Effects of operating a solar air heater on the indoor air quality in classrooms during the winter

A case study of Palmerston North primary schools

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To all my grandparents, in memoriam.

To my amazing parents, with love and thanks.

Abstract

Schools are densely populated places, where children spend a large amount of their time. The indoor air quality (IAQ) in classrooms impacts students' health, academic outcomes and school absences (Borras-Santos *et al.*, 2013; Mi *et al.*, 2006; Shendell, Prill, *et al.*, 2004; Smedje and Norbäck, 2000; Taskinen *et al.*, 2007). Three New Zealand (NZ) studies have found low ventilation rates, low temperature levels, high relative humidity (RH) levels and high carbon dioxide (CO_2) levels during the winter months in NZ primary schools (Bassett and Gibson, 1999; Cutler-Welsh, 2006; McIntosh, 2011). These results show a need to improve the indoor environment in NZ schools during the winter. NZ school hours, from 9 am to 3 pm, are well aligned with the optimum solar radiation and classrooms lend themselves to heat from solar energy. A project was undertaken to investigate if operating a roof-mounted solar air heater (SAH) could improve the classroom IAQ during the winter.

This two-year crossover project was undertaken in four Palmerston North (PN), NZ primary schools in 2013 and six PN, NZ primary schools in 2014. These consisted of the four schools participated in 2013 plus two additional schools. In each school, two adjacent classrooms with similar construction characteristics and population characteristics participated in this project. The two adjacent classrooms were randomly assigned either to a treatment group (SAH installed and operated) or to a control group (SAH installed but not operated). The main objective of this project was to investigate the change in levels of the classroom temperature, RH, CO_2, and ventilation rate from when a roof-mounted SAH was operating (treatment) and was not operating (control).

Resulting from operating the roof-mounted SAH, the temperature in treatment classrooms was on average 0.5 °C higher than in the control classrooms, when both the control and treatment classrooms had the same heater use. When the control and treatment classrooms achieved the same temperature, the heater use in the treatment classrooms was 27% less than the heater use in the control classrooms. Across all schools, CO_2 levels in the treatment classrooms were on average 96 ppm lower than in the control classrooms. In five out of 10 schools (50%), the levels of CO_2 in the treatment classrooms were lower than in the control classrooms. Only in one treatment classroom did the ventilation rate meet the NZ Ministry of Education recommended level of 4 air changes per hour.

Overall, operating a roof-mounted SAH played a positive role in increasing the temperature and ventilation rate in classrooms during the winter. However, there was not sufficient airflow to satisfy the ventilation requirements. Future research should investigate the impact of operating a SAH on the school ventilation and temperature considering increasing the SAH outlet air volumetric flow rate and keeping the outlet air temperature around 18 °C to bring more heated air into classrooms.

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"Isn't it funny how day by day nothing changes, but when you look back, everything is different…" -- C.S. Lewis, Source: "Prince Caspian 1951"

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At the moment I achieve this big milestone, I have thought a lot about all my four late grandparents and how you would be immensely proud of your little granddaughter and how your approval would have been expressed in proud smiles, emotional tears and celebratory meals.

Finally, but most importantly, thanks to myself for the hard-working throughout this project.

List of Abbreviations

ACH	air changes per hour (ACH, h^{-1})
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
ASTM	American Society for Testing and Materials
BRANZ	Building Research Association of New Zealand
CEN	European Committee for Standardisation
CI	confidence interval (95% CI)
CO_2	carbon dioxide
dCO_2	the difference between indoor CO_2 levels and ambient CO_2 levels
DQLS	Design Quantity Learning Space
HHH study	Housing, Heating and Health study
HR	humidity ratio (g/kg)
HVAC	Heating, ventilation and air conditioning
IAQ	indoor air quality
ISO	International Organisation for Standardisation
l/s/person	litres of fresh air per second per person
NIWA	National Institute of Water and Atmospheric Research
NZ	New Zealand
NZBC	New Zealand Building Code
NZMoE	New Zealand Ministry of Education
NZS	New Zealand standards
OR	odds ratio
PM	particulate matter
PN	Palmerston North
ppm	parts per million
Q_1	the first quartile
Q_3	the third quartile
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
RH	relative humidity (%)
SAH	solar air heater
SNZ	Standards New Zealand
SD	standard deviation
SINPHONIE	Schools Indoor Pollution and Health: Observatory Network in Europe
T/C ratio	The ratio of the heater use in the treatment classrooms to the heater use in the control classrooms
US EPA	United States Environmental Protection Agency
VOCs	volatile organic compounds
WHO	World Health Organisation
ΔT ($T_{outlet} - T_{inlet}$)	the temperature difference between the outlet air and the inlet air of a solar air heater

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List of Papers

The preliminary results of this PhD study have been published in the following papers. These papers are listed in date order of publication.

