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

May 2022

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Feedback, Review Date

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Foreward

The New Zealand Ministry of Education's approach to addressing ventilation in schools, in response to the COVID-19 pandemic has been informed by evidence supporting good natural ventilation where possible.

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 (natural ventilation).

In March 2022, the Ministry's ventilation programme in collaboration with research institutes carried out the next phase of targeted studies performed in an unoccupied classroom at Epuni School in Wellington. This study was to further verify a subset of the NIWA study findings and more closely study the impacts of lower outdoor temperatures, and the effectiveness/impact of in room features such as portable air cleaners, ceiling and extract fans and supply fans.

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

This document is freely available for download from the Ministry's ventilation guidance page.

Sam Fowler

Associate Deputy Secretary - Property Delivery

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Executive Summary

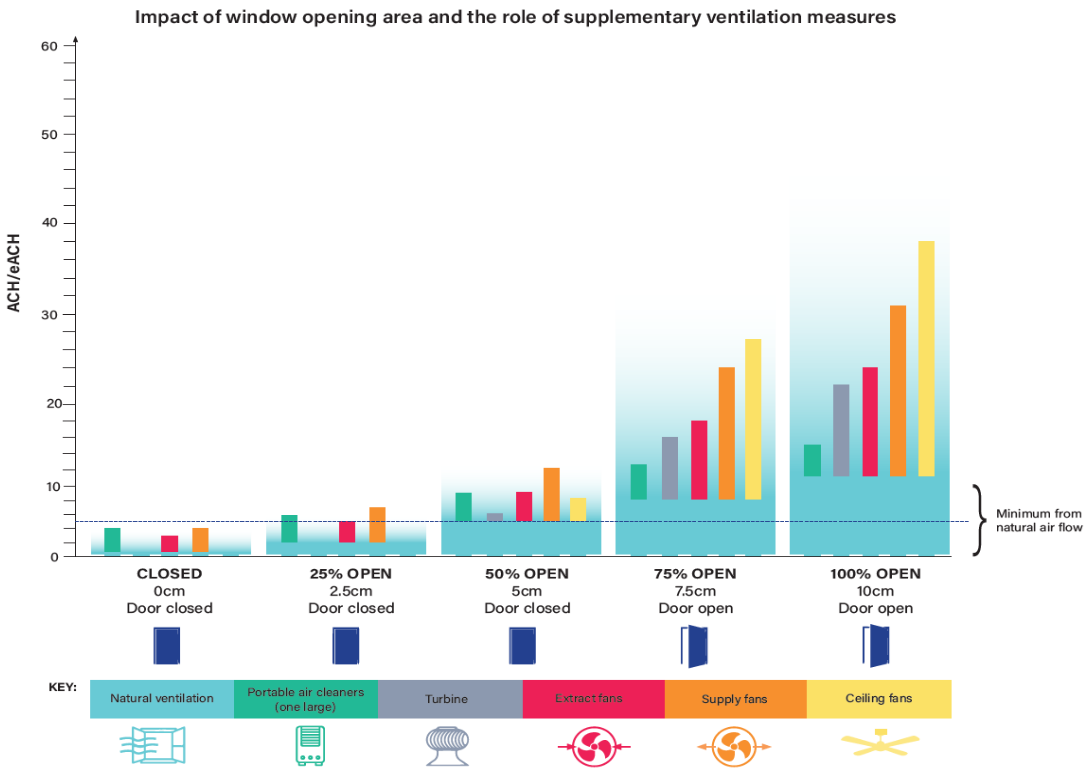
In November 2021, the New Zealand Ministry of Education, in collaboration with the National Institute of Water and Atmospheric Research (NIWA) carried out a rapid observational study on ventilation and air quality in 18 classrooms at three New Zealand schools. This study confirmed that an efficient way 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 southern hemisphere), there is a concern that fully opening windows and doors to achieve good ventilation may not be desirable or possible without excessive heat loss.

Building on the approach and findings from the rapid ventilation study, a further study was carried out in a '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 carried out over two weeks to inform the winter ventilation guidance to be provided by the Ministry to New Zealand schools.

To similate occupation, a gas cylinder was used to release CO_2 (gas tracer method), while smouldering incense sticks were used to generate aerosols. The decay in concentrations were 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 findings indicate that:

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



- Ceiling fans and a Turbine increased ventilation when natural ventilation was already effective (ie. >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 low opening area.
- A supply fan had the largest effect in boosting ventilation. Although tested on only one day, it provided at least an additional 5 ACH regardless of opening area.
- The extract and supply fans had a rated flow rate of 297L/s (1070m3/hr), and variations in wind speed and direction resulted 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 meduim PAC provided 2.7 effective air changes per hour.
- With the door shut, and the upper north and south windows (on both sides) opened by 50%, an ~5.5 ACH was achieved.
- At 25% window opening, with ~ 8 ^{o}C indoor/outdoor temperature differential, the temperature penalty observed within 45 minutes was generally <1^{o}C, in the presence of common heating equipment such as oil heater or heat pump, indicating that there was no significant temperature drop due to ventilation.

Summarily, the study findings indicate that typical, naturally ventilated New Zealand classrooms can achieve good ventilation through partial window openings and in some cases can be assisted by supplementary measures such as fans and 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 introduce thermal discomfort.

The ‘uncocupied’ classroom windows had restrictiors, and if there were no restrictors, opening the windows wider could greatly exceed the ACH found in this experiment. 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, this could be up to 29 ACH.

Future studies should explore various ventilation measures 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, this study provides insightful findings and can in principle be transferred to similar situations in closed rooms that are occupied by more than a single person, 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 by opening windows and doors. The COVID-19 pandemic has resulted in increased attention on how, through everyday actions and practices, the effectiveness of natural ventilation is improved in indoor spaces without converting these spaces to more controlled mechanically ventilated spaces. The aim during pandemic response has been to MAXIMISE ventilation

Achieving high levels of ventilation performance in naturally ventilated buildings will require changes to human behaviours and an increased appreciation for what enables, and what impedes good ventilation. It also requires looking carefully at the use of supplementary technologies to explore 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. The appropriate operation of windows throughout the day therefore becomes 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 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, it is counterintuitive that fully opening windows and doors to achieve good ventilation may not be desirable or possible without excessive heat loss. 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 measures.

Building on the rapid classroom ventilation study, a 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 according to different window/door opening percentages and ventilation methods (cross- and single-sided ventilation).

2. Identify the role of supplementary ventilation measures (air cleaners, ceiling fans, turbine, supply and extract fans) 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 measures was not within the scope of this study. Another limitation was the urgency to inform winter ventilation approaches, which restricted the experiments to a total duration of two weeks.

2.0 Control Study Methodology

2.1 Experimental Design

Carbon dioxide occurs naturally, 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 poor indoor environment, but the opposite is not true, as a low CO_2 level doesn't indicate clean air, as 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 (early 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 (door and window openings, including repeats on other days), and exploring the role of technologies (air cleaners and fans) in improving ventilation.

As shown in Table 1 below, four test scenarios annotated with A1-4, were carried out exploring different window opening percentages from 25% to a 100% window opening as shown in Table 2 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.	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 explore ventilation rates and temperature differentials.	Week one and two

2.2 Building Design and Characteristics

The study was conducted in Room 1 at Epuni School (the "control room"). Illustrated in Figure 1 below, the length and width of the room is 10 m by 7.5m, and it is a typical purpose-built "Open Air" classroom building type. This type of block was generally constructed between 1955 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).

Room Floor Plan

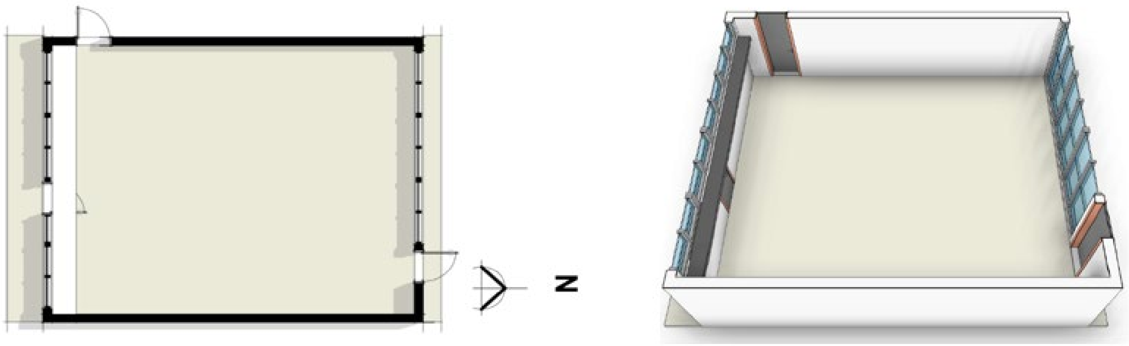


Figure 1: Plan sketches of the control room

Room Interior and Exterior Images

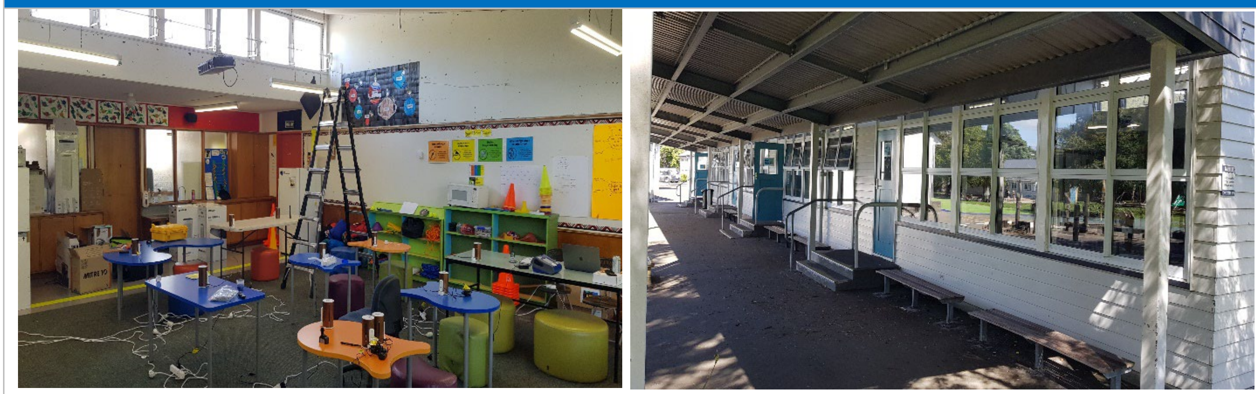


Figure 2: Images of the control room

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 shows the modifications carried out in the second week of the experiment to investigate the various test scenarios, while

Figure 3 shows the classroom annotated with A-C and colour coded 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 direct cooling breeze, and operated clockwise in winter 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

Specification of Fan Unit Modifications				
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 Conditions Methodology

New Zealand Building Code 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) used 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, New Zealand Building Code 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, and the maximum opening of the north façade windows were restricted to a 100 mm. The clerestory centre-pivot windows on the south façade opened to 220 mm, both top and bottom.

Tables 4 and 5 and Figures 4 and 5 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 open 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) and 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). There are many uncertainties when it comes to calculation of effective window opening area. Typically, discharge coefficient's are around 0.60 – 0.65 for large external openings, though 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 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 (12 windows)	Door opening area (always at 100%)	Total effective window opening area (12 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

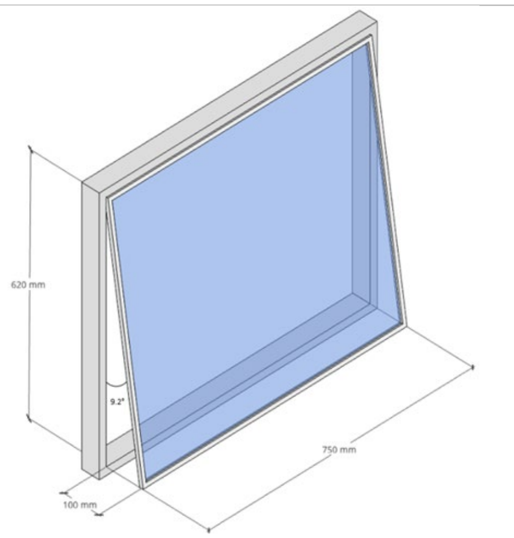


Figure 4: North elevation window design and opening ratio illustration

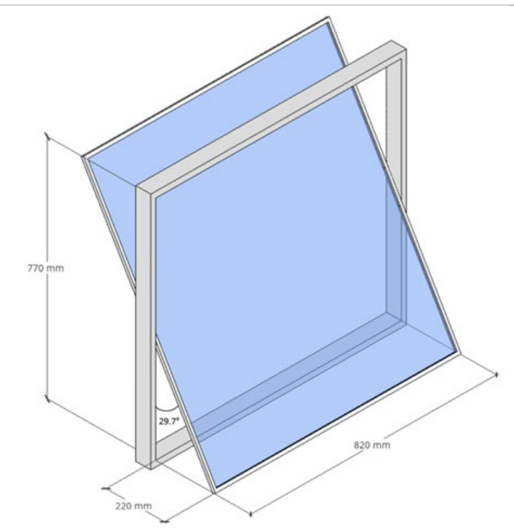


Figure 5: South elevation window design and opening ratio illustration

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 (8 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, which 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 (5 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 for ventilation. Cross ventilation means that both the north and south façade windows were open, and single-sided ventilation means that 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 HauHau™ 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 Figure 7, nine Hau-Hau monitors were deployed in the control room in a rectangular grid pattern. This design 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 5 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 experiment. The door in the south façade opened into an adjoining corridor, and was also kept closed during the experiment. .

