from the three medium PACs and one large PAC operating simultaneously ranged from 56 to 59 dBA, while the noise levels from the large PAC on its own ranged from 54 to 56 dBA.

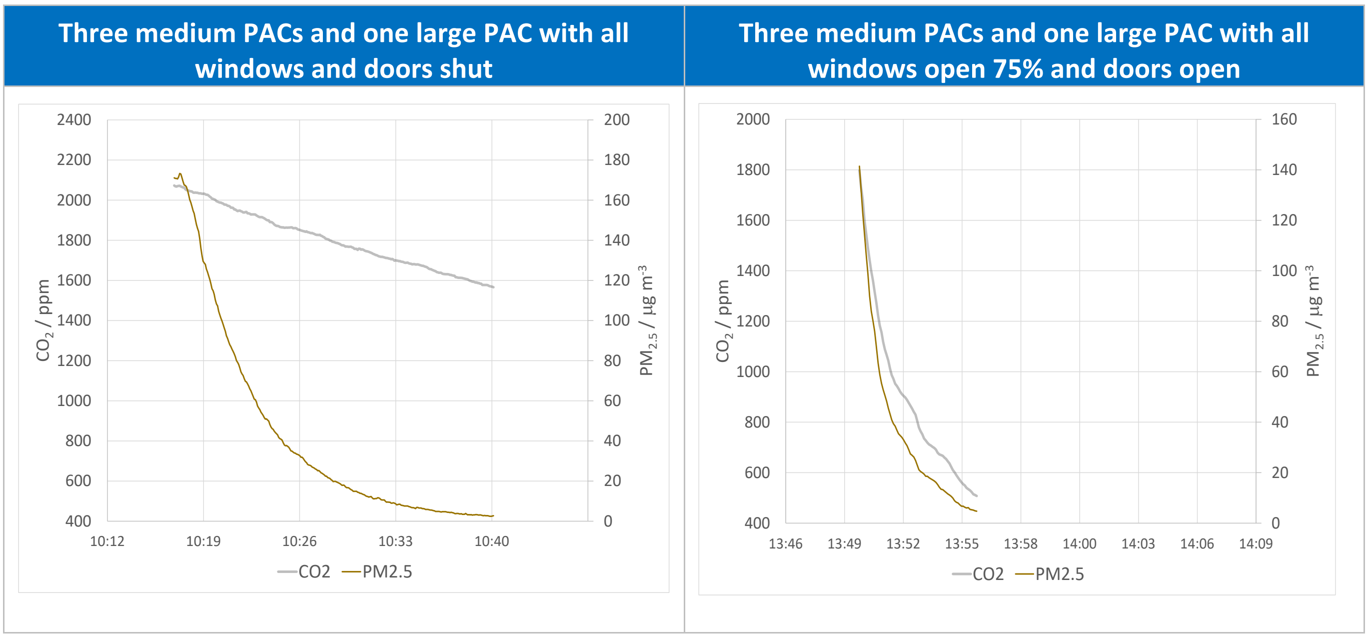


Figure 18: PAC's particle removal rate

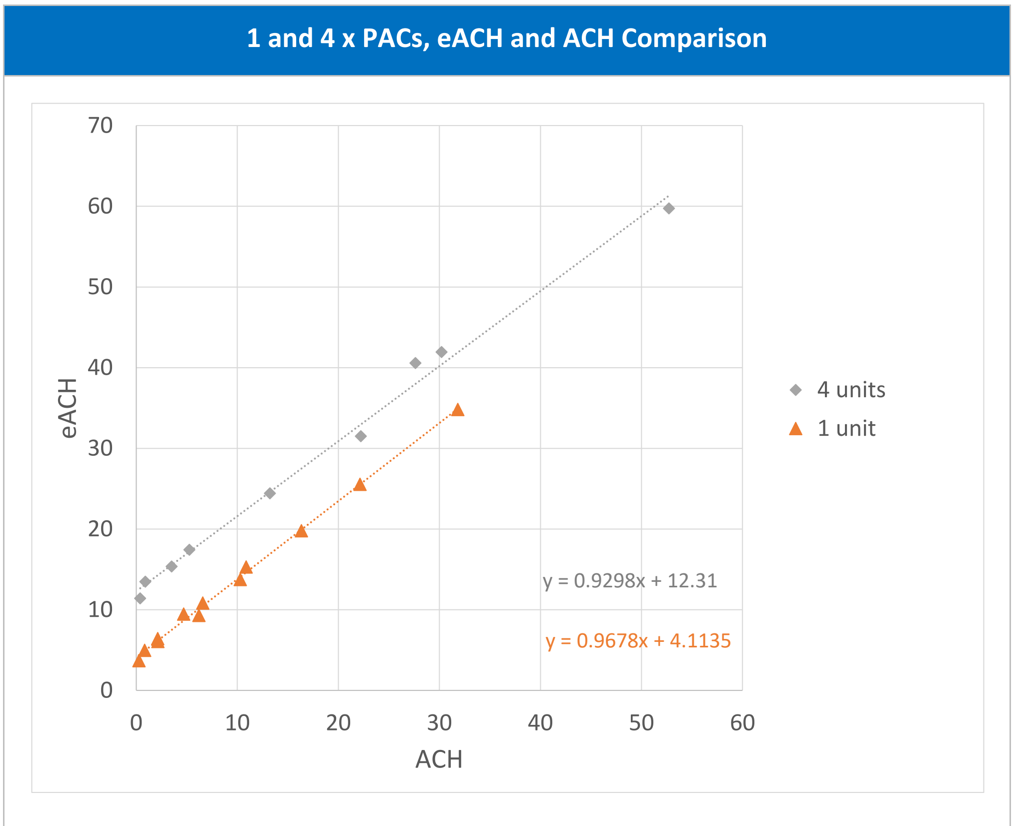


Figure 19: ACH and eACH comparison

3.3.3 Summary of Non-filtration Tests

The control room result indicates that portable air cleaners have an additive effect on decreasing $PM_{2.5}$ levels (average levels of PM are considerably reduced, which could lead to a long-term health benefit), but expectedly had no effect on reducing CO_2 levels.

One large air cleaner with a CADR of ~700 increased effective ACH (i.e., removal of particles) by ~4. This effect was independent of the natural ventilation level and wind speed. This makes a PAC roughly equivalent to an additional 1.6 m^2 of window opening (for particles only) in low winds.

The portable air cleaner's additional particle removal is relatively independent of the air change rate over the range of values likely in a classroom.

3.4 Temperature Differential (Test Scenario A4)

Over the two weeks of the study, a temperature differential test was carried out around 4 am on three different days to simulate winter conditions. Table 7 summarises the test scenarios, the ACH rate, indoor and outdoor temperature differences, and the wind speed.

The data reveals that under simulated winter conditions (with a 9–15 ^{0}C indoor/outdoor temperature difference), at 25% openings ~3 ACH rate was achieved, and at 50% openings ~7 ACH rate was achieved. With the door shut and the upper north and south windows (on both sides) opened to 50%, ~5 ACH was achieved.

The temperature drop rate in these tests are discussed in Section 3.3.2 below.

Table 7: Temperature differential test

Window Opening Configuration	ACH	Average Indoor Temperature (°C)	Average Outdoor Temperature (°C)	Difference between Indoor and Outdoor Temperature (°C)	Estimated Wind Speed (m s^{-1})
25% all windows open with door shut	3.4	22.5	7.4	15.1	0.2
25% all windows open with door shut	2.4	28.4	16.9	11.5	1.0
25% all windows open with door shut	2.5	30.3	16.1	14.2	1.3
50% all windows open with door shut	7.5	23.0	13.3	9.7	0.1
50% all windows open with door shut	6.5	28.6	16.3	12.3	1.4
50% (upper north and south façade windows only)	4.9	30.3	16.4	13.9	1.2

3.3.1 Temperature Penalties of Ventilation

Figure 20 shows the indoor temperature drop in the first 5 minutes of each test from 4am to 5pm as a standardised metric. The size of each point is the opening area, and the 'tiny' dots represent the tests when all windows and doors were closed. The graph shows the large uncertainty in comparing the ACH rate with temperature change in the short test duration.

The large temperature drop rate, which ranged from -0.4 to 0.2 °C/min, were related to large opening areas but may be independent of the magnitude of the indoor and outdoor temperature difference. The smaller dots (small opening area) scattered in a narrow range of approximately -0.1 to 0.1 °C/min indicate a lower temperature drop. The blue dots above 0.0 °C/min indicates the impact of solar gain over the course of the day.

Indoor temperature appears to drop faster if the opening area is larger. The indoor temperature fell with 3750 W heating but not 6000 W heating. However, the tests were too short to properly extrapolate them to understand what the temperature loss might be after 1 hour.