I. **Wang Y.**, Boulic M., Phipps R., Plagmann M., Cunningham C., Theobald C., Howden-Chapman P., Baker M., (2014). Effects of solar collectors on indoor air quality in junior classrooms in winter 2013. *In Building a Better New Zealand Conference (BBNZ 2014)*. Auckland, New Zealand.

II. Boulic M., **Wang Y.**, Phipps R., Plagmann M., Cunningham C., Theobald C., Howden-Chapman P., Baker M., Trompetter B., (2014). Improving health and well-being in low decile classrooms with a solar ventilation system. *Proceedings of the 4th Annual New Zealand Built Environment Research Symposium (NZBERS 2015)*. Auckland, New Zealand, 115-117.

III. Boulic M., **Wang Y.**, Phipps R., Plagmann M., Cunningham C., Theobald C., Howden-Chapman P., Baker M., (2016). Increasing the ventilation rate and temperature in New Zealand classrooms using a solar roof collector. *In Central European towards Sustainable Building 2016 (CESB16)*. Prague, Czech Republic.

IV. **Wang Y.**, Boulic M., Phipps R., Plagmann M., Cunningham C., Theobald C., Howden-Chapman P., Baker M., (2016). Impacts of a solar ventilation unit on temperature and ventilation rate in New Zealand schools: an intervention study. *Proceedings of the 14th International Conference of Indoor Air Quality and Climate (INDOOR AIR 2016)*. Ghent, Belgium.

V. **Wang Y.**, Boulic M., Phipps R., Plagmann M., Cunningham C., Theobald C., Howden-Chapman P., Baker M., (2017). Estimate the ventilation rate in two New Zealand primary classrooms. *In the 5th Annual New Zealand Built Environment Symposium (NZBERS 2017)*. Auckland, New Zealand.

VI. **Wang Y.**, Boulic M., Phipps R., Plagmann M., Cunningham C., Theobald C., Howden-Chapman P., Baker M., (2018). Is the temperature and ventilation of New Zealand classrooms following the newly released requirements? *Proceedings of the 15th International Conference of Indoor Air Quality and Climate (INDOOR AIR 2018)*. Philadelphia, USA.

VII. Trompetter W.J., Boulic M., Ancelet T., Garcia-Ramirez J.C., Davy P.K., **Wang Y.**, Phipps R. (2018). The effect of ventilation on air particulate matter in school classrooms. *Journal of Building Engineering*. 18, 164-171.

VIII. **Wang Y.**, Boulic M., Phipps R., Plagmann M., Cunningham C., (2020). Experimental Performance of a Solar Air Collector with a Perforated Back Plate in New Zealand. *Energies*. 13(6), 1415.

Further papers (related to but not directly from my PhD project) have been published during the time I was working on my PhD project.

IX. **Wang Y.**, Boulic M., Phipps R., Chitty C., Moses A., Weyers R., Jang-Jaccard J., Olivares G., Ponder-Sutton A., Cunninghan C., the Healthy School Research Team, (2017). Integrating open-source technologies to build a school indoor air quality monitoring box (SKOMOBO). *In the 4th Asia-Pacific World Congress on Computer Science and Engineering (APWC on CSE)*. Nadi, Fiji.

X. Weyers R., Jang-Jaccard J., Moses A., **Wang Y.**, Boulic M., Chitty C., Phipps R., Cunningham C., the Healthy School Research Team, (2017). Low-cost indoor air quality platform for healthier classrooms in New Zealand: engineering issues. *In the 4th Asia-Pacific World Congress on Computer Science and Engineering (APWC on CSE)*. Nadi, Fiji.

XI. **Wang Y.**, Jang-Jaccard J., Boulic M., Phipps R., Chitty C., Weyers R., Moses A., Olivares G., Ponder-Sutton A., Cunningham, C., the Healthy School Research Team, (2018). Deployment issues for integrated open-source based indoor air quality school monitoring box (SKOMOBO). *In 2018 IEEE Sensors Applications Symposium (SAS)*. Seoul, South Korea.

XII. Boulic M., **Wang Y.**, Phipps R., Chitty C., Cunningham C., Moses A., Weyers R., Jang-Jaccard J., Olivares G., Shekar A., Longley I., Tookey L., Ponder-Sutton A., the Healthy School Research Team, (2018). A breath of fresh air: engaging school-aged students with air quality science in New Zealand schools. *Proceedings of the 15th International Conference of Indoor Air Quality and Climate (INDOOR AIR 2018)*. Philadelphia, USA.