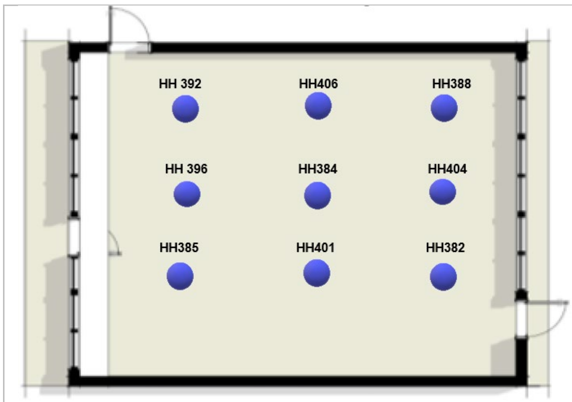


Figure 6: Plan of control room showing Hau-Hau monitor locations

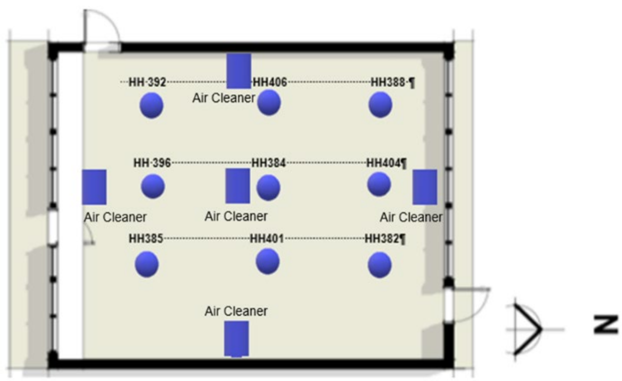


Figure 7: Figure 7: Plan of control room showing Hau-Hau monitor locations, the location of the three meduim and one large air cleaners around the periphery, and the location of the single large air cleaner at the centre of the room.

Figure 8: Interior image of control room showing Hau-Hau monitors location

For each test scenario, the following process was followed:

- The window and door configuration was set, according to the window opening percentage in Tables 4, 5 and 6.
- CO_2 was released from a gas cylinder, and incence 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 experiment, 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, while the $PM_{2.5}$ sensor had a measurement range of 0-1000 µg m^{-3}, a resolution of 1 µg m^{-3} and 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

An Microsoft Excel workbook was used to collate the manual records of test start and end times 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 that appeared to have large reading errors were excluded from the analysis. For each test scenario, ACH 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 air changes per hour 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 completely 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.

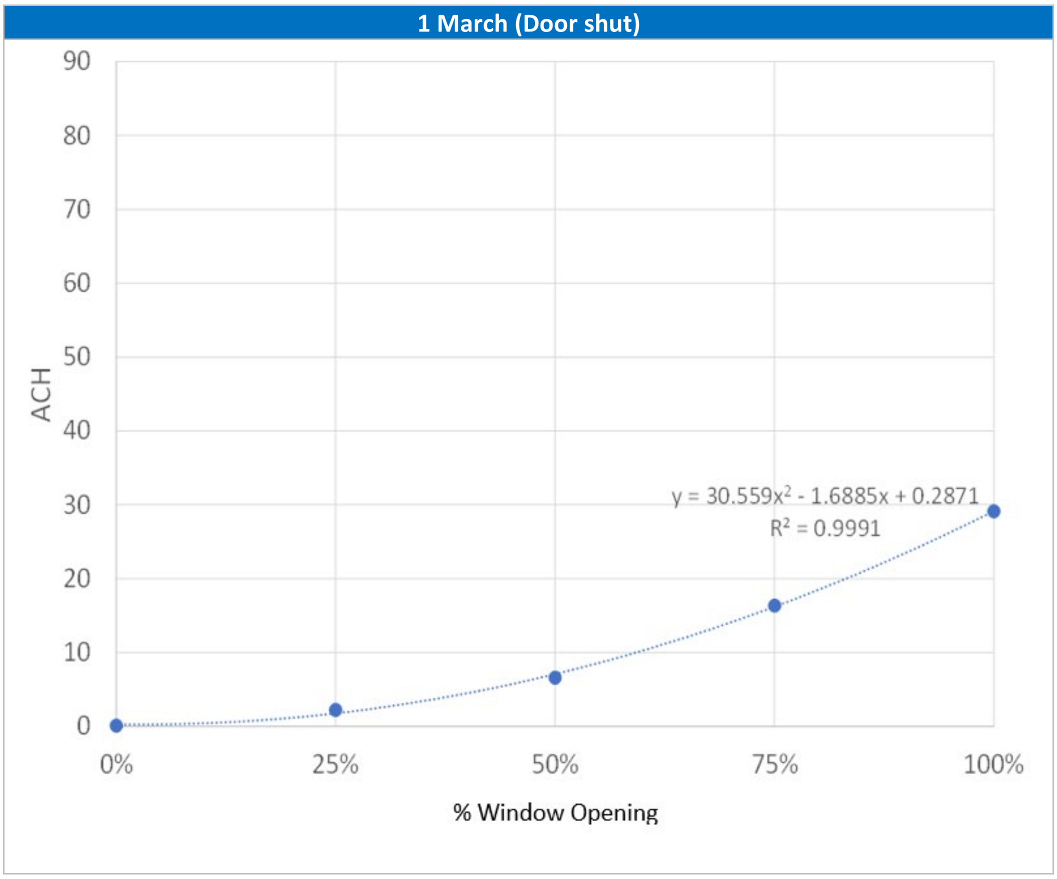
3.0 Control Study Results

3.1 Natural Ventilation (Test Scenario A1)

3.1.1 Natural Ventilation with Cross-Flow

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

Figure 9 show that, whereas there was generally a relationship between air change rate and 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.



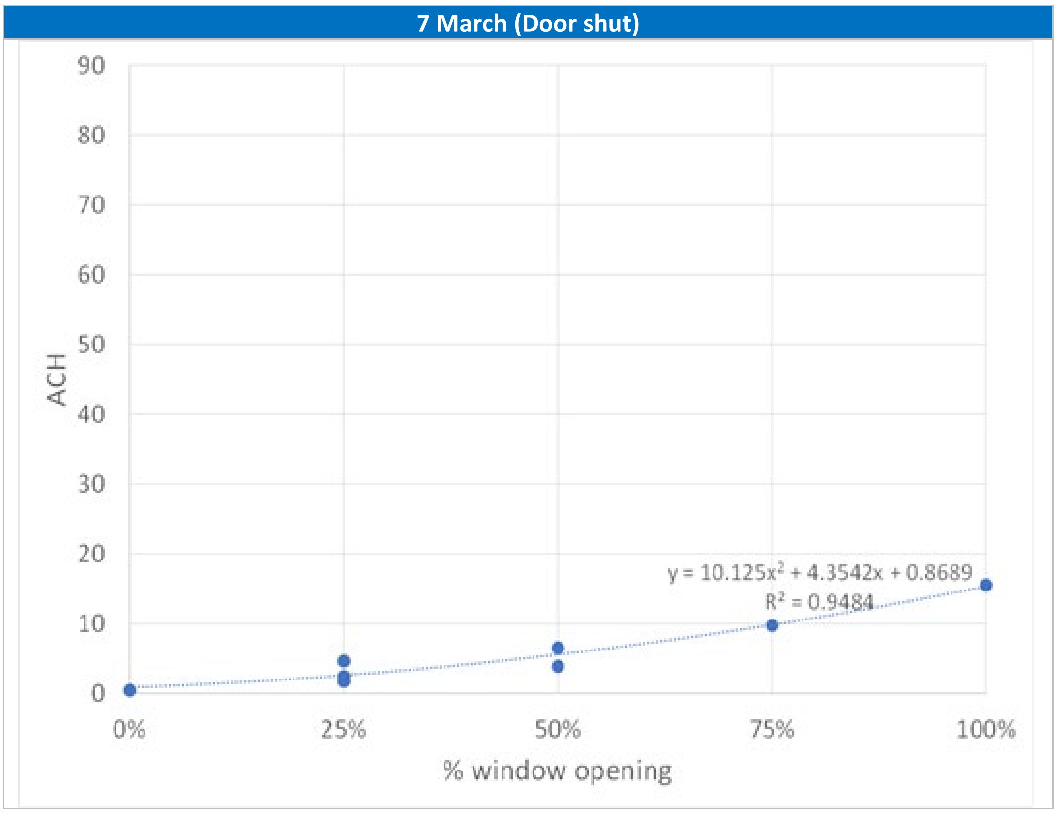


Figure 9: ACH in cross flow configuration

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 response for the same opening configurations between 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}). ACH 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 result 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 air changes rate and opening area.

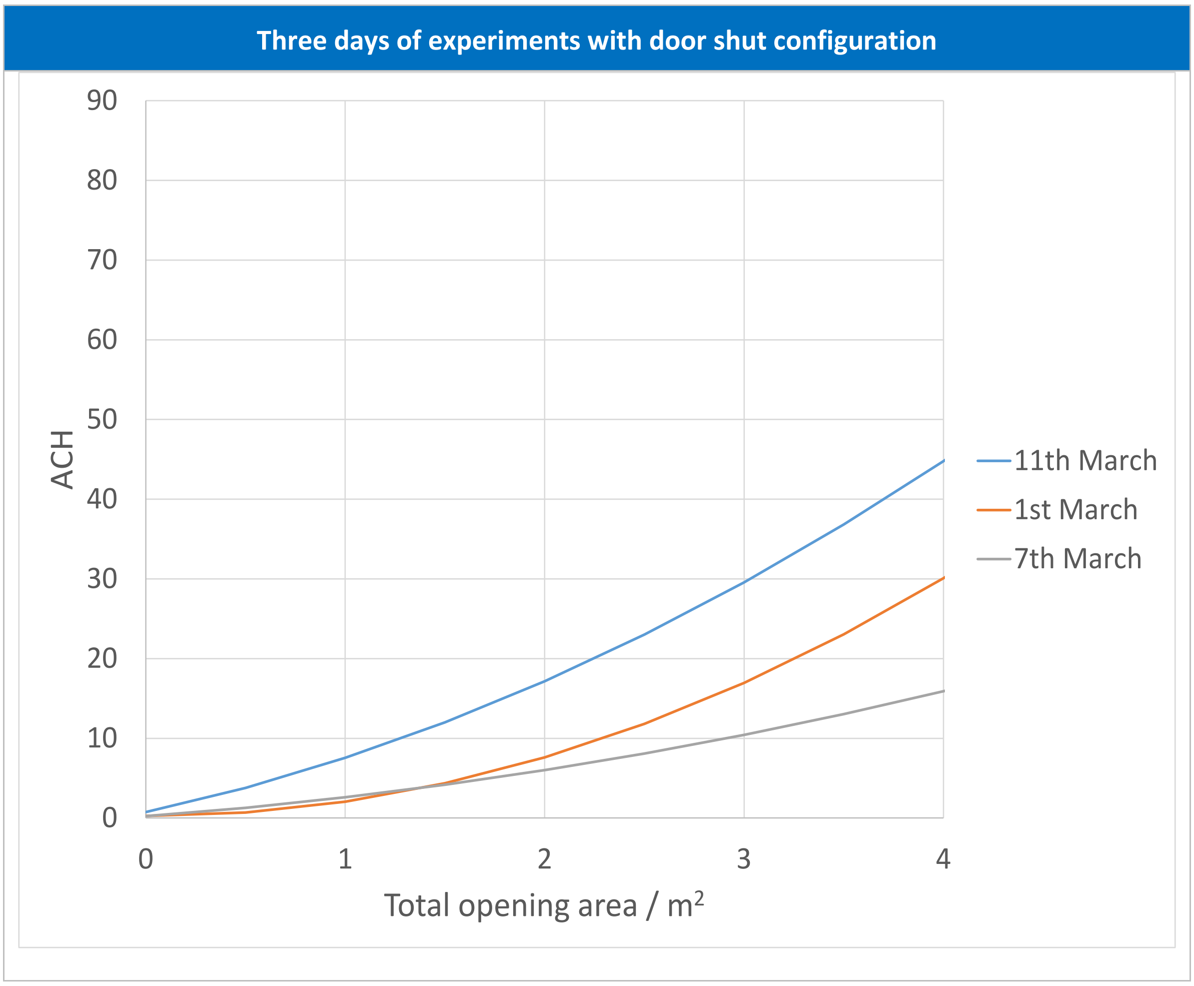


Figure 10: ACH comparing patterns between days

In Figure 11, 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 is numerically equal to 2.5 times the total effective opening area (i.e., 1 m^2 = 2.5 ACH minimum).