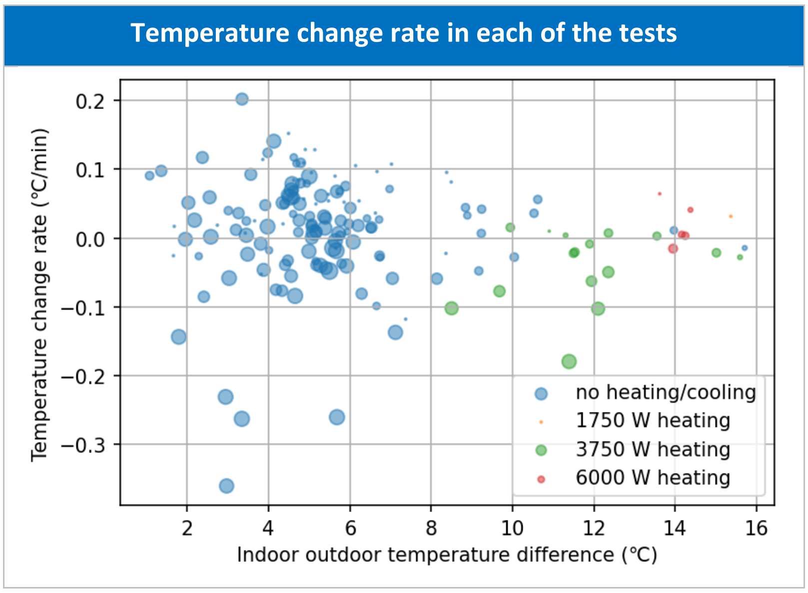


Figure 20: Temperature penalties

3.3.2 Summary of Temperature Differentials – Impacts on Ventilation

The temperature differential results indicate that on cold days, having classroom windows open by approximately 50%, with exterior doors closed, >5 ACH rate can be achieved.

In cross-ventilated rooms, and when there is ±10 °C difference between indoor and outdoor temperatures, ~5 ACH rate can be achieved by having only top level (high) windows on both sides of the room opened by 50%, with exterior doors closed. This will reduce cold draughts in the room while promoting good airflow.

The results generally show that at 50% window opening, and with a ±10 °C temperature difference (Table 7), in which tests the ACH was 6.5 to 7.0, a 6 kW heating power is adequate to maintain the temperature. During an actual class this 6 kW of heating would be supplied by the installed heaters (e.g., heat pump) plus body heat of the occupants (typically 2 kW for a class of 32 people with minimal physical activity) and heat-emitting equipment such as computers and projectors.

4.0 Discussion

The importance of sufficient ventilation for diluting the concentration of virus particles has been demonstrated by various studies in recent years (Burridge et al., 2021; Melgar et al., 2021; Nourmohammadi et al., 2020; Park et al., 2021).

Even if opening windows provided good ventilation, the ACH rate varies depending on the window opening area and positions, weather conditions such as temperature and wind, and whether single-sided or cross-ventilation is available and used.

This study explored the impact of different window opening areas on the effectiveness of natural ventilation and on temperature differential, as well as the role of supplementary ventilation technologies. The key findings are highlighted under the following headings:

4.1 Effects of Natural Ventilation in a Typical New Zealand Classroom

- A conservative low wind scenario (or minimum ACH for a given opening area) should be the basis of operational guidance on how to achieve good ventilation.
- This case study suggests that each m^2 of window or door effective opening area provides approximately 2.5 air changes per hour.
- However, this result is based on only a few days of testing. It is possible that lower air change rates could be achieved in lower wind speeds than were observed in this study.
- In the study classroom, the preferred minimum air change rate of 5 was achieved by creating at least 2 m^2 of openings, by opening all north and south facade windows by 50% (or 35 % with the door open), or all north façade windows only by 100% (or 56 % with the door open).
- Other window configurations could provide 2 m^2 opening area or more, but the resulting air change rates were not explicitly tested in this study.
- In stronger wind conditions, the data suggests 5 ACH could be achieved with ~1 m^2 of openings (e.g., 30 % of all north façade windows open).
- The feasibility of relying on natural ventilation alone in winter depends on the temperature loss and the thermal discomfort associated with maintaining 2 m^2 of openings (half of the maximum in the study classroom).

4.2 Effects of Augmented Ventilation in Improving the Effectiveness of Ventilation in Classrooms

- Augmented ventilation is most likely needed where maintaining ~2 m^2 of openings is impractical due to excess heat loss, wind or rain intrusion, or where natural ventilation is unable to provide 5 ACH in low to normal wind speeds.
- Devices providing a constant increase in ACH (rather than a proportional, or percentage increase) are likely to be more effective as they provide proportionally more benefit in low-ventilation cases.
- In the range of openings from 0 – 4 m^2, the supply fans appeared to make the largest positive absolute improvement to ventilation providing at least 5 extra air changes per hour, meaning (in principle) that doors and windows could be kept closed.
- The turbine and ceiling fan appeared to rely on there being a degree of effective natural ventilation, to which they would provide a proportional boost.

- However, the rapid nature of this study and limited testing means that the consistency of these results, or modification of the effectiveness by variations in wind or thermal conditions, were not tested and remains unknown at this stage.

4.3 Effects of Air Cleaners in Improving the Effectiveness of Ventilation in Classrooms

- The study found portable air cleaners (PAC) provided a consistent improvement in particle removal, regardless of ventilation rate.
- A single larger PAC operating at maximum speed provided 4 effective air changes per hour, and a medium PAC provided 2.7 effective air changes per hour.
- Using additional PACs provided a proportional boost to the space's ventilation with three units providing three times the particle removal.
- None of the PACs were tested at lower fan settings.

4.4 The Balance between Effective Ventilation and Staying Warm in Winter in Classrooms

- The study found that by opening all north and south facade windows by 50%, the preferred minimum air change rate of 5 was achieved and there was a lower temperature drop at lower opening areas.
- Generally, air flow behaves differently at different temperatures – for example, the larger the temperature difference between indoors and outdoors, the more efficiently fresh outside air is drawn in through open windows. The airflow is improved through thermodynamics and windows will only need to be opened a small amount (i.e., approximately 5 cm) to achieve good ventilation.
- However, given that this involved simulating winter conditions in late summer/autumn and the limited duration of testing, the consistency of these results on a typical cold winter day and for the eight hours of a school day, remains unknown at this stage.

5.0 Conclusions and Recommendations

Previous studies have extensively discussed the important role of ventilation in minimising the spread of viruses in indoor spaces. Given the COVID-19 pandemic, the aim has been to achieve 5–6 ACH in indoor learning environments. In this study, we assessed the impact of different window opening areas on temperature differential and the role of supplementary ventilation technologies. Our findings generally conclude that:

- In a typical classroom of ±10% net floor area to openable window area ratio and a maximum effective window opening area of 4.7 m^2, opening windows by 50% can readily replace indoor air with fresh air from outside.
- These findings further confirm that opening windows and doors is an effective way to get fresh air into classrooms or indoor spaces.
- Ceiling fans in either summer or winter mode can be used in conjunction with opened windows and doors to promote air flow, especially where there is already substantial natural ventilation.
- When a naturally ventilated room is otherwise poorly ventilated, supply and extract fans are a good solution to consider, provided noise discomfort is mitigated.
- When the loss of thermal comfort is not manageable and cannot be offset by other heating systems/sources, and this results in windows being opened less and not achieving 5 ACH, then portable air cleaners become a practical supplementary solution that is not dependent on ambient conditions.
- However, portable air cleaners are not a substitute for ventilation and do not reduce CO_2 levels.
- On cold days, having all classroom windows open by approximately 50%, with exterior doors closed, can achieve ~5 ACH.
- Greater than 5 ACH can also be achieved by having only high-level windows on both sides of the room opened by 50%, with exterior doors closed. This will reduce cold draughts in the room while promoting good airflow.
- At 50% window opening, and with a ±10 ^{o}C temperature difference, a 6 kW heating power is adequate to maintain the temperature. During an actual class, this 6 kW of heating would be supplied by the installed heaters and the various sources of internally generated heat.

Overall, the study indicates that partially opening all windows by a small amount during colder weather can achieve good ventilation outcomes. Fully opening windows and doors for very short periods (between and during classes) could also be effective in achieving appropriate air changes.

The limitations of this study are:

- The tests were carried out over a two-week period during late summer/autumn. To replicate winter conditions, testing was conducted during the early morning.
- Variations in wind and a large range of thermal conditions over a school day were not tested.

Future studies could explore various ventilation technologies with natural ventilation on the same day (ideally simultaneously in near-identical control and intervention rooms), as well as under the range of wind and thermal conditions over a typical winter school day.

However, the study results provide insightful findings and can, in principle, be transferred to similar situations in rooms without good natural ventilation that are occupied by more than a single occupant, such as conference rooms, waiting rooms and shared offices.