XIII. Bennett J., Davy P., Trompetter B., **Wang Y.**, Pierse N., Boulic M., Phipps R., Howden-Chapman P., (2018). Sources of indoor air pollution at a New Zealand urban primary school: a case study. *Atmospheric Pollution Research*. 10 (2), 435-444.

My contribution to the papers

For papers (I to VII), I carried out the fieldwork and collected the data, with the assistance of Dr. Mikael Boulic. For Paper I and papers (IV to VI), I analysed the data and wrote the first draft of these papers. For Paper II and Paper III, I analysed the data, while Dr Mikael Boulic wrote the first draft. The co-authors made comments and edited these papers.

For Paper VIII, Y.W., M.B. and R.P. conceived and designed the experiment; Y.W. performed the experiment, analysed the data and wrote the paper; M.B., R.P., M.P. and C.C. reviewed the paper and provided the useful feedback.

Papers IX to XIII report the research output from a sequel school indoor air quality monitoring project. I worked on this project as an Assistant Research Officer (part-time). I was in charge of the sub-project management, product development lab testing and fieldwork supervision. I carried out the fieldwork, undertook the data collection, analysed the data for these five papers and wrote the draft of Paper IX and Paper X. For paper XIII, I undertook the fieldwork and analysed the data (classroom ventilation part).

I presented the results from Paper I and Paper V, as the principal researcher at the conferences.

1 Introduction

The New Zealand (NZ) Housing, Heating and Health study (HHH study) showed that improving the home environment (consisting of an upgrade to the insulation and heating) significantly improved children's asthma, namely there was less coughing/wheezing, fewer episodes of colds and respiratory symptoms, fewer visits to the general practitioner (Howden-Chapman *et al.*, 2008), and reduced preventable absences from school (Free *et al.*, 2010). A natural follow up study from this successful NZ home intervention study, was to investigate the environment where children spend the second largest proportion of their time, namely the school environment.

In NZ, previous studies reported that temperature and ventilation levels in primary schools in winter fail to meet World Health Organisation (WHO) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) guidelines (Bassett *et al.*, 1999; Cutler-Welsh, 2006; McIntosh, 2011). The learning environment is vital to the student health and academic performance (Chatzidiakou *et al.*, 2012). The substandard school environment adversely affects children's health and academic performance. Therefore, it is needed to find solutions to provide children with a healthy learning environment. Traditional solutions use the purchased energy to operate the heater or run the mechanical ventilation system. However, NZ Ministry of Education (NZMoE) introduced the capped energy in 2010, namely the heat, light and water funding was fixed at an amount for each school, based on the school's relevant expenditure over the previous three years (Ministry of Education, 2010). This means an alternative and affordable method for providing a good indoor air quality (IAQ) in NZ primary schools in winter is needed. In NZ, school hours, generally from 9 am to 3 pm, are closely aligned with the optimum solar radiation (Jaquiery, 2018). Consequently, NZ schools are an ideal environment for the use of solar energy. In this context, this study is conducted with the aim to investigate the change in classroom temperature, humidity, carbon dioxide (CO_2) and ventilation rate when a roof-mounted solar air heater (SAH) is operated.

1.1 Background

The school environment is important, as children spend a large amount of time in a classroom, they have an underdeveloped immune system, and they inhale a higher volume of air per kilogram of body mass than adults (Mathieu-Nolf, 2002). The WHO, ASHRAE and the European Committee for Standardisation (CEN) have set recommended levels for many environmental parameters for the healthy and comfortable IAQ (ASHRAE, 2013, 2016; CEN, 2007; WHO, 1987, 2009, 2010).

Temperature, humidity and ventilation are the important monitored parameters for IAQ in schools (Nielsen, 2004). These three parameters are interdependent and must be considered together (BRANZ, 2007a). Levels of CO_2 can be used to estimate the ventilation rate of a building (or a room), where there are significant metabolic or combustion sources (Health Canada, 1989) or when the indoor CO_2 level is above the outdoor CO_2 level (Persily, 1997). An indoor CO_2 concentration below 1000 ppm is required to achieve the minimum ventilation rate (ASHRAE, 2016). NZMoE has set recommended levels for ventilation and thermal comfort in the school environment (Ministry of Education, 2017a). The mandatory requirements from NZMoE are the mean CO_2 concentration in the occupied space should be in the 1000–1500 ppm range. The temperature levels should average 18–25 °C during the winter seasons.