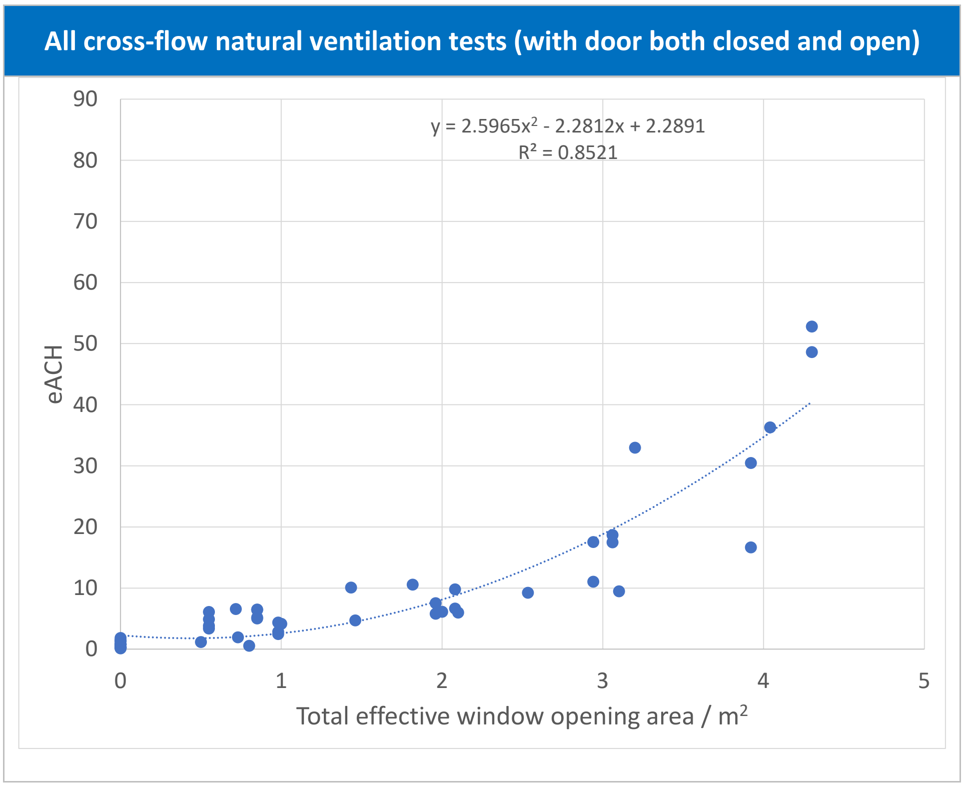


Figure 11: Combination of data from all natural ventilation tests

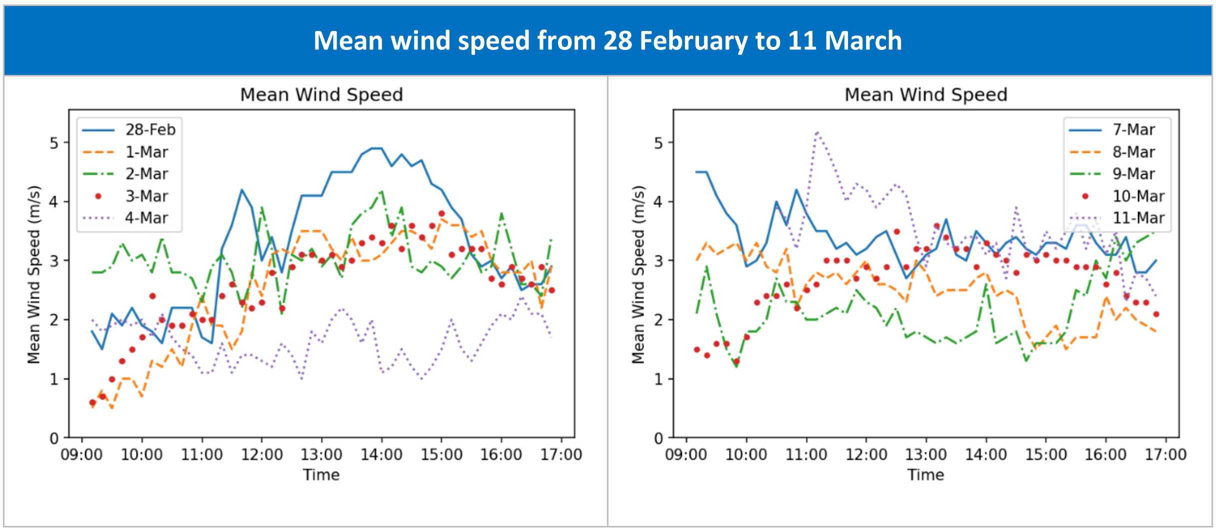


Figure 12: Mean wind speed over the two weeks of the experiment

3.1.2 *Natural Ventilation with Single-Sided Flow*

The impact of natural ventilation with openings on one façade only (i.e., north façade windows open) was also explored. In Figure 13, the results for single-sided ventilation are consistent with the relationship between minimum ACH 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 cross-flow ventilation tests. A comparison of Figures 11 and 13 shows that with the same window opening area and at comparable mean wind speeds, cross-flow ventilation is significantly more effective than single-sided ventilation.

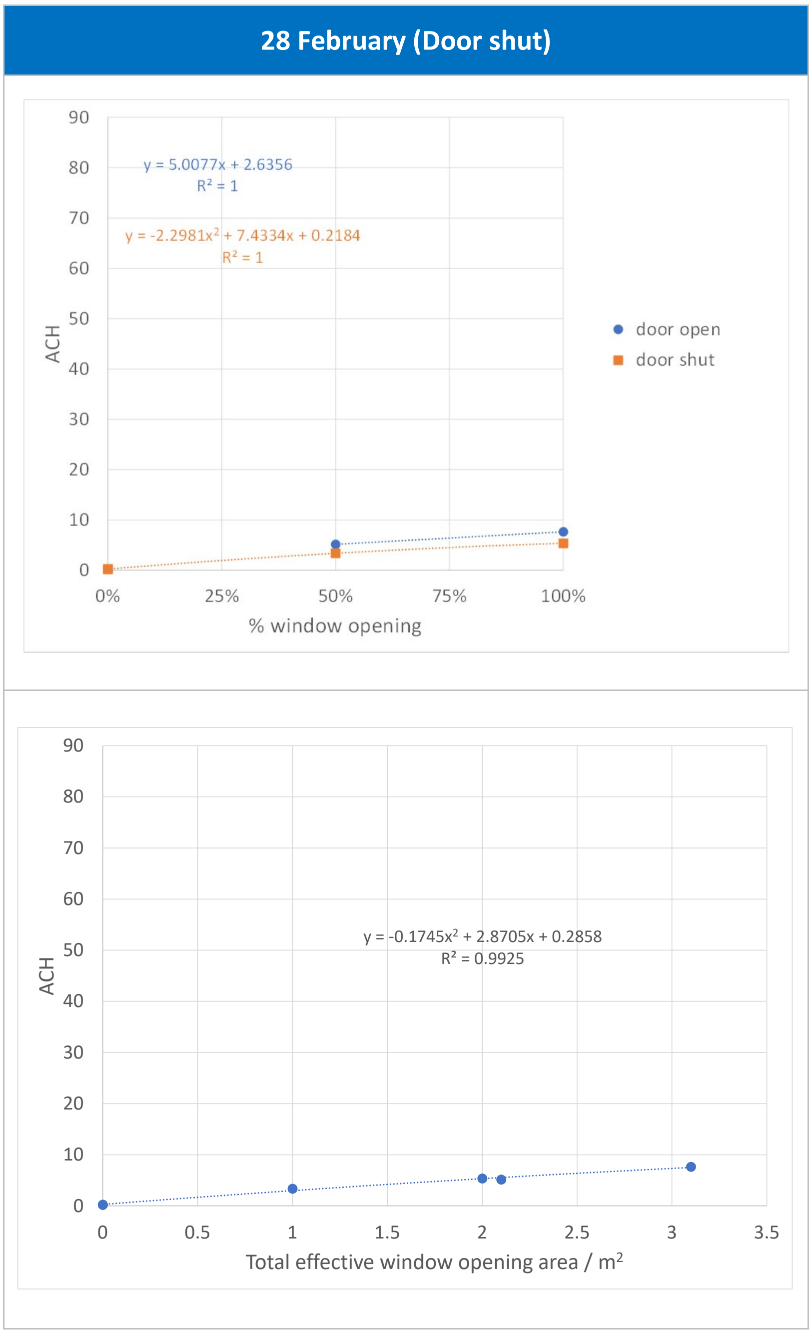


Figure 13: ACH in single-sided configuration

3.1.3 Summary of Natural Ventilation Test Scenario - 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 air changes per hour in low wind conditions using single-sided natural ventilation alone (1.5 m^2 opening area achieved 5 ACH with cross-flow ventilation). In this classroom 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.

2nd order polynomial functions have been fitted to most of the test series due to relatively good fit in many, but not all cases. The plausibility of a polynomial expression representing the physical processes was not further investigated, and we cannot verify that such a non-linear relationship between ACH 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, and this could be up to 51 ACH.

3.2 Augmented Ventilation (Test Scenario A2)

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.
- Whereas the Ceiling fan and Turbine (working independently) provided more than an additional 5 ACH at larger opening areas, with openings below 25% the Ceiling fan 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 on ceiling fans).
- A extractor fan (nominal flow rate 297 l/s) added 3 - 5 additional ACH at low opening area.

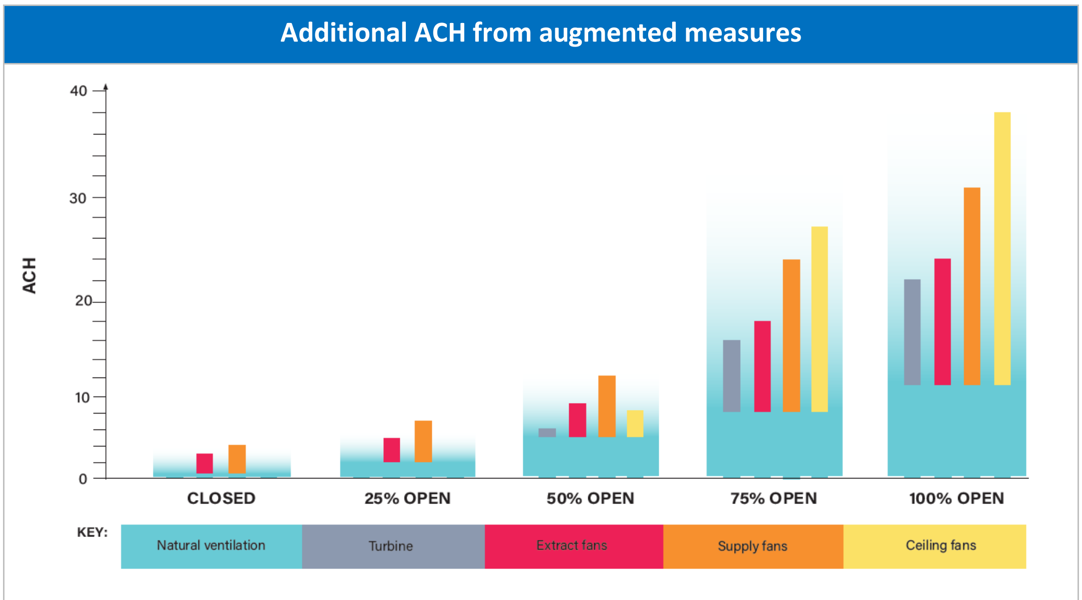


Figure 14: ACH added by different augmented ventilation methods

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

10 March – Exploring different augmented ventilation methods

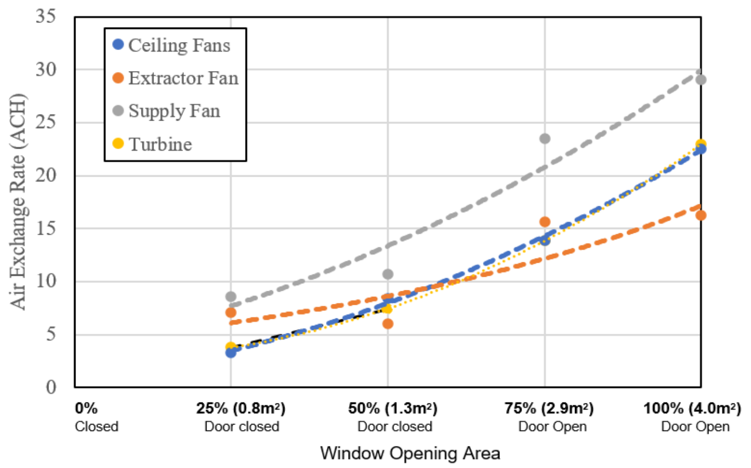


Figure 15: ACH at different augmented ventilation methods

11 March - Exploring two augmented ventilation methods

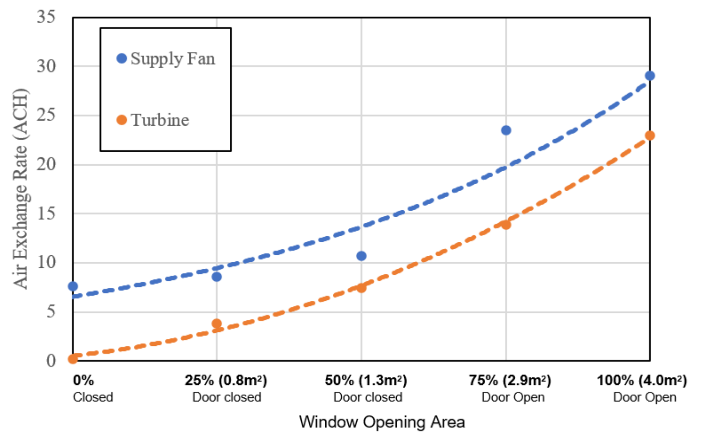


Figure 16: ACH comparison of supply fan with turbine

8 March – Exploring Different Augmented Ventilation Methods

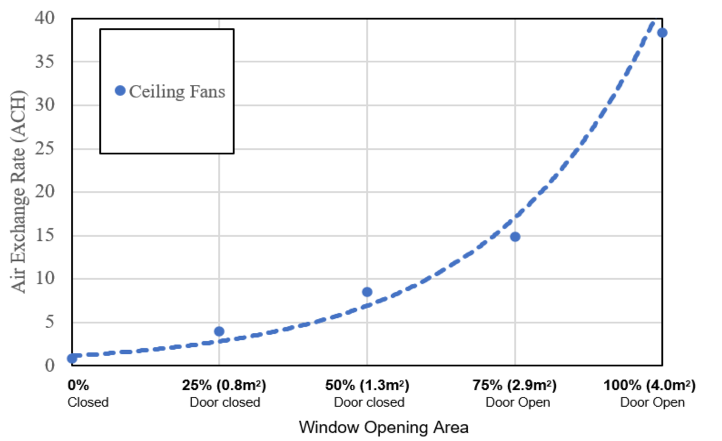


Figure 17: ACH at different augmented ventilation method

3.2.1 *Summary of Augmented Ventilation Test Scenario - Impacts on Ventilation*

The data generally indicates that the Ceiling fans and Turbine tested deliver a proportional increase in air change rate (e.g., fixed % improvement), regardless of opening area, meaning 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 at least 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 set 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 meduim PACs and one large PAC operating simultaneously ranged from 56 to 59 dBA, while the noise levels from 1 PAC ranged from 54 to 56 dBA.