6.0 Acknowledgements

The Ministry would like to thank the following people for reviewing this document:

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Dr Mikael Boulic	Massey University
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Rob Omeara	eCubed Building Workshop

The Ministry would also like to thank the principal and staff of Epuni Primary School for their support, while this study was conducted on their premises.

7.0 Glossary of Abbreviations and Terms

Abbreviations	Description
ACH	Air Changes per Hour
eACH	Effective Air Changes per Hour
CO_2	Carbon dioxide
ppm	Parts per million
Turbine	Referred to as a 'Roofquip whirly vent'. They are a wind-powered ventilation system
PAC	Portable Air Cleaner

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List of Tables

List of Figures

Appendix A – Discharge Coefficient Calculation

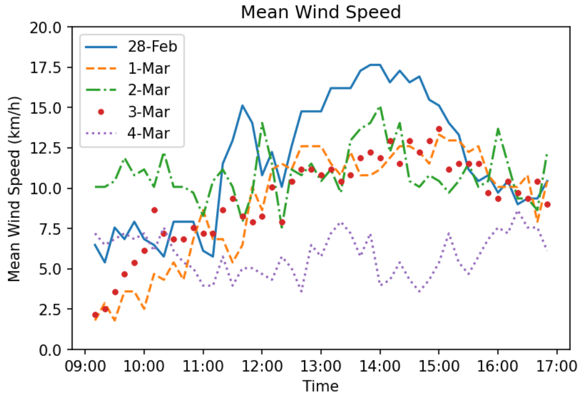
The ‘effective window opening area’ and the discharge coefficient below has been calculated as per Jones et al., (2016a, 2016b).

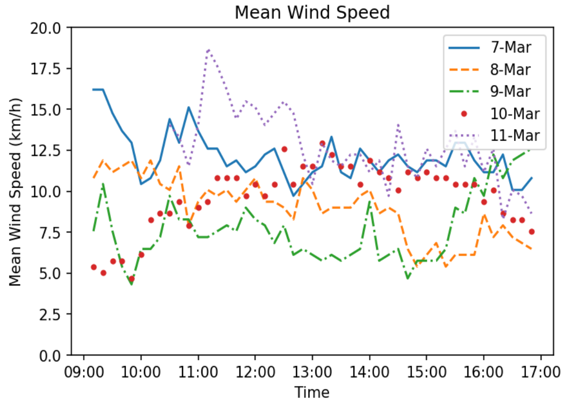
North Elevation Windows (Double Row)			
Description of window opening	Restrictor opening length	Effective Openable Area	Discharge Coefficient (C_d)
25%	25mm	0.023m^2	0.05
50%	50mm	0.044m^2	0.10
75%	75mm	0.064m^2	0.14
100%	100mm	0.084m^2	0.17

South Elevation Windows			
Description of window opening	Restrictor opening length	Effective Openable Area	Discharge Coefficient (C_d)
25%	55mm	0.10m^2	0.13
50%	110mm	0.16m^2	0.24
75%	165mm	0.20m^2	0.31
100%	220mm	0.24m^2	0.37

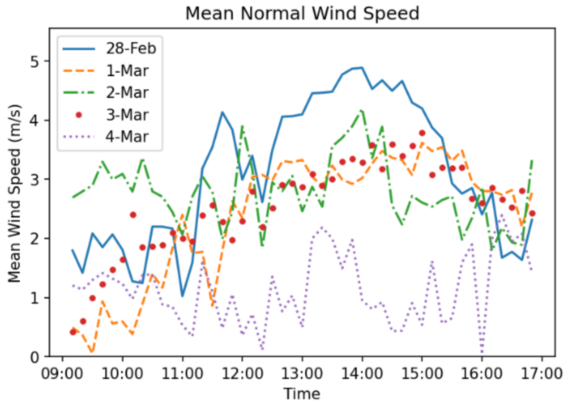
Appendix B – Wind Results

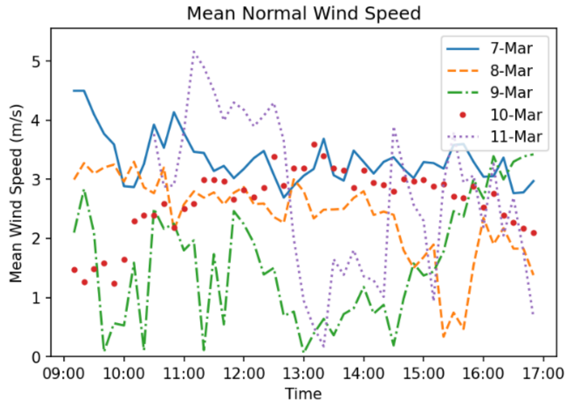
Mean Wind Speed from 28 February to 11 March