NZ studies have reported low indoor temperature, high relative humidity (RH) and high CO_2 levels (equivalent to a low ventilation rate) in primary schools in winter (Bassett *et al.*, 1999; Cutler-Welsh, 2006; McIntosh, 2011). Poor IAQ in primary schools can adversely impact on students' respiratory health, learning outcomes and productivity (Al Horr *et al.*, 2016; Borras-Santos *et al.*, 2013; Mi *et al.*, 2006; Shendell, Prill*, et al.*, 2004; Smedje *et al.*, 2000; Taskinen *et al.*, 2007). Therefore, there is a need to provide children with a good IAQ (temperature, humidity and ventilation) in NZ primary schools in winter.

The total ventilation rate of a building (or a room) is equal to the sum of the natural ventilation, mechanical ventilation and infiltration. Infiltration is a result of air moving through the cracks or openings of the building envelope. Research shows that well designed, well maintained and well operated mechanically ventilated classrooms had an acceptable ventilation rate (Canha *et al.*, 2013; Gao *et al.*, 2014). However, mechanical ventilation systems are capital and energy expensive, and need maintenance (Angelon-Gaetz *et al.*, 2015; Cutler-Welsh, 2006). Mechanical ventilation systems are not affordable for most NZ schools, especially following the introduction in 2010 by NZMoE of the capped budget for purchased energy (Ministry of Education, 2010). Consequently, an alternative and affordable method for providing a good IAQ (temperature, humidity and ventilation) in NZ primary schools in winter is needed.

In NZ, school hours are closely aligned with the optimum solar radiation (Jaquiery, 2018). Consequently, NZ schools are an ideal environment for the use of solar energy. Solar chimneys, Trombe walls, solar walls and SAHs can be used for space heating and ventilation (Kalogirou, 2004; Saadatian *et al.*, 2012; Thirugnanasambandam *et al.*, 2010).

The working principle of these technologies varies because of the differences in the design and application (Chan *et al.*, 2010). The performance of each of these solar thermal technologies is climate dependent. They are more efficient in regions with a high level of solar radiation during the cold winter months. A solar chimney consists of a black-painted chimney. It can be used to harness solar energy to generate vertical stack ventilation. However, solar chimneys are commonly used during the cooling seasons, and are rarely used in single storey buildings, like NZ primary schools, as a sufficient height is needed to drive the stack effect (Zhai *et al.*, 2011).

The Trombe wall was invented for the regions at high altitudes with cold climates (Gupta and Singh, 1987). The classical Trombe wall is a large blackened high thermal mass wall (normally concrete) located behind a sun-facing glazed outer skin. It has an air gap between the exterior glazed layer and the blackened wall. However, NZ primary schools are typically constructed with a timber-framed wall (light thermal mass). A large Trombe wall will reduce daylighting availability in a building, as the blackened high thermal mass wall will prevent the sunlight from getting into buildings. Therefore, both solar chimneys and Trombe walls would not be suitable as retrofit solutions to existing NZ school buildings (single storey and light thermal mass wall).

The solar wall system is composed of a metal cladding installed over the high thermal mass exterior walls. The metal cladding can be either perforated or non-perforated. Two NZ studies have been reported using both perforated and non-perforated solar walls to improve the indoor environment of residential and school buildings (Heinrich, 2007; Jaques and Burgess, 2010). Results from these two studies showed shading from adjacent structures, solar wall mounting levels and building interior wall thermal mass levels influenced the outlet air temperature. There were no significant differences in the outlet air temperature from these two types of solar wall (perforated and non-perforated). These two studies only looked at the flow rate and the air temperature rise (temperature difference between the outlet and inlet air) of the solar wall (Heinrich, 2007; Jaques *et al.*, 2010). Neither measured any change in indoor IAQ (such as temperature, RH, CO_2 and ventilation rate) following the intervention.

Stasinopoulos (2002) illustrated the advantage of roof-mounted solar energy applications over vertically mounted ones from the aspects of size, orientation, shading, safety and indoor effects. However, there have been no studies in NZ investigating the performance of roof-mounted solar energy applications in schools, nor any change these might produce in IAQ (temperature, RH, CO_2 and ventilation rate) in the school environment following the intervention.

This study is proposed to fill this gap in knowledge by investigating the change in the temperature, humidity, CO_2 and ventilation rate in schools from when a roof-mounted SAH was operating (treatment group) and not operating (control group).