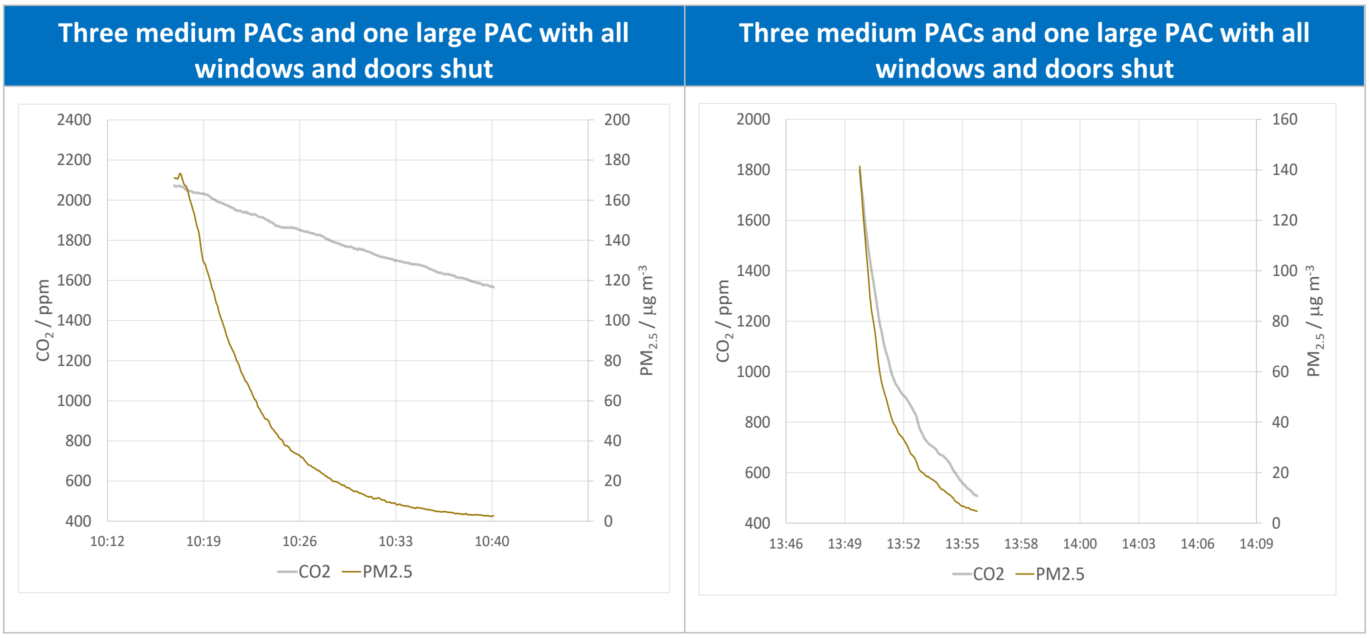


Figure 18: PAC's particle removal rate

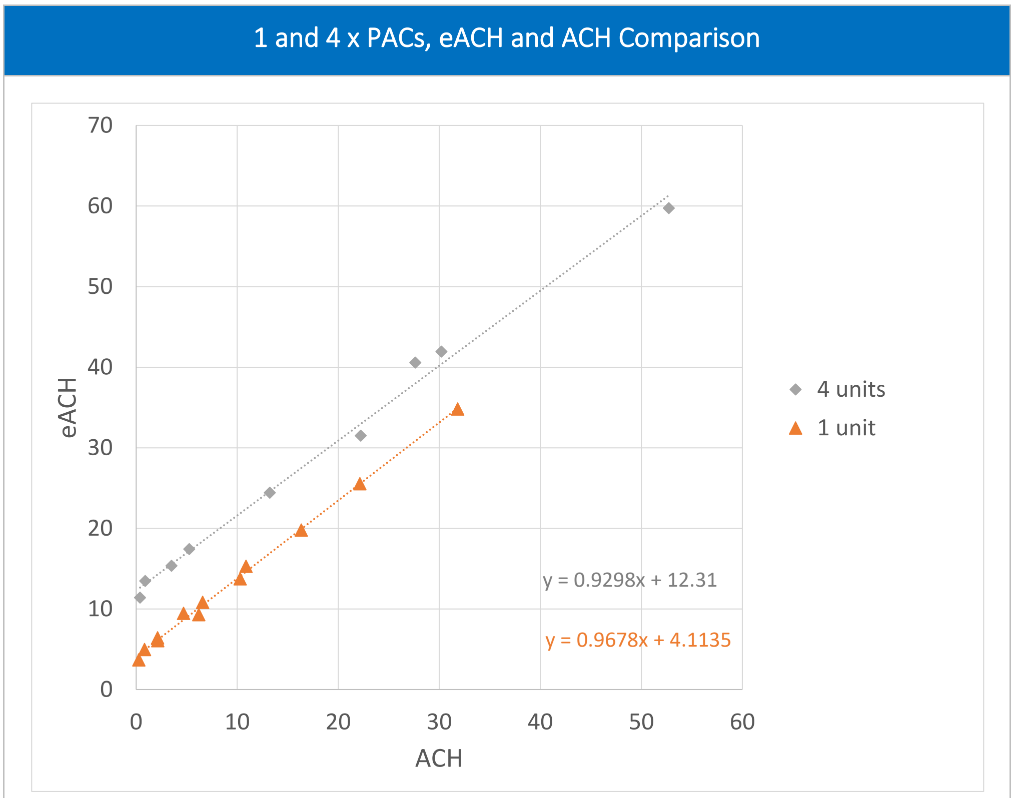


Figure 19: ACH and eACH comparison

3.3.3 Summary of Non-filtration Tests

The control room result indicates that portable air cleaners have an additive effect on decreasing $PM_{2.5}$ level (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 CADR ~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.

3.3 Temperature Differential (Test Scenario A4)

Over the two weeks of the experiment, a temperature differential test was carried out on three different days as shown in Table 7 below. The test was carried out around 4 am in each day to simulate winter conditions.

Table 7: Temperature Differential Test

Date	%Window Opening	Average Indoor Temperature (°C)	Average Outdoor Temperature (°C)	Difference between Indoor and Outdoor Temperature (°C)	Estimated Wind Speed (m s^{-1})
3/03/2022	25%	22.5	8	14.5	2.2
7/03/2022	25%	28.5	17	10.5	2.7
9/03/2022	25%	30.3	17	13.3	4.7

3.3.1 Temperature Penalties of Ventilation

Figure 20 shows 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 indicated 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 are too short to properly extrapolate them to understand what the penalty might be after 1 hour.

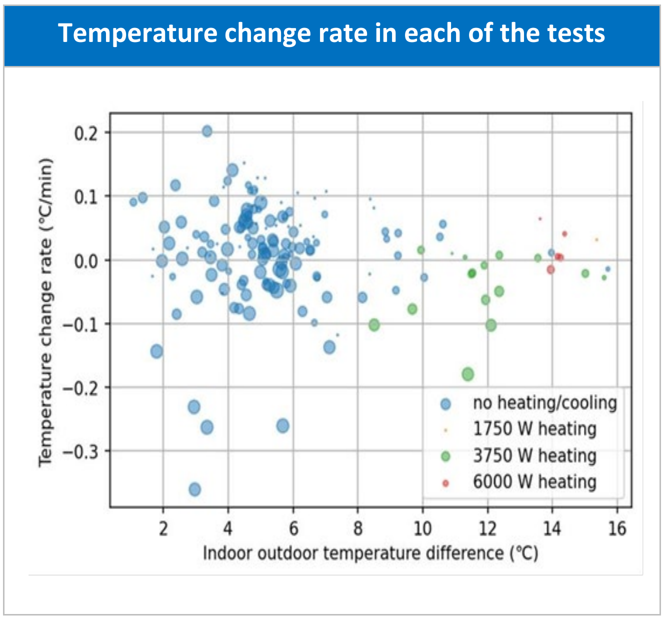


Figure 20: Temperature Penalties

3.3.2 *Ventilation vs Temperature*

Table 12 shows a comparison of indoor and outdoor temperatures with the ventilation rates associated with different window opening configurations, and with the average temperature change in degrees per minute after 45 minutes.

The data reveals that under simulated winter conditions (with a 8-14 ^{O}C indoor/outdoor temperature difference), at 25% openings ~3 ACH was achieved, and at 50% openings ~7 ACH was achieved (highlighted in green), and after 45 mins, there was no significant temperature drop.

Table 8: Ventilation vs Temperature

Window Opening Configuration	Averaged Outdoor Temperature	Averaged Indoor Temperature	Temperature Difference	Averaged Temperature Change Rate (ºC/min)	Temperature after 45 min	ACH	eACH
All windows and door shut	8.1	23.2	15.1	-0.013	22.4	1.0	1.5
25% north façade windows open with door shut	8.0	23.0	15.0	-0.028	21.7	1.7	2.2
25% all windows open with door shut	8.0	22.5	14.5	-0.022	22.0	3.0	3.8
25% upper north and south façade windows open, with door shut	7.8	22.6	14.8	0.003	23.1	2.4	3.2
25% all windows open, door shut, with 1 large PAC	9.1	23.0	13.9	0.006	23.3	2.7	6.2
50% all windows open with door shut	11.0	23.3	12.3	-0.038	21.3	7.7	8
75% all windows open with door shut	12.0	23.3	11.3	-0.100	18.5	11.6	12.4
100% all windows open with door shut	14.0	23.0	9.0	-0.108	18.1	9.6	10.2

3.3.2 *Temperature Drops Near the Windows*

Given that no significant temperature drop was observed, a heating test was carried out to compare the temperature change after 45 mins between the Hau-Hau monitor at the centre of the space (most frequently occupied part of a classroom) with the Hau-Hau monitors closer to the windows.

The ventilation and temperature differential tests were carried out with a window configuration of 50% upper north and south façade windows open, with door shut to ascertain the effectiveness of stack ventilation.

Table 13 shows that with the door shut, and the upper north and south windows (on both sides) opened to 50%, ~5.5 ACH was achieved and there was no significant temperature drop (highlighted in green).

Table 13 also shows that the variation between the two Hau Hau monitors placed closer to the windows, and the Hau-Hau monitor at the centre of the room was also relatively minor (-0.8°C).

Table 9: Temperature drops near the window

Window Opening Configuration	Averaged Outdoor Temperature (°C)	Averaged Indoor Temperature (°C)	Temperature Difference (°C)	Temperature at centre (°C)	Averaged Temperature Change Rate (°C)	Temperature after 45 min (°C)	Averaged Temperature near front windows (°C) and Averaged Temperature Change Rate (°C/min)		ACH	eACH
All windows and door shut	17	29.6	12.6	29.6	0.064	25.9	29.7	0.1	0.6	0.9
25% north facade windows open with door shut	17	30.1	13.1	30.1	0.041	24.8	29.8	-0.3	2	2.2
25% all windows open with door shut	17	30.3	13.3	30.2	0.003	23.1	29.8	-0.4	2.5	2.5
25% upper north and south façade windows open, with door shut	17	30.3	13.3	30.3	0.005	23.2	29.9	-0.4	2.2	2.1
50% upper north and south façade windows open, with door shut	17	30.3	13.3	30.4	-0.015	22.3	30.2	-0.2	5.5	5.3
25% all windows open with door shut (heating test)	17	30.2	13.2	30.4	0.002	23.1	29.6	-0.8		

3.3.3 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 air changes per hour can be achieved.