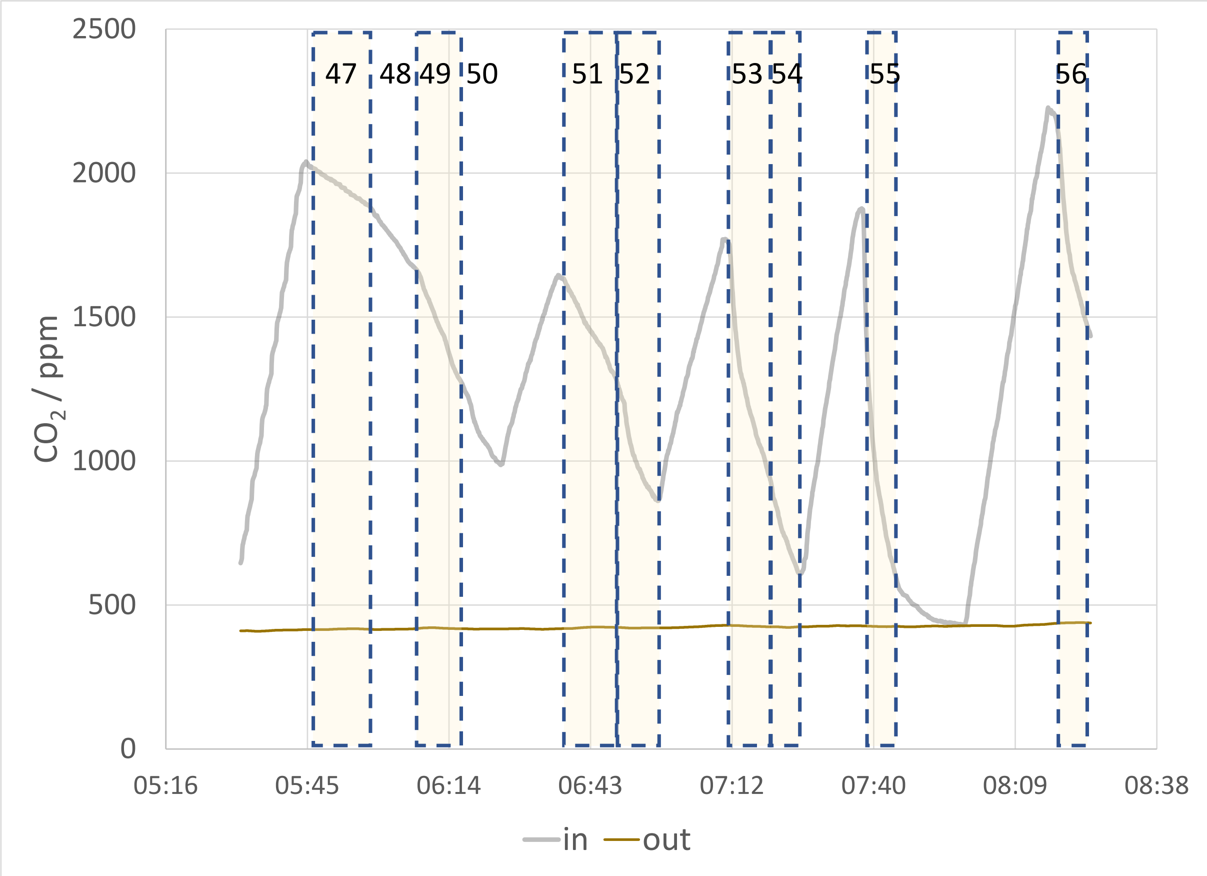


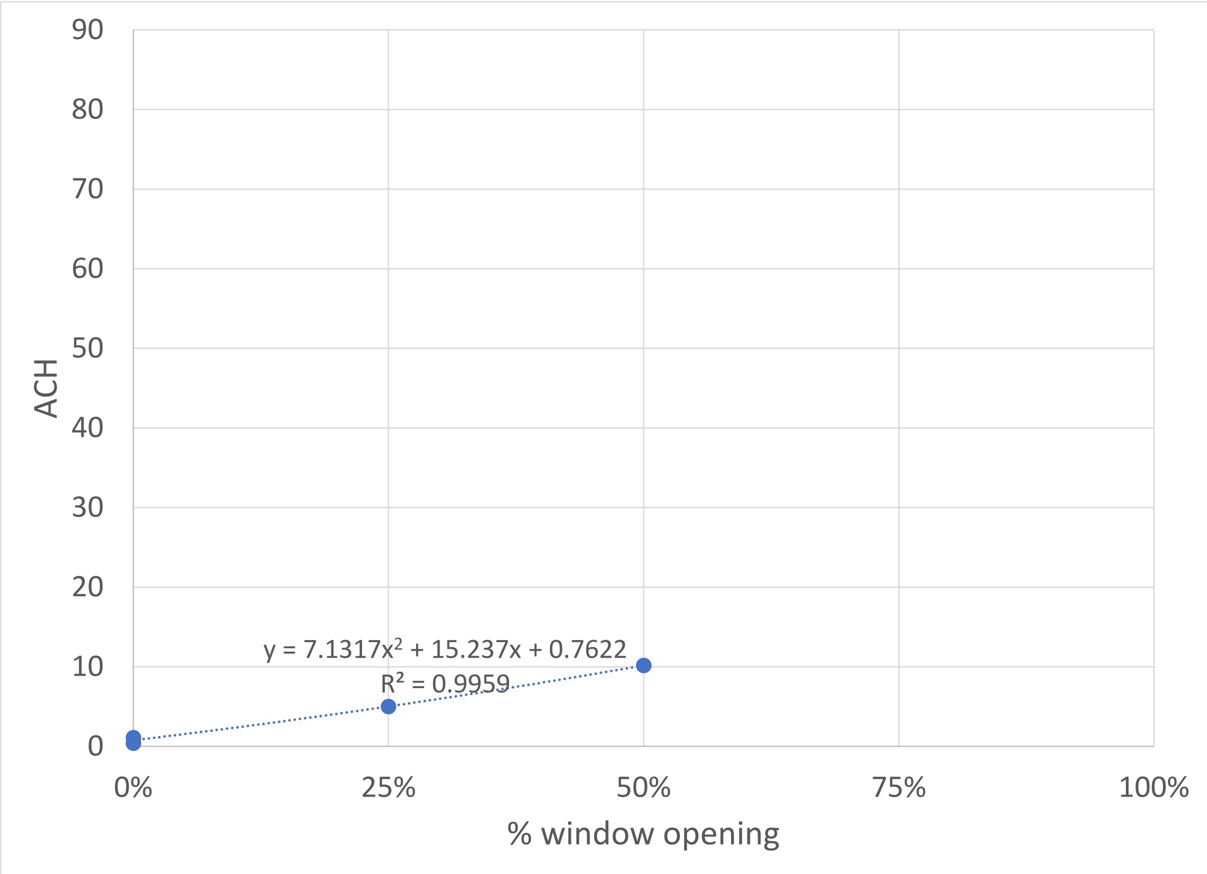
Mean Normal Wind Speed from 28 February to 11 March