In order to fill the gap, an interventional case study was carried out in Palmerston North (PN), NZ. A commercially available SAH (SolarVenti SV30 air collector), that used solar energy to preheat outdoor air, was installed on the roof of eight naturally ventilated classrooms in four primary schools in 2013, and 12 classrooms in six primary schools in 2014. These consisted of the four schools studied in 2013 plus two additional schools in 2014. Each school had two adjacent classrooms that were with the similar design, construction, heating and ventilation. Of the two classrooms in each school, one was randomly selected to be a control, where the SAH was installed but not operated, while the other classroom had the SAH installed and operated to be a treatment. The control group was very similar in construction to the treatment classroom; however, there may be differences in the number and age of students and the heater and window use between the treatment and control classrooms. Levels of temperature and velocity of the SAH outlet air, IAQ parameters (temperature, RH and CO_2) and heater use within the classrooms were monitored.

1.2 Research aim, questions and objectives

1.2.1 Research aim

The aim of this study was to investigate the impact from the operation of a roof-mounted SAH on temperature, humidity, CO_2 and ventilation rate in PN, NZ primary schools in winter.

1.2.2 Research questions

The core research question of this study was:

'How did the operation of a roof-mounted SAH affect the level of temperature, humidity, CO_2 and ventilation rate in PN, NZ primary schools in winter?'

Three following sub-questions were composed:

1. What was the experimental thermal performance of the SAH, when it was operated under different air mass flow rates?

2. What was the outlet air temperature, the temperature difference between the outlet and inlet air, the outlet air volumetric flow rate, and the thermal efficiency of the SAH in the fieldwork study, when it was roof-mounted on PN, NZ school buildings?

3. What was the change in the classroom temperature, humidity, CO_2 and ventilation rate from when the SAH was operating (the treatment classroom) and not operating (the control classroom)?

1.2.3 Research objectives

Three research objectives are as follows:

- Objective 1: To investigate the experimental thermal performance of the SAH, when it was operated under different air mass flow rates.

- Objective 2: To investigate the outlet air temperature, the temperature difference between the outlet air and inlet air, the outlet air volumetric flow rate, and the thermal efficiency of the SAH, when it was roof-mounted on PN, NZ school buildings.

- Objective 3: To investigate the change in the classroom temperature, humidity, CO_2 and ventilation rate from when the SAH was operating and not operating.

1.3 Scopes and limitations

PN is roughly located at the mid latitude of NZ. In the winter, the levels of solar radiation, ambient temperature and sunshine hours in PN are close to the mean levels of NZ winter weather conditions. The mean (SD) levels in PN and NZ were 77.2 (19.9) W/m^2 and 77.9 (20.4) W/m^2 for the solar radiation, 9.0 (0.3) °C and 7.9 (2.6) °C for the ambient temperature and 3.3 (0.6) hours and 4.1 (0.9) hours for the daily sunshine (NIWA, 2018). Accordingly, it was assumed that the performance of the SAH in PN could be indicative of the medium level compared to NZ as a whole. In other words, it will not produce the best nor the worst data.

This study focuses on the changes in levels of temperature, RH, CO_2 and ventilation rate in the classroom. As temperature levels are affected by heater use, the heater use in classrooms was monitored.

The limitations of this study are listed as follows:

1) In the first year fieldwork (2013), due to technical constraints, the SAH installation in primary schools took longer than anticipated. This delayed

the commencement of the fieldwork to late July rather than the beginning of May.

2) It was assumed that the operation of windows and doors in the adjacent control and treatment classrooms were similar. However, according to the observational data, this assumption may not be true for some schools. This effect was assumed to be randomised.

3) The ventilation rate was estimated using the tracer gas technique. CO_2 was selected as the tracer gas in this study. The source strength number (the student number) was the enrolment number in each classroom. This was not adjusted based on the daily attendance report. This has the potential to overestimate the ventilation rate.

4) Particulate matter (PM), volatile organic compounds (VOCs), formaldehyde, benzene, toluene, ethylbenzene, xylene, acetaldehyde, aldehydes, bacteria and fungi are air pollutants in the school environment (Madureira, Paciencia, Rufo*, et al.*, 2015). When the concentration of these air pollutants exceeds the guidelines, it causes negative health effects to children. However, due to financial constraints and technical constraints, the limited available equipment to measure these air pollutants that were available for this study, and the limited availability of technical assistance to process the laboratory analysis, VOCs, PM and other indoor air pollutants are not included in this study.

5) At the beginning of this project, it was not intended to investigate the SAH experimental performance. However, after analysing the fieldwork results, it was identified that the efficiency of the SAH was lower than expected. To figure out the decrease in the SAH efficiency when it was operated in fieldwork comparing to the experiment, an experiment was carried out. The comparison of the SAH outlet air temperature between the experiment and the fieldwork was conducted via the regression model, as it was impossible to have the identical weather conditions when the experiment and fieldwork were conducted in different time and locations.