In cross ventilated rooms, and when there is ±8 ºC difference between indoor and outdoor temperatures, >5 ACH 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 temperature drop over 45mins is a single test, an extened thermal test may provide more insightful findings. The control room is located in Wellington and different locations in New Zealand may have different required heating power.

4.0 Discussion

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

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

This study explored the impact of different window opening areas on the effectiveness of natural ventilation and on temperature differential, and the role of supplementary ventilation measures. 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.
- This case study suggests that each m^2 of window or door effective opening area provides approximately 2.5 air changes per hour.
- This result is based on only a few days of testing. It is plausible that lower air change rates would have been achieved in lower wind speeds than were observed in this study.
- In the study classroom, the preferred minimum air change rate of 5 was therefore 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 and comfort penalty 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, or wind or rain intrusion, and 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, was 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 meduim PAC provided 2.7 effective air changes per hour.
- Units were additive with three units providing three times the particle removal.
- Units were not tested at lower speed 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 no significant drop in temperature within 45 minutes.

- Generally, air flow behaves differently at different temperatures – for example, the bigger 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., 2.5-5 cm) to achieve good ventilation.

- However, given that this involved simulating winter conditions in late summer/early autumn and the limited duration of testing, the consistency of these results on a typical cold winter day and for the 8 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 minimizing 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 measures. 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 affirm that opening windows, doors, and any other openings 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 when 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 air cleaners become a practical supplementary solution that is not dependent on ambient conditions.
- However, 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.

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

The limitations of this study are:

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

Future studies should explore various ventilation measures 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 closed rooms that are occupied by more than a single person, such as conference rooms, waiting rooms and shared offices.

6.0 References

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Glossary of Abbreviations and Terms

Abbrevations	Description
ACH	Air Changes per Hour
eACH	Effective Air Changes per Hour
CO_2	Carbon dioxide
ppm	Parts per million
Turbine	Also called ‘Roofquip whirly vent’ are wind-powered ventilation system
PAC	Portable Air Cleaner

List of Tables

List of Figures

Appendix A – Discharge Coefficient Calculation

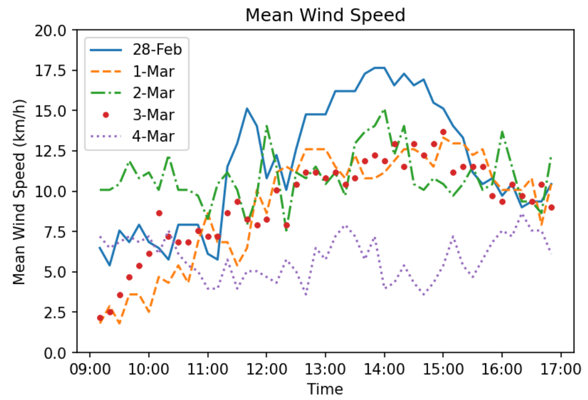
The 'effective window opening area' and the discharge coefficient below has been calculated as per Jones et al., (2016a, 2016b).

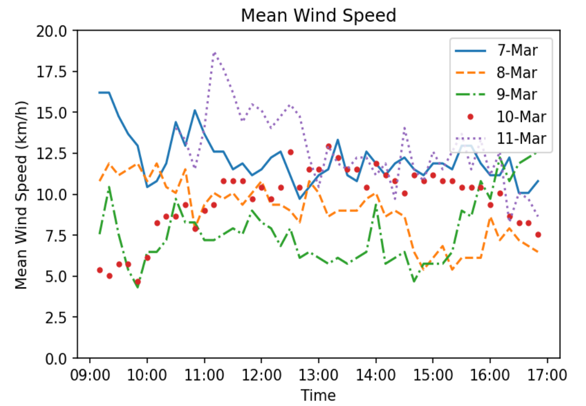
North Elevation Windows (Double Row)			
Description of window opening	Restrictor opening length	Effective Openable Area	Discharge Coefficient (C_d)
25%	25mm	0.023m^2	0.05
50%	50mm	0.044m^2	0.10
75%	75mm	0.064m^2	0.14
100%	100mm	0.084m^2	0.17

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

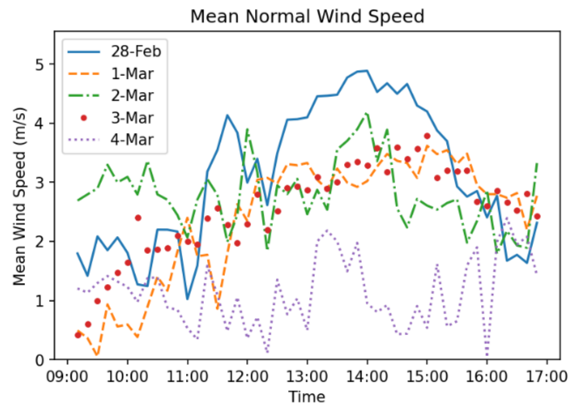
Appendix B – Wind Results

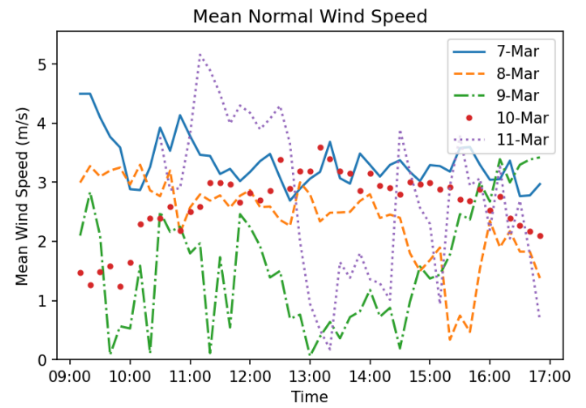
Mean Wind Speed from 28 February to 11 March



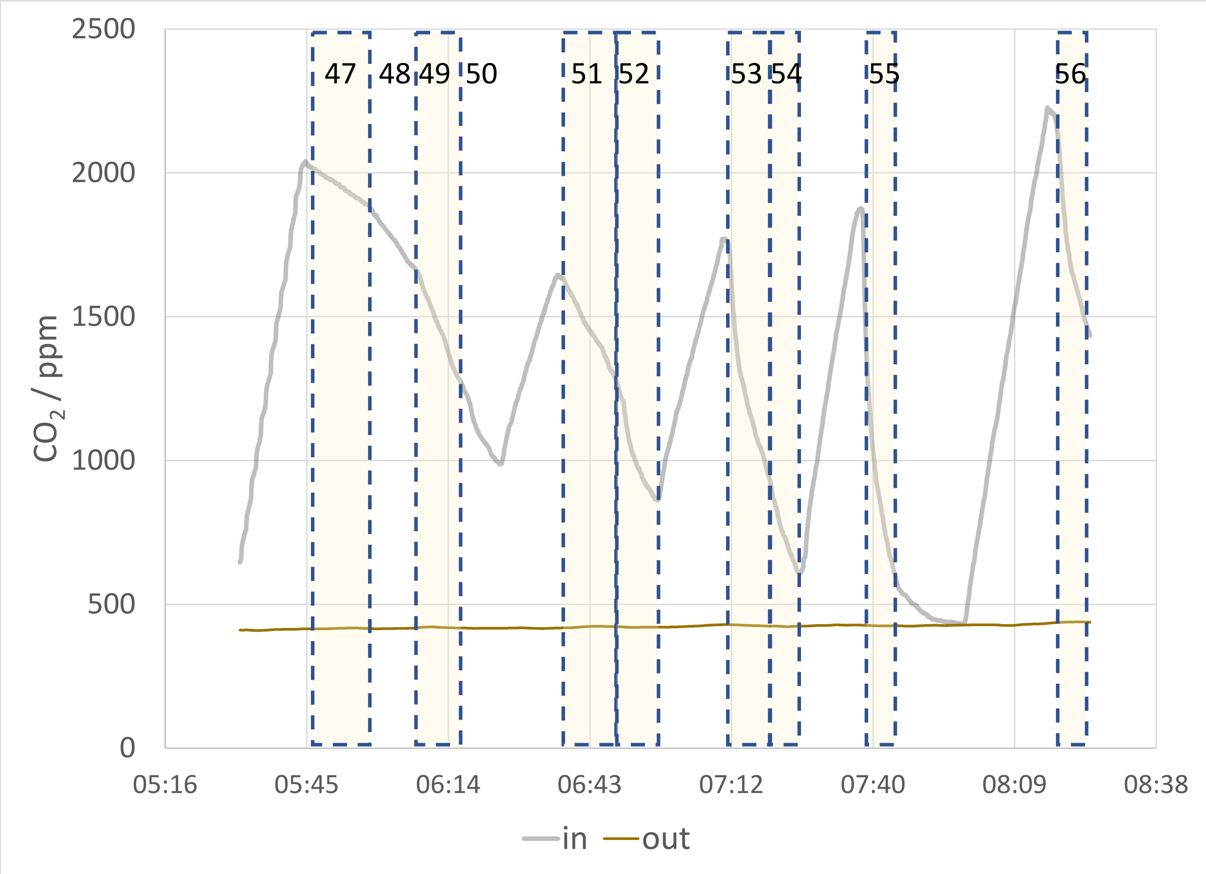


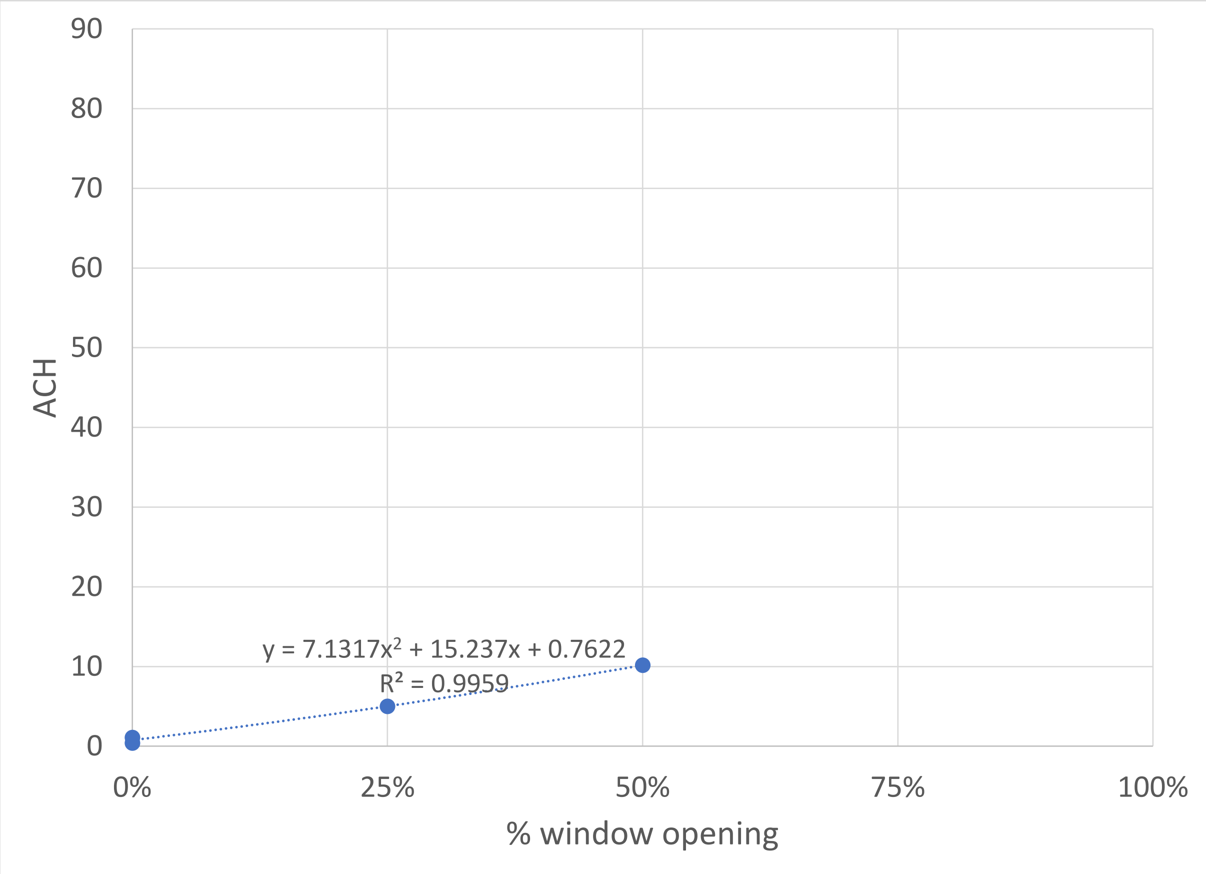
Mean Normal Wind Speed from 28 February to 11 March