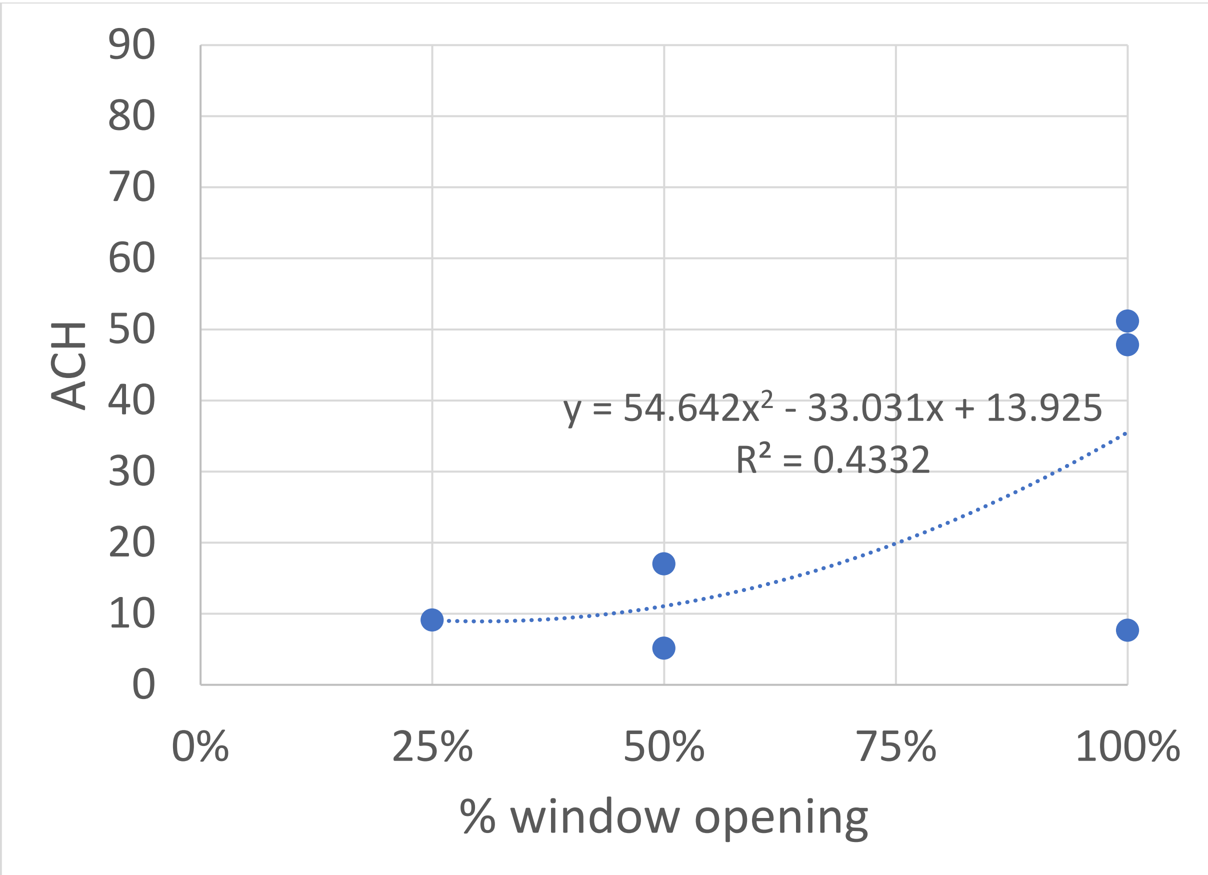


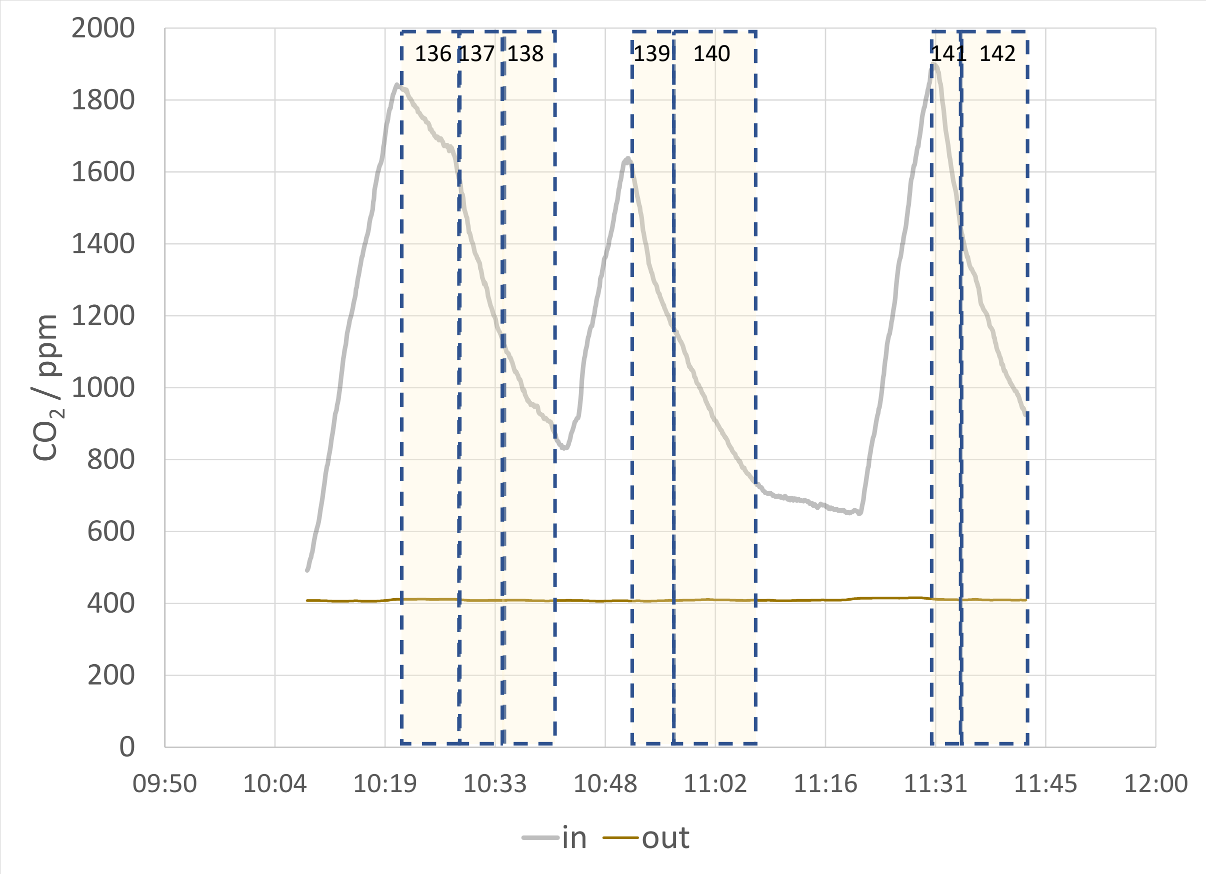


Appendix C – Natural Ventilation Results

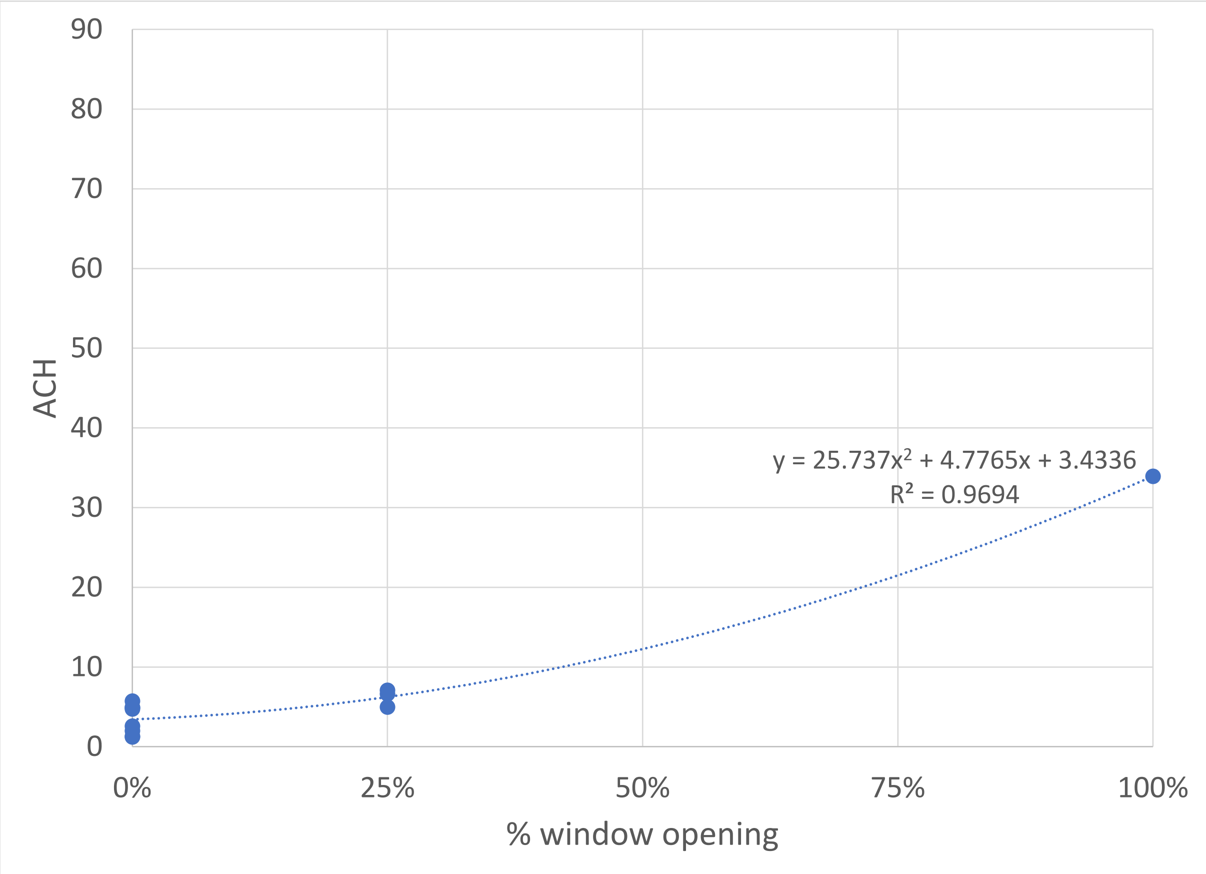



90
80
70
60
50
40
30
20
10
0
ACH
y = 7.1317x² + 15.237x + 0.7622
R² = 0.9959
0%
25%
50%
75%
100%
% window opening

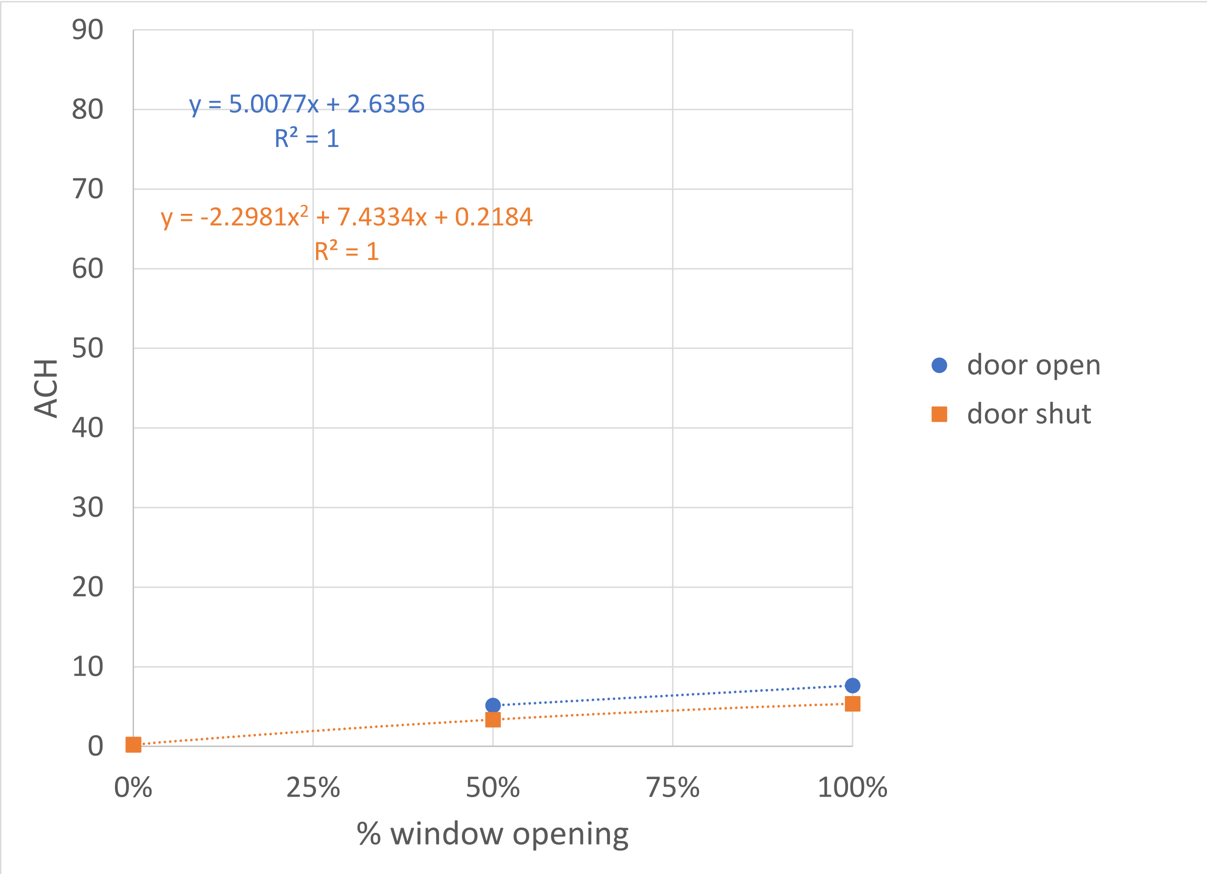

90
80
70
60
50
40
30
20
10
0
ACH
y = 54.642x² - 33.031x + 13.925
R² = 0.4332
0%
25%
50%
75%
100%
% window opening



2000
1800
1600
1400
1200
1000
800
600
400
200
0
CO_2 / ppm
136
137
138
139
140
141
142
09:50
10:04
10:19
10:33
10:48
11:02
11:16
11:31
11:45
12:00
in
out