1.4 Conceptual framework

Figure 1-1 shows the conceptual framework of this project.

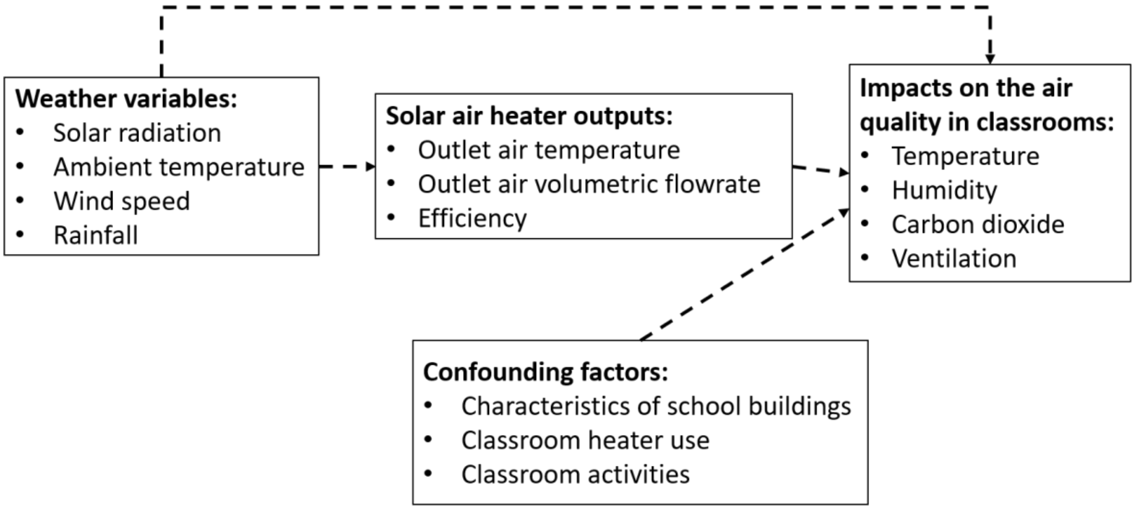

Figure 1-1 Project conceptual framework

The variables investigated in this study and the links between each concept are demonstrated by the project conceptual framework. The conceptual framework showed that the weather conditions, the SAH outputs and the confounding factors all affected the air quality in classrooms. The weather conditions incorporated the solar radiation, ambient temperature, wind speed and rainfall. These factors impacted both the SAH performance (Skalík, 2015) and the indoor temperature (Nguyen *et al.*, 2014). The SAH outputs included the outlet air temperature, the outlet air volumetric flowrate and the efficiency. The confounding factors considered for this study were characteristics of school buildings, classroom heater use and classroom activities.

As mentioned in Section 1.3, the SAH experimental study was conducted after the fieldwork. However, to make the thesis logically presented and the stages linked together, the experimental study was regarded as the first stage of this study, following by the SAH fieldwork performance and the changes in classroom air quality with the operation of the roof-mounted SAH. Therefore, the three stages of this thesis are:

Stage 1: experimentally investigate the SAH performance when it was operated under different air mass flow rates;

Stage 2: investigate the SAH fieldwork performance during periods when the classroom was unoccupied, focusing on SAH outlet air temperature, volumetric flow rate and efficiency;

Stage 3: investigate the change in the classroom temperature, humidity, CO_2 and ventilation rate from when the SAH was operating and not operating.

1.5 Outline of the thesis

This thesis comprises seven chapters: Chapter 1 was the introduction. Chapter 2 is the literature review. Chapters 3 to 5 present the three stages of this study. Chapter 6 is the general discussion. Chapter 7 is the conclusion. The research chapters (Chapter 3, Chapter 4 and Chapter 5) are presented in the publication format. Figure 1-2 shows the thesis framework.