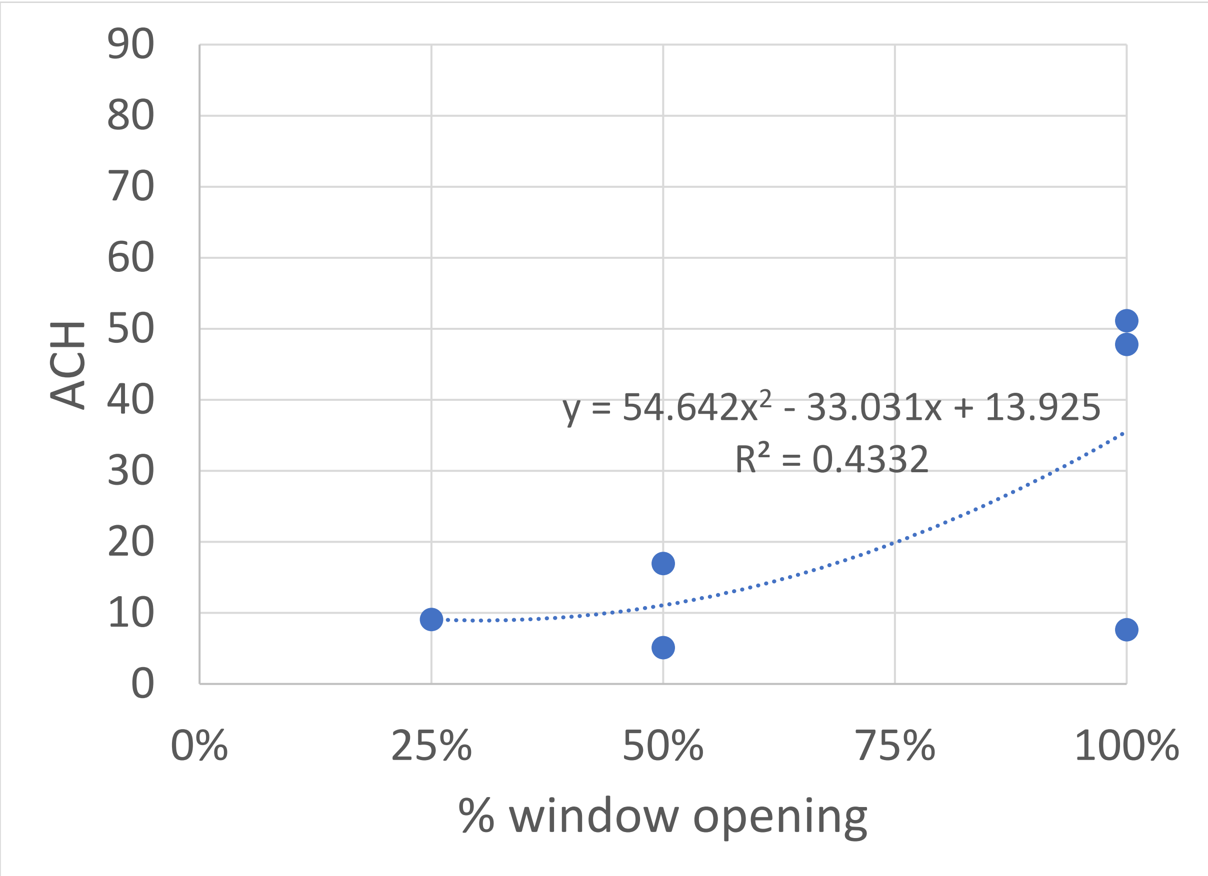


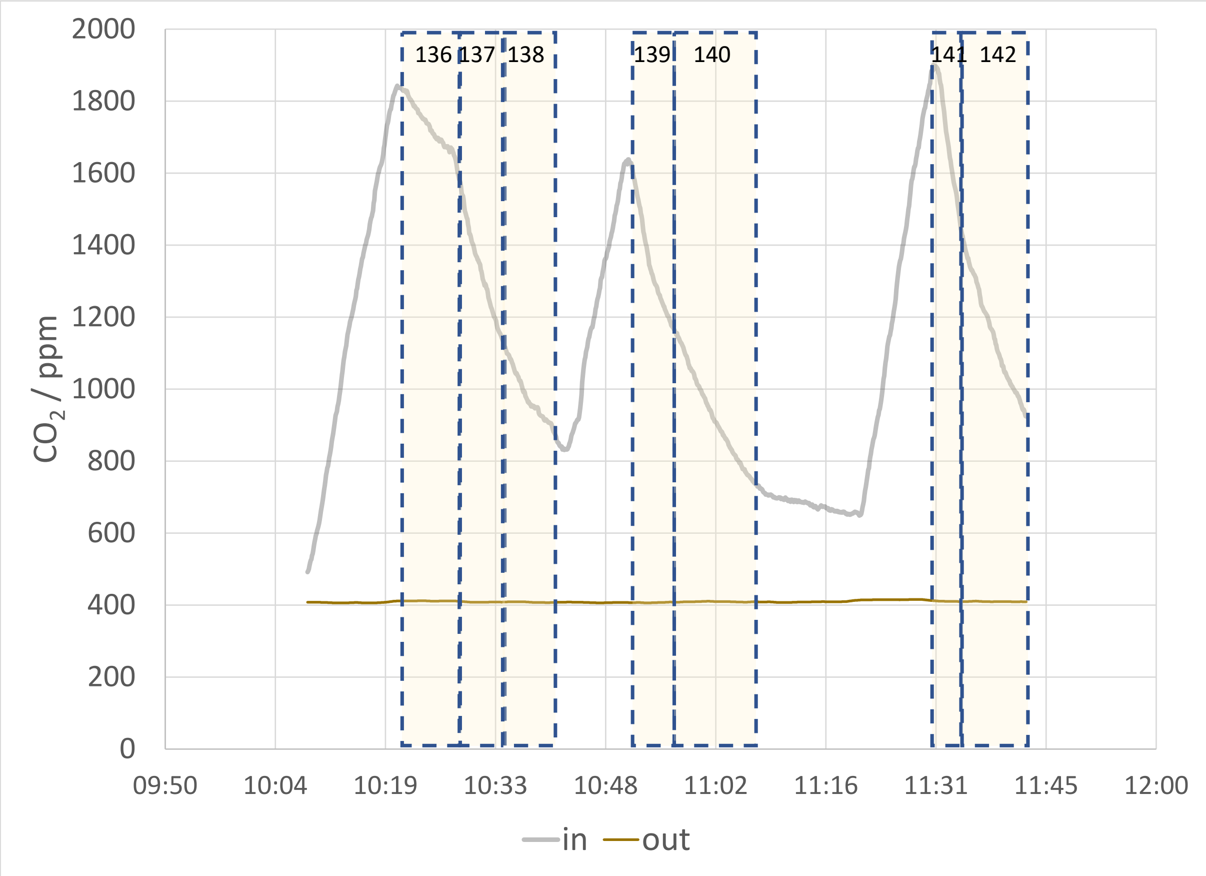


Appendix C - Natural Ventilation Results

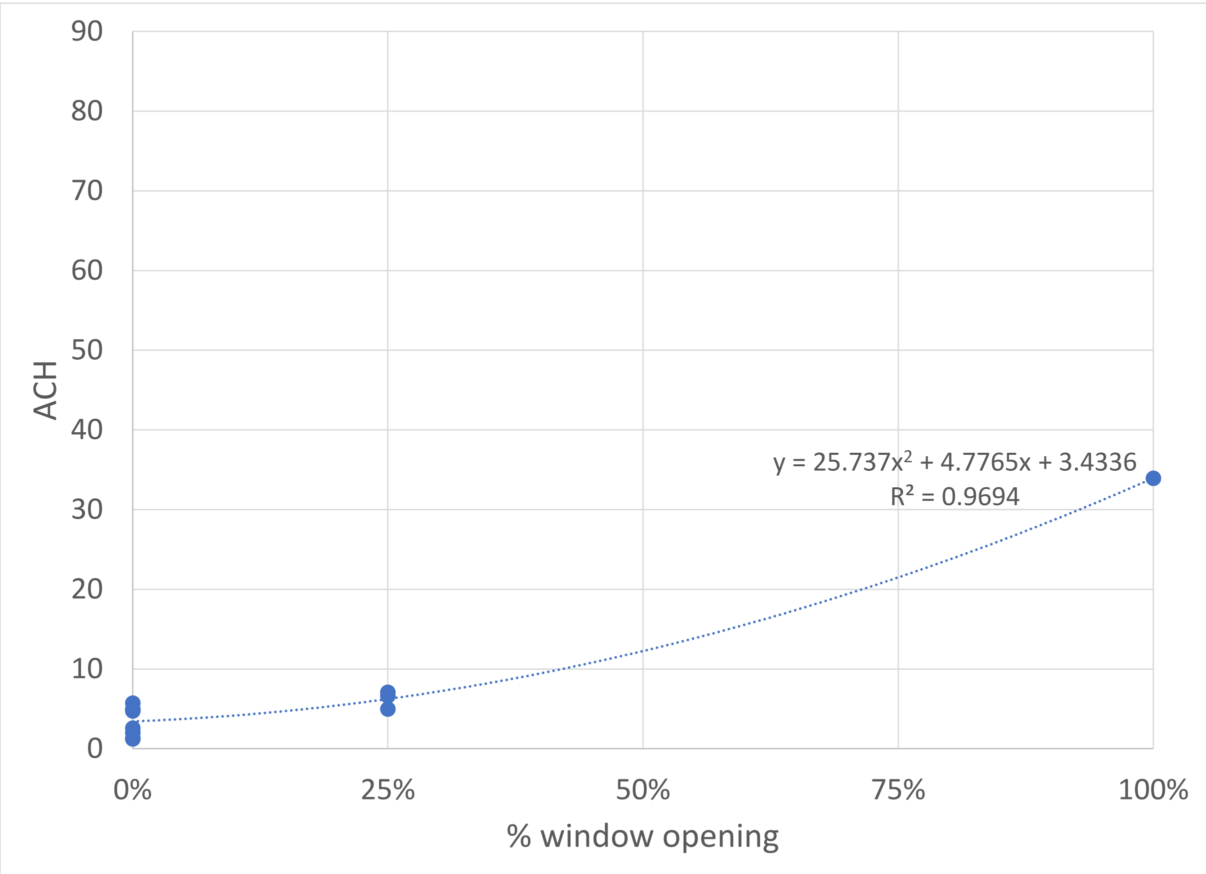



ACH
90
80
70
60
50
40
30
20
10
0
y = 7.1317x² + 15.237x + 0.7622
R² = 0.9959
0%
25%
50%
75%
100%
% window opening

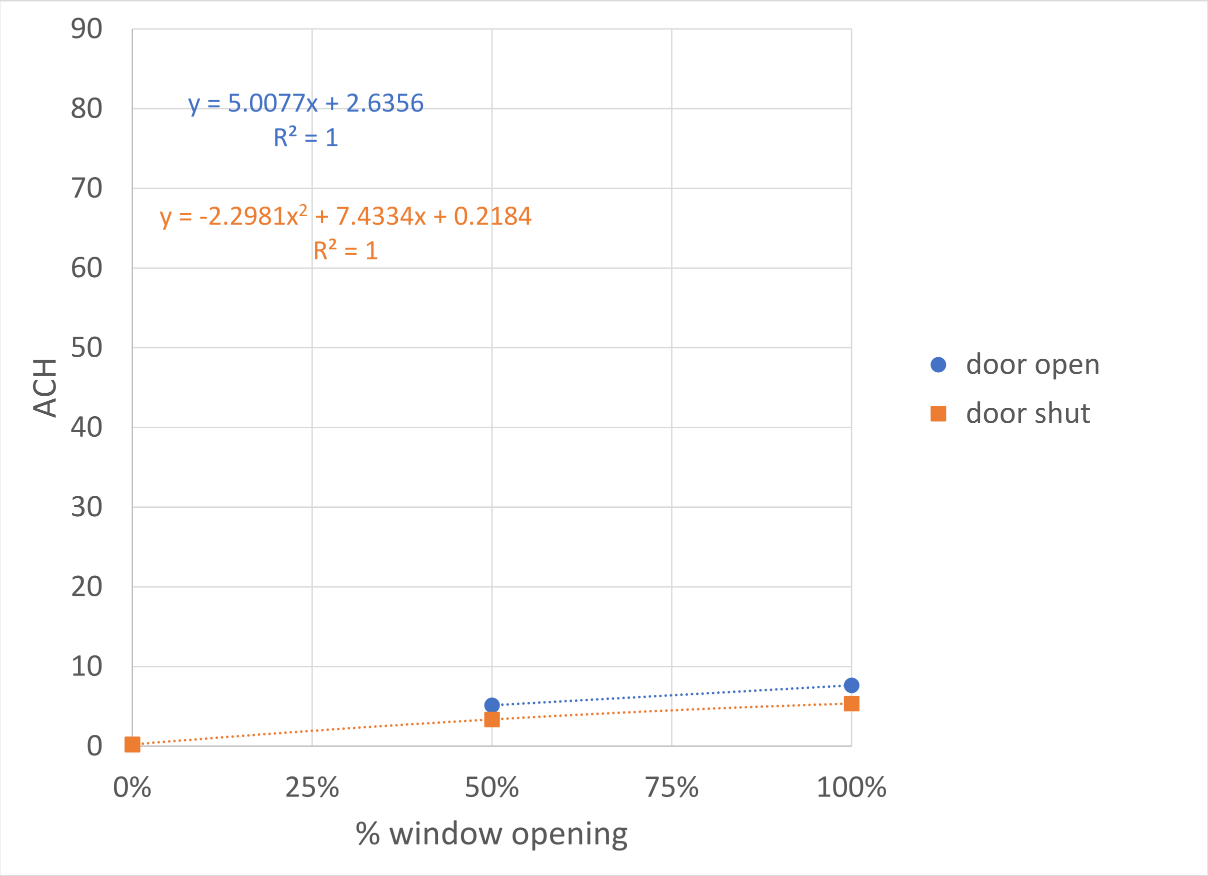

ACH
90
80
70
60
50
40
30
20
10
0
y = 54.642x² - 33.031x + 13.925
R² = 0.4332
0%
25%
50%
75%
100%
% window opening