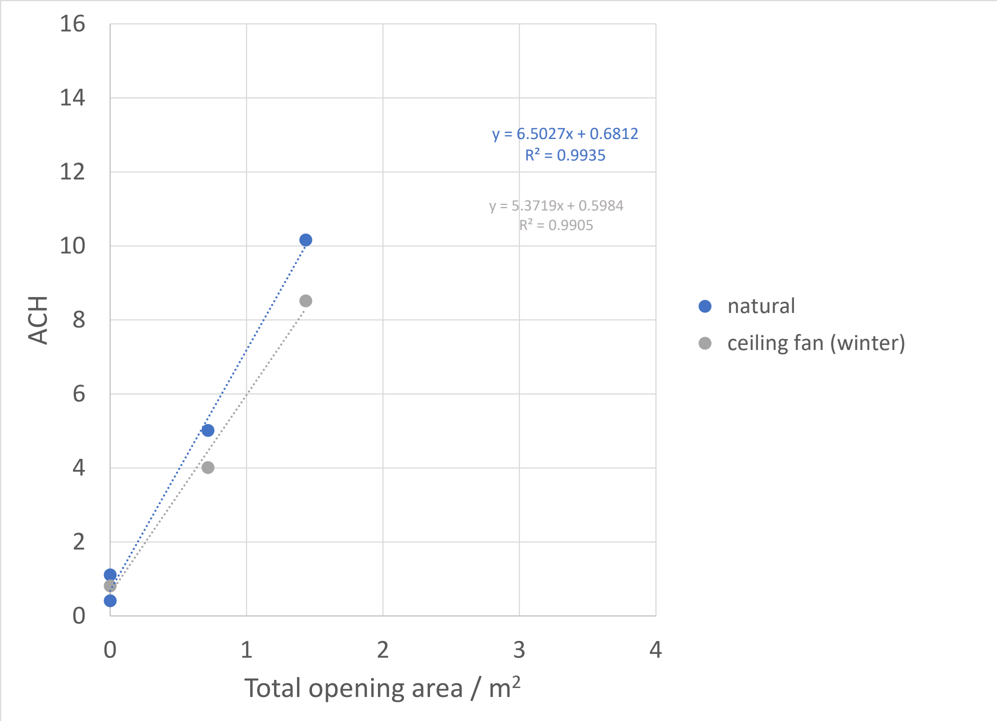


90
80
70
60
50
40
30
20
10
0
ACH
y = 25.737x² + 4.7765x + 3.4336
R² = 0.9694
0%
25%
50%
75%
100%
% window opening

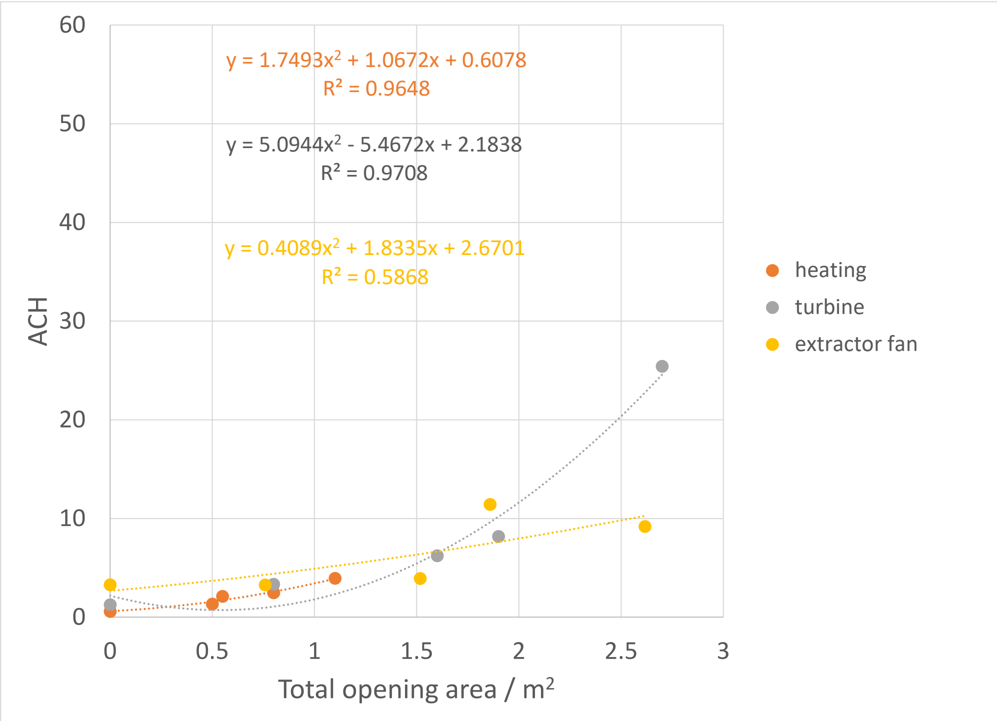

90
80
70
60
50
40
30
20
10
0
ACH
y = 5.0077x + 2.6356
R² = 1
y = -2.2981x² + 7.4334x + 0.2184
R² = 1
door open
door shut
0%
25%
50%
75%
100%
% window opening