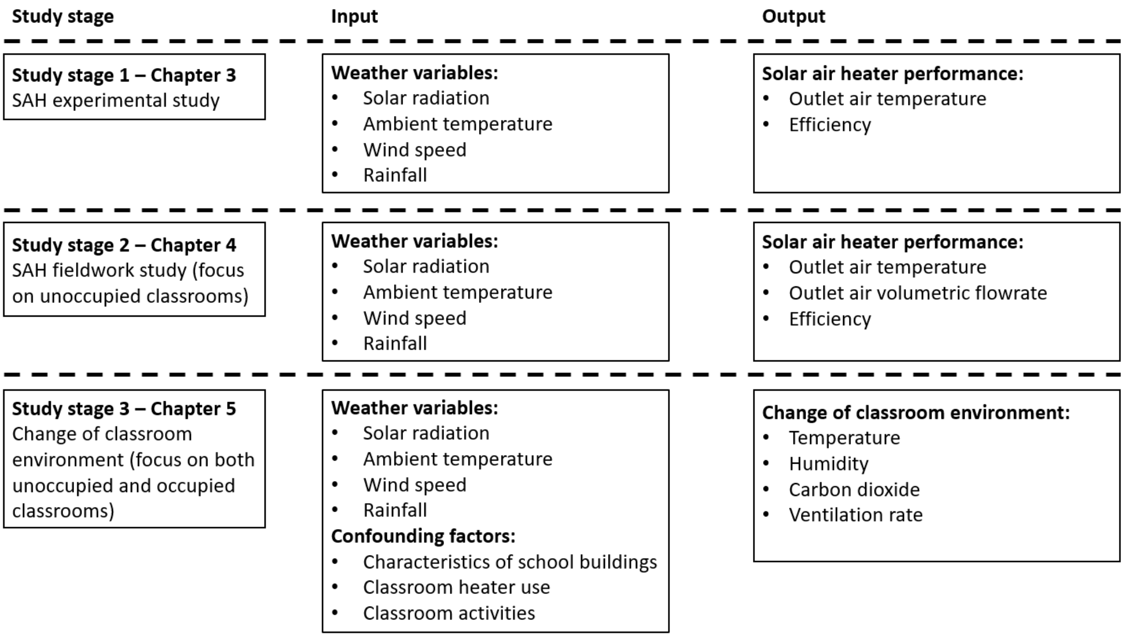

Figure 1-2 Thesis framework

Chapter 3 reports the first stage of this study, which investigated the experimental performance of the SAH when it was operated under different air mass flow rates. In the experimental study, the SAH was mounted on a custom-made support frame and had an air duct of 0.5 m in length. During the experiment, levels of temperature and velocity of the outlet air were measured at the outlet of this duct

(0.5 m from the SAH back plate). Solar radiation, temperature of the SAH inlet air (as same as the ambient air) and wind speed were measured.

Chapter 4 describes the second stage of this study, which addressed the fieldwork performance of the SAH, when it was roof-mounted on PN, NZ school buildings. The fieldwork was carried out in the winter 2013 and 2014. It was estimated that the duct had a length of 5.0 m, measured from the SAH back plate to the endpoint in the classroom. During the fieldwork, levels of temperature and velocity of the outlet air were measured at the outlet of this duct inside school buildings (5.0 m from the SAH back plate). Solar radiation, ambient temperature, wind speed and rainfall data were retrieved from a local climate monitoring station. The ambient air temperature was assumed to be the same as the SAH inlet air temperature. The outlet air temperature drop from the measurement conducted at 0.5 m from the SAH back plate to the measurement conducted at 5.0 m from the SAH back plate was estimated using a regression model.

Chapter 5 is the third stage of this study, which outlined the change in the classroom temperature, humidity, CO_2 and ventilation rate from when the SAH was operating (treatment classrooms) and not operating (control classrooms). Levels of temperature, RH, and CO_2 were measured using an IAQ monitoring device located inside classrooms. The heater use in all classrooms was monitored. The results from the treatment classrooms were compared to the control classrooms.

Chapter 6 discusses the result of this study. Chapter 7 concludes this study, including the limitations and contribution. It also lists suggestions for future research.

2 Literature Review

The first section of this literature review provides background information on Palmerston North (PN) weather conditions (the location of this study) and New Zealand (NZ) primary schools (the subject of this study). This first section is followed by a review of studies that have investigated indoor air quality (IAQ) parameters in primary schools in winter. The IAQ parameters include temperature, relative humidity (RH), carbon dioxide (CO_2) and ventilation. The influence of these parameters on students' respiratory health and students' absenteeism (due to medical reasons) is briefly summarised. In the last part of the literature review, the application of a solar air heater (SAH) for space heating and ventilation in winter is discussed.

2.1 Palmerston North weather conditions in winter

NZ spreads from the latitude of 34 °S to 47 °S. There are two main islands in NZ, namely the North Island (from 34 °S to 41 °S) and the South Island (from 41 °S to 47 °S). PN, the site of this project, is the main city of the Manawatu-Wanganui Region in the North Island. Figure 2-1 shows the location of NZ within the world and the location of PN within NZ.