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



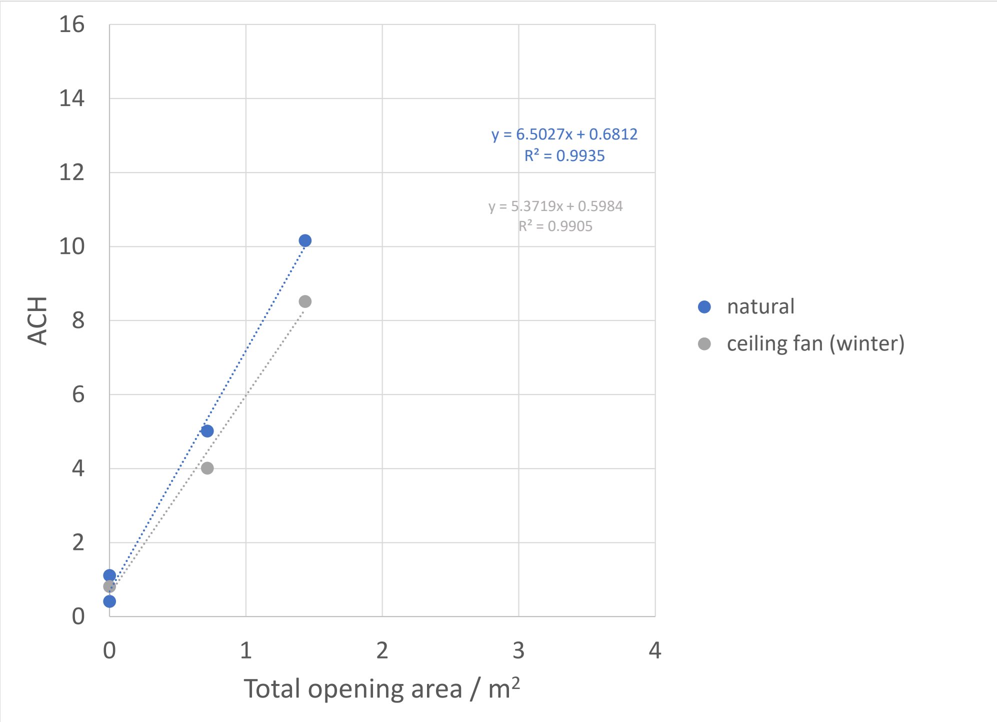
90
80
70
60
50
40
30
20
10
0
ACH
$y = 25.737x^2 + 4.7765x + 3.4336$
$R^2 = 0.9694$
0%
25%
50%
75%
100%
% window opening



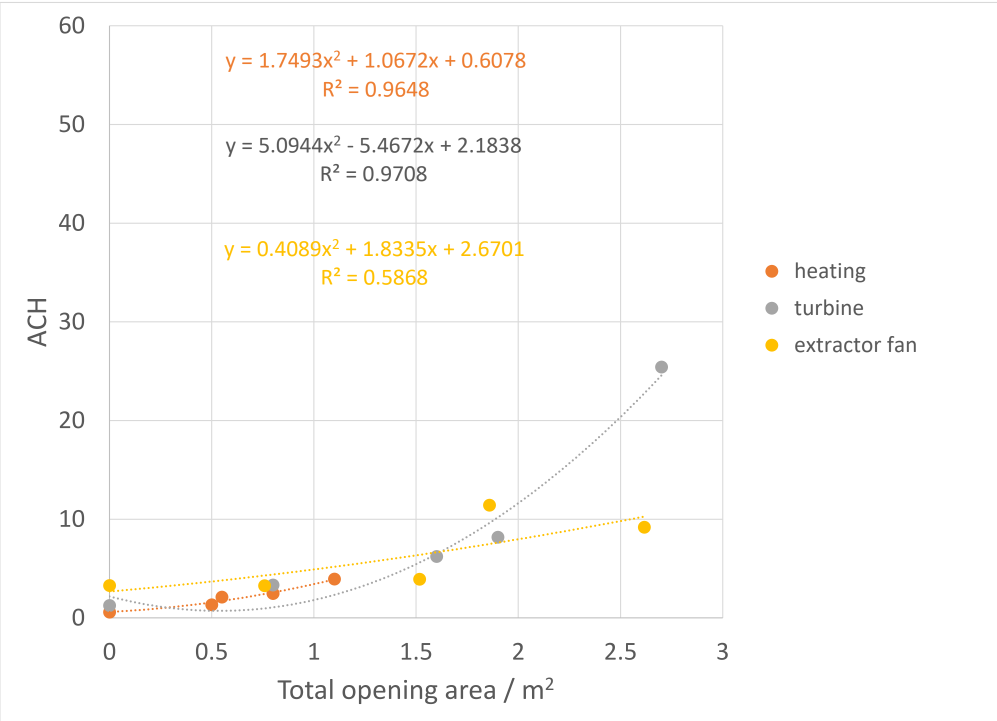
90
80
70
60
50
40
30
20
10
0
ACH
y = 5.0077x + 2.6356
R² = 1
y = -2.2981x² + 7.4334x + 0.2184
R² = 1
0%
25%
50%
75%
100%
% window opening
door open
door shut

Appendix D - Augmented Ventilation Results

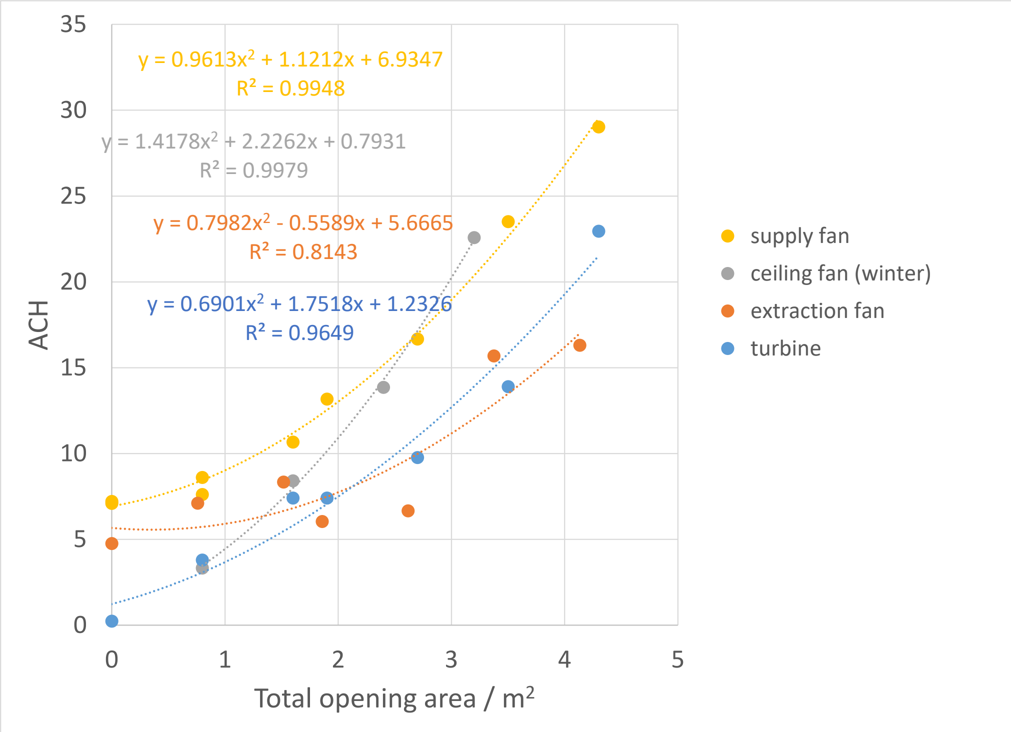
8 March: Ceiling fan test



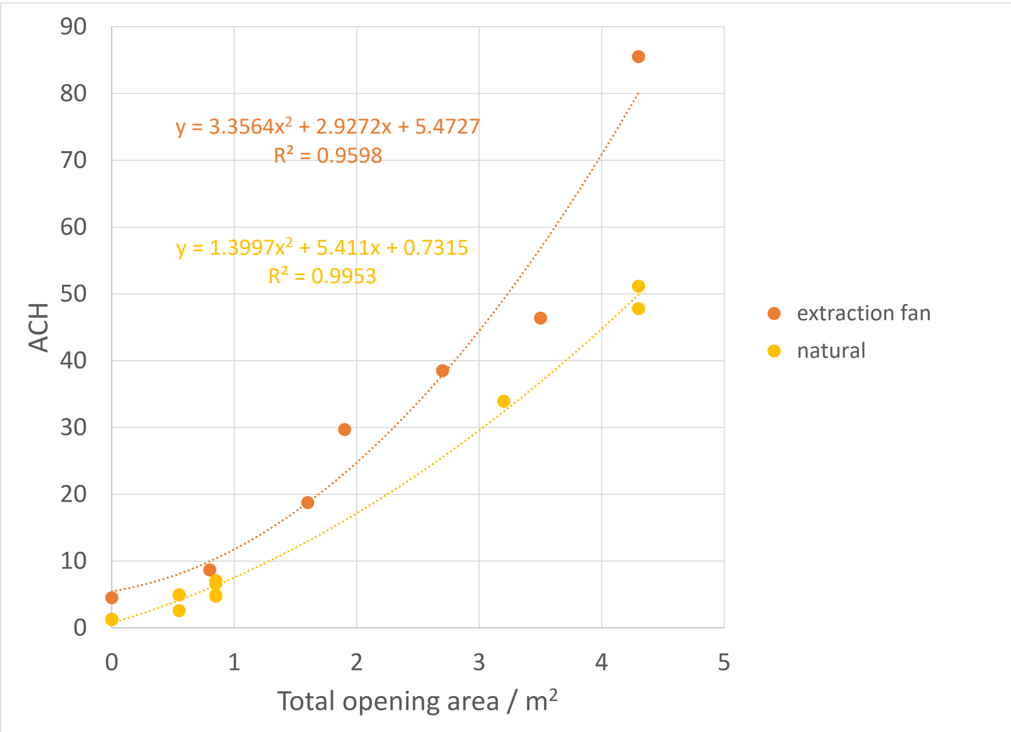
9 March: Heating, turbine, extractor fan



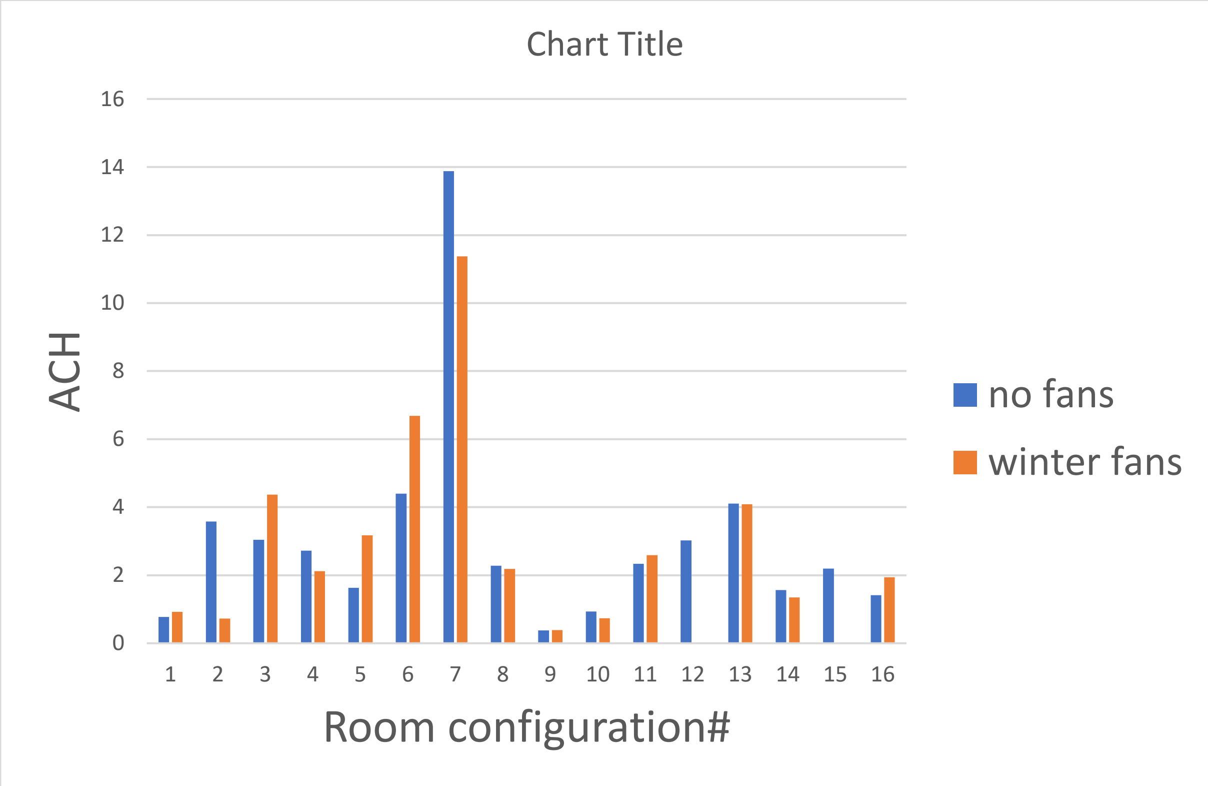
10 March: supply fan, extractor fan, turbine, ceiling fan