Appendix D – Augmented Ventilation Results

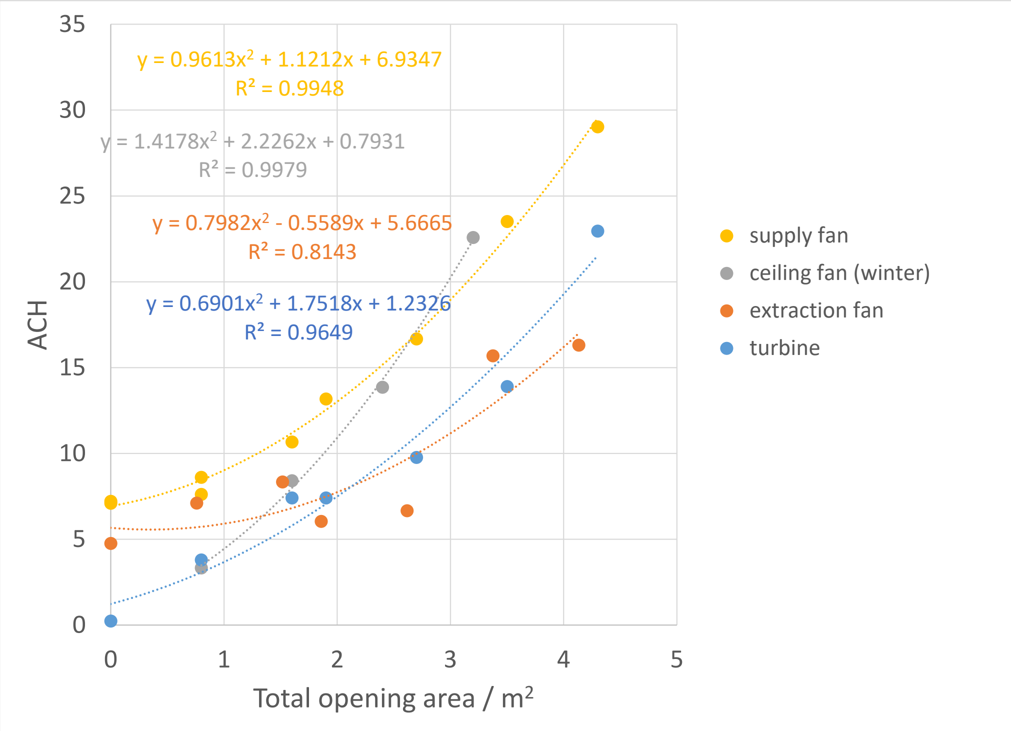
8 March: Ceiling fan test



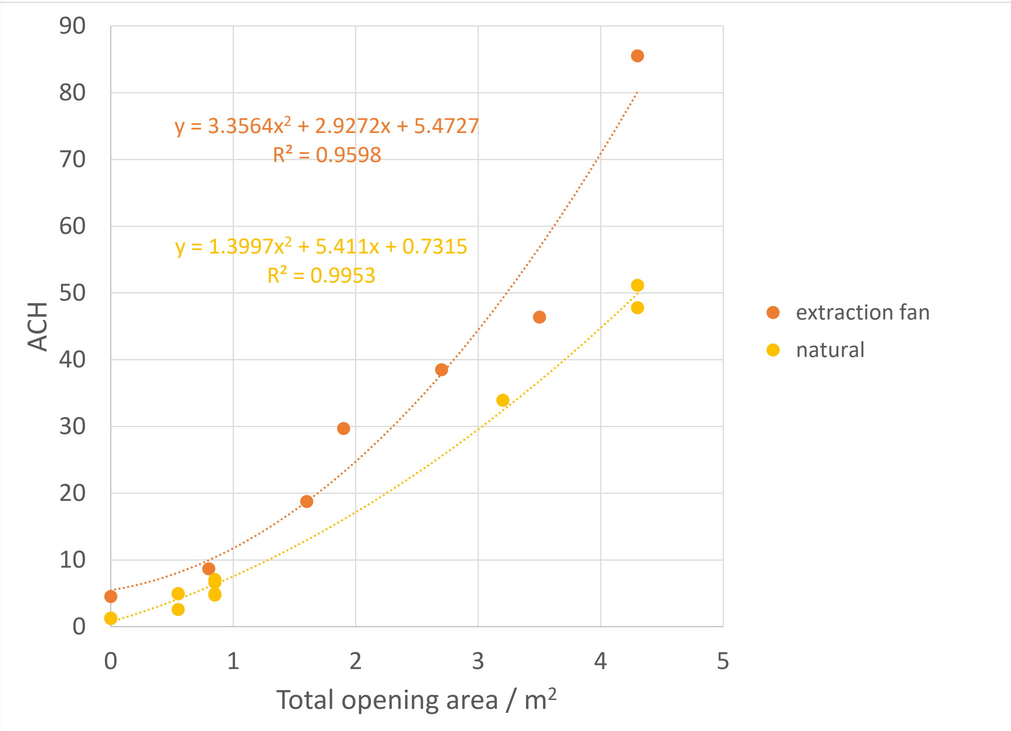
9 March: Heating, turbine, extractor fan



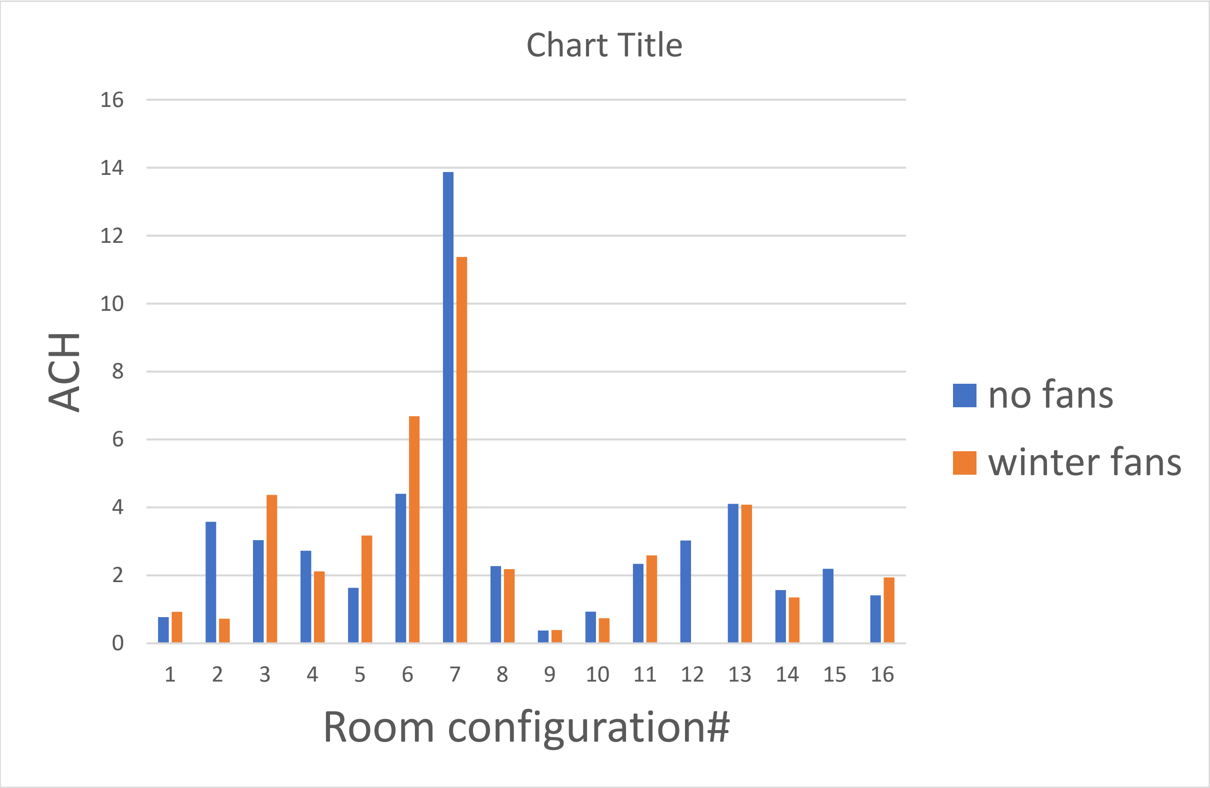
10 March: supply fan, extractor fan, turbine, ceiling fan