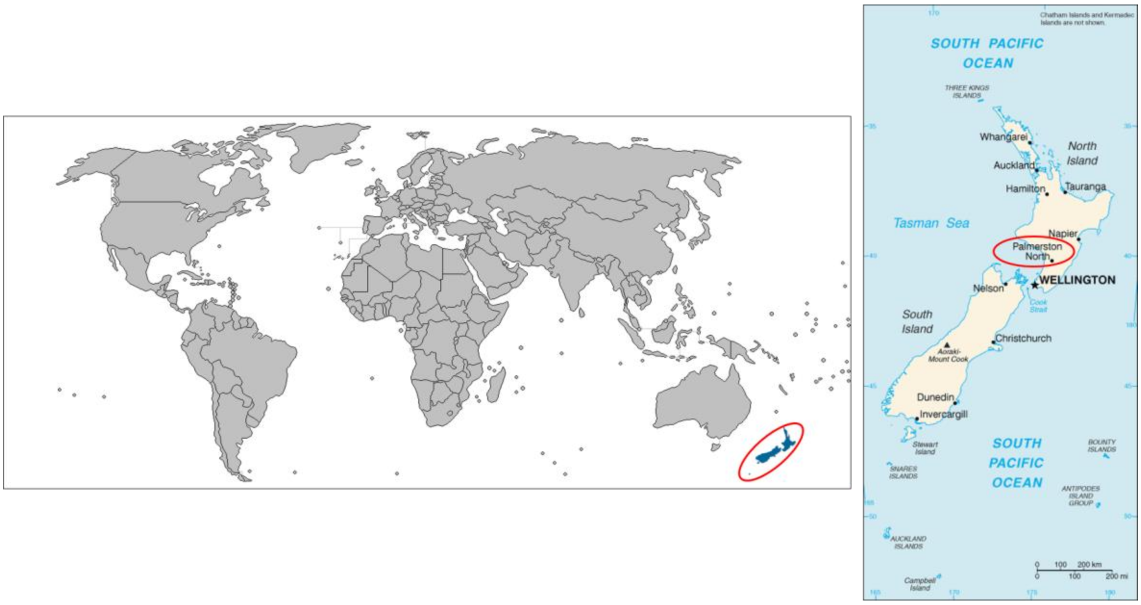

Figure 2-1 Location of New Zealand (NZ) within the world and location of Palmerston North within NZ

Source: https://commons.wikimedia.org/wiki/File:BlankMap-World-v7-Borders.png, https://www.cia.gov/library/publications/the-world-factbook/geos/nz.html

PN is located at latitude 40 °S that is close to the midline of NZ. PN city is inland 35 km from the Tasman Sea. The climate in NZ has large regional variations (BRANZ, 2007a). Generally, the northern regions have warmer climatic conditions than the southern regions, especially in winter.

The NZ National Institute of Water and Atmospheric Research (NIWA) monitors the climate across the whole country. NIWA meteorological scientists have summarised monthly, seasonal and annual climate conditions over 30-year periods from 1981 to 2010 (normal climate). Table 2-1 shows mean levels of solar radiation, sunshine hours and ambient temperature during the winter months (June, July and August) from 1981 to 2010 in PN and NZ. Subantarctic islands and Antarctica territories have been excluded from the weather statistics, as these are not representative of NZ weather conditions. Further, there are no schools in these areas.

Table 2-1 Solar radiation (W/m^2), sunshine hours (hours) and ambient temperature (°C) from 1981 to 2010 in Palmerston North and New Zealand in winter

Weather parameter	Location	Mean (SD)	Minimum	Maximum
Solar radiation (W/m^2)	Palmerston North (PN)	77.2 (19.9)	61.3	99.5
	New Zealand (NZ)	77.9 (20.4)	40.5	116.9
Sunshine hours (hour)	PN	3.3 (0.6)	2.6	3.9
	NZ	4.1 (0.9)	2.1	5.9
Ambient temperature (°C)	PN	9.0 (0.3)	8.6	9.2
	NZ	7.9 (2.6)	1.4	12.8

Source: (NIWA, 2018)

Table 2-1 shows that, during the winter months, the mean solar radiation levels in PN are close to the mean NZ solar radiation levels (77.2 vs 77.9 W/m^2). The mean daily sunshine hours in PN are 0.8 hours lower than the mean NZ sunshine hours (3.3 vs 4.1 hours). The mean ambient temperature levels in PN are 1.1 °C higher than the mean NZ ambient temperature (9.0 vs 7.9 °C). Overall, the winter weather conditions in PN are close to the mean levels of NZ winter weather conditions. This suggests that the performance of solar energy applications in PN could be at the medium level compared to NZ