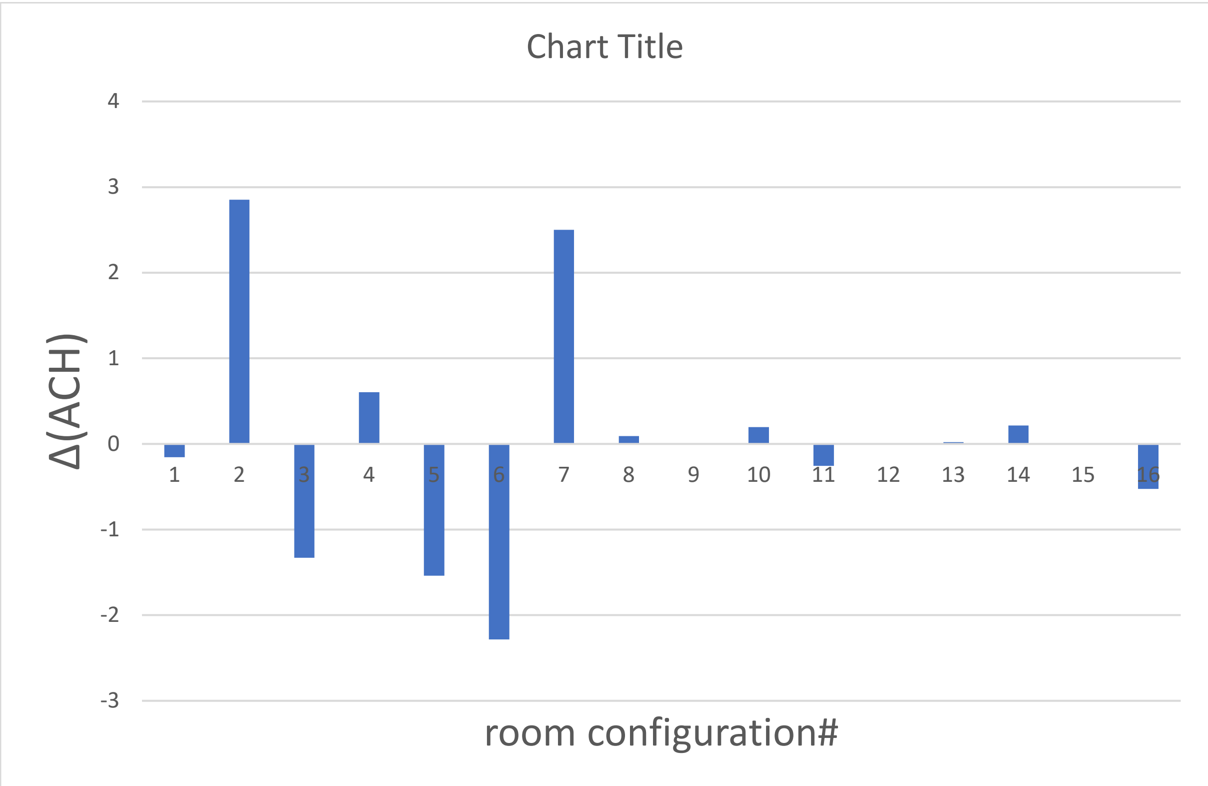


11 March: extractor fan



Supplementary Ceiling Fan Test





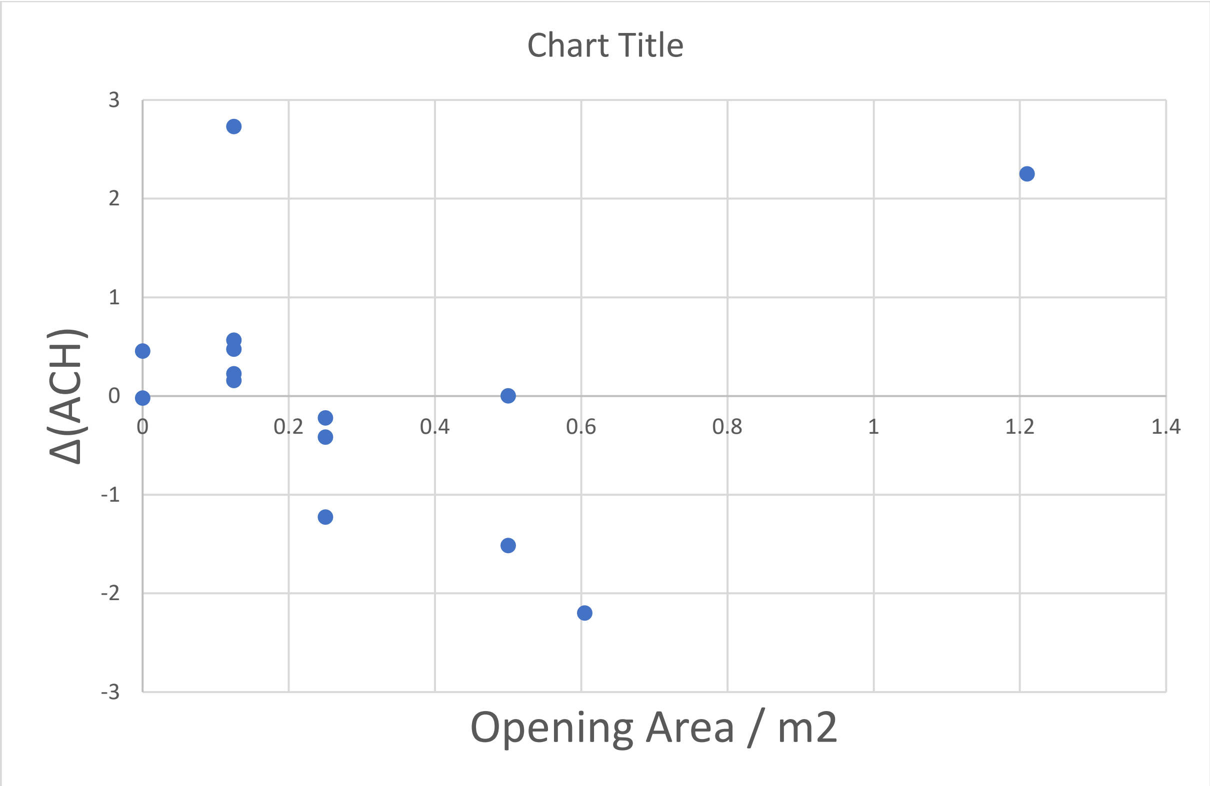


Chart Title
Δ(ACH)
Opening Area / m2
3
2
1
0
-1
-2
-3
0
0.2
0.4
0.6
0.8
1
1.2
1.4

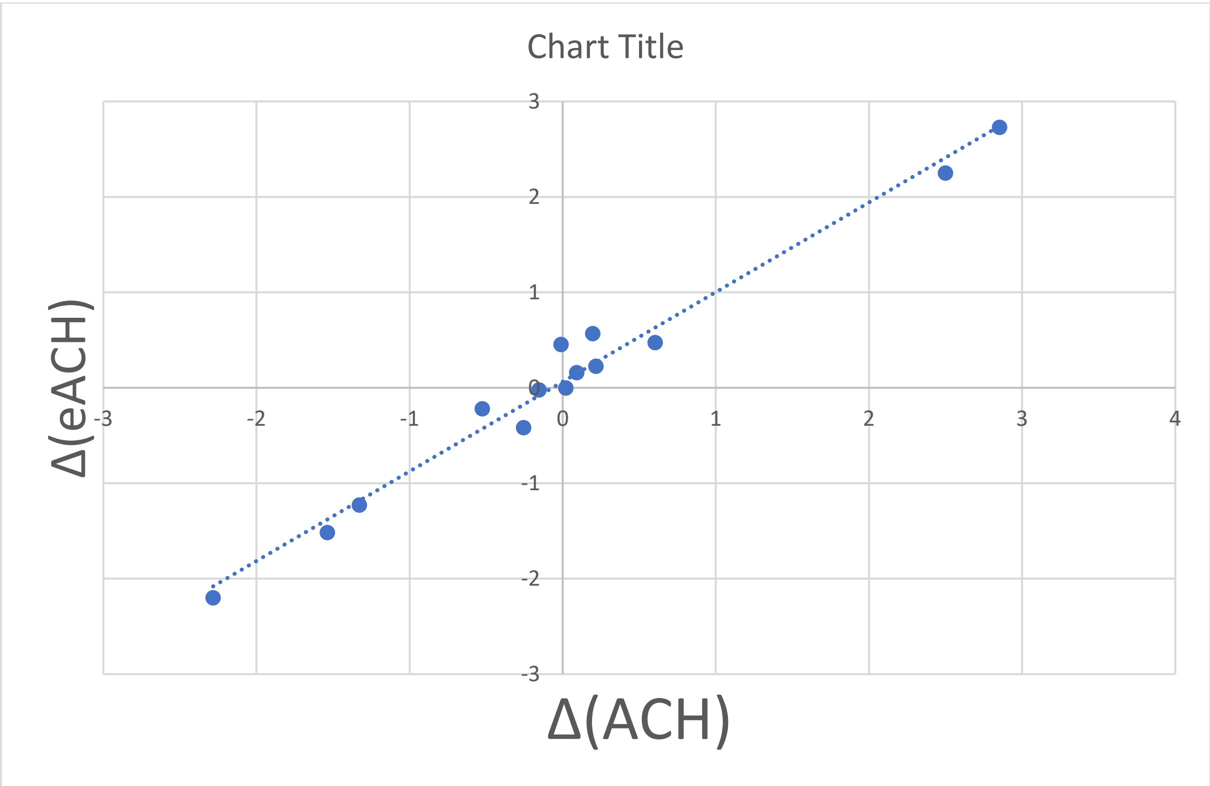


Chart Title
Δ(eACH)
Δ(ACH)
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3
4

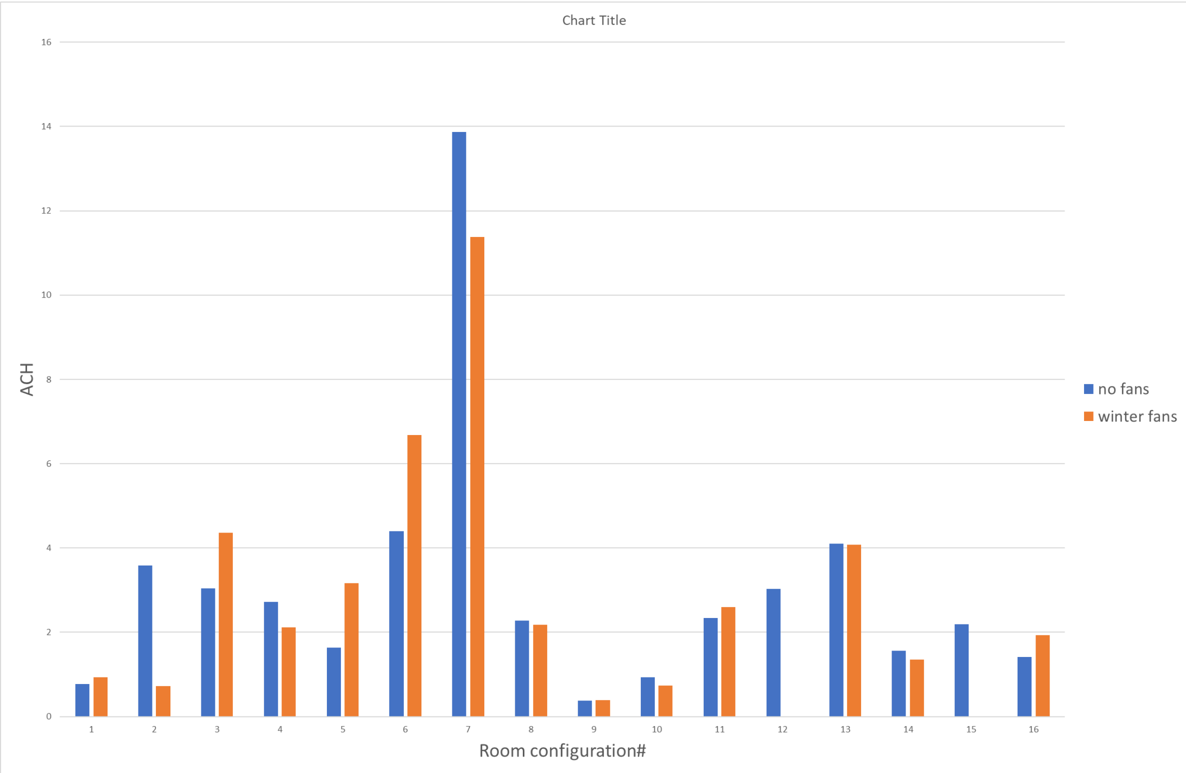


Chart Title
ACH
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Room configuration#
no fans
winter fans