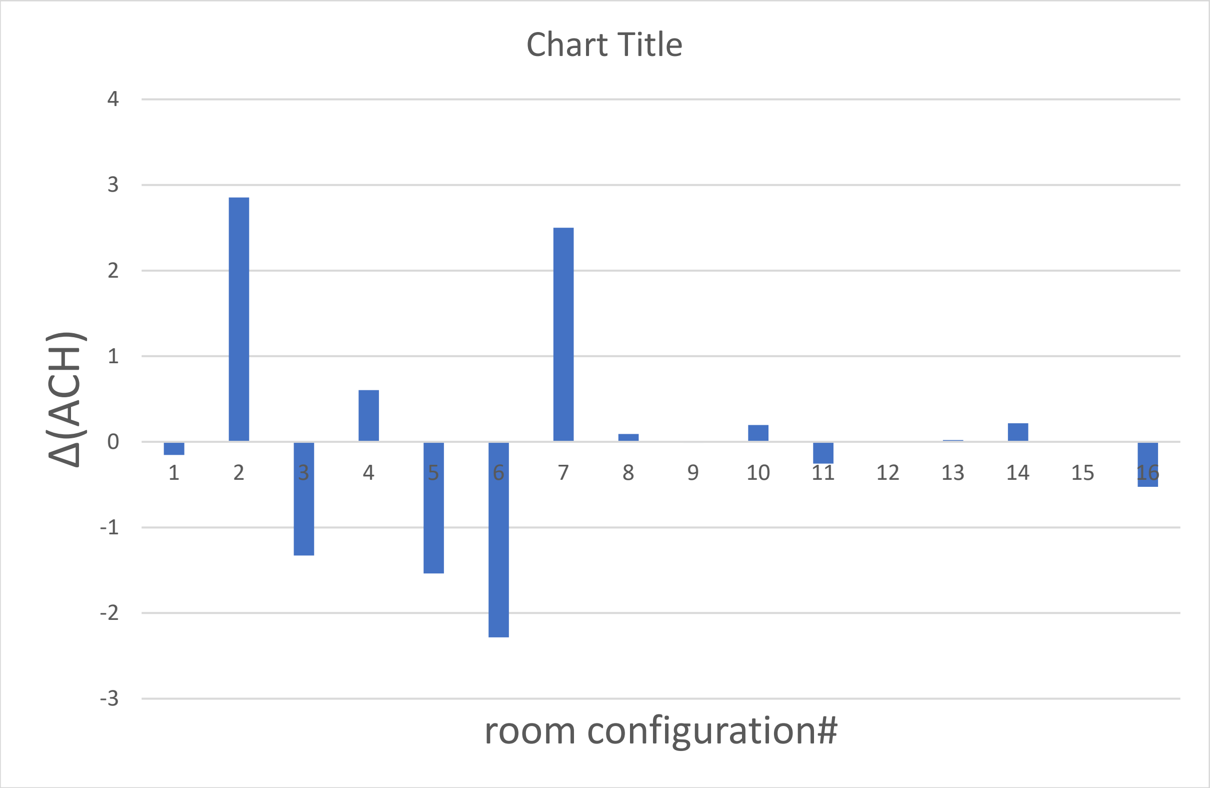


11 March: extractor fan



Supplementary Ceiling Fan Test





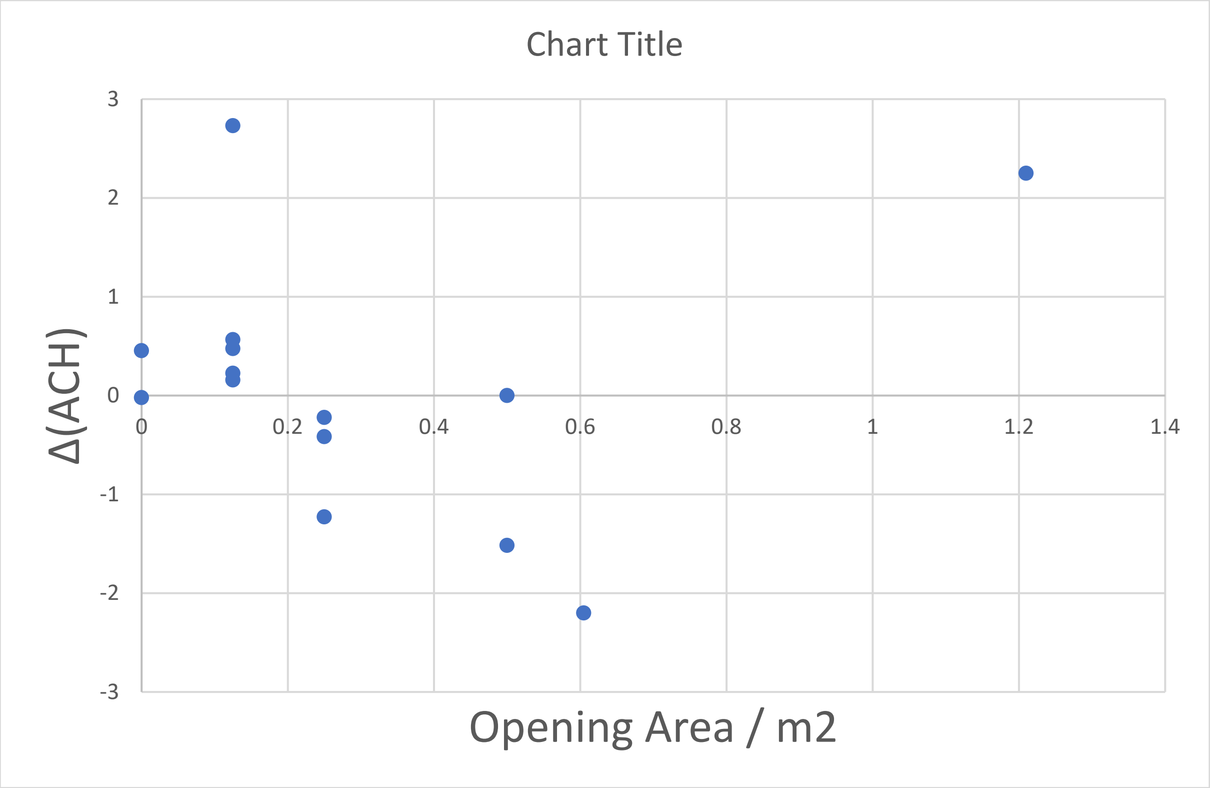


Chart Title
3
2
1
0
-1
-2
-3
Δ(ACH)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Opening Area / m2

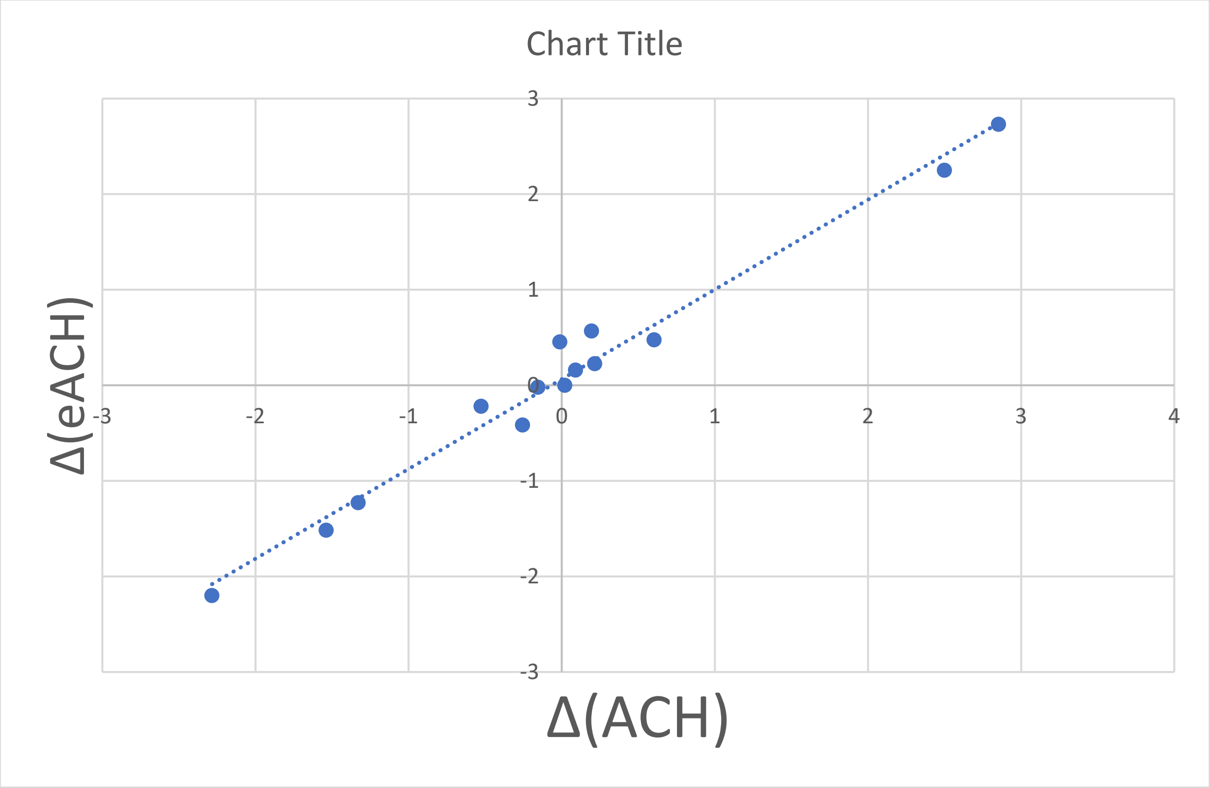


Chart Title
3
2
1
0
-1
-2
-3
Δ(eACH)
-3
-2
-1
0
1
2
3
4
Δ(ACH)

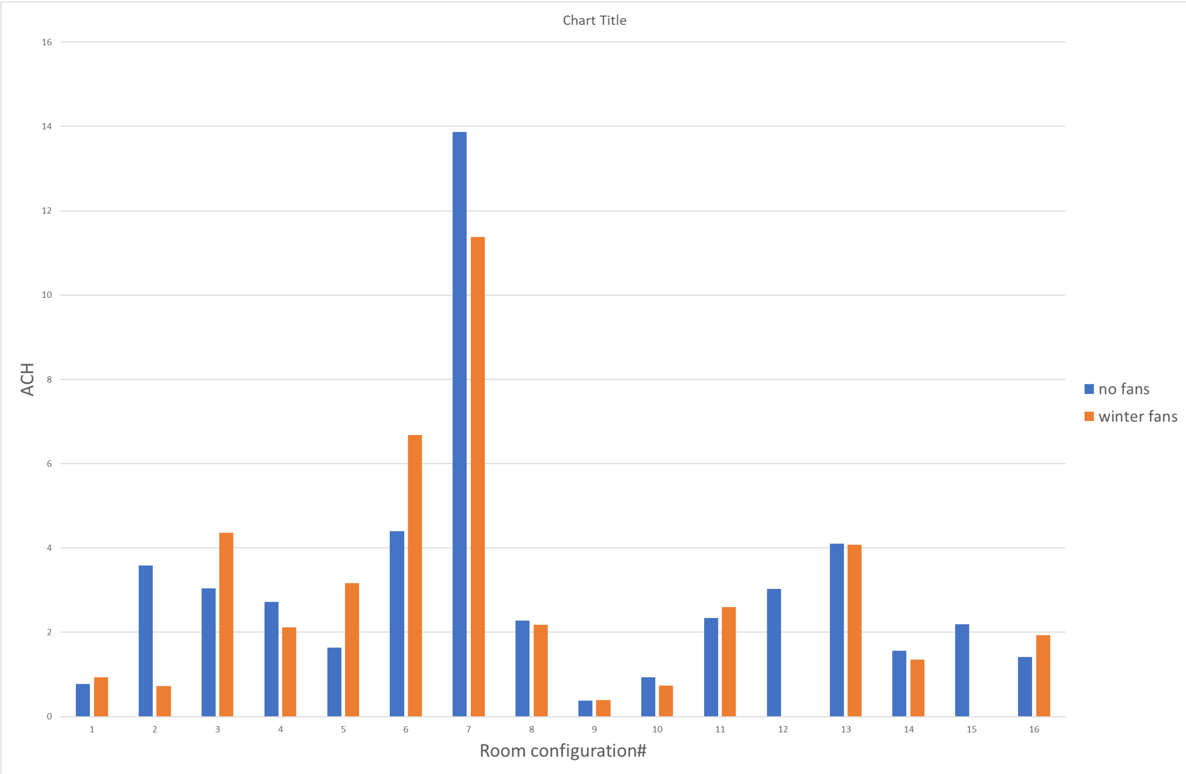


Chart Title
ACH
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Room configuration#
no fans
winter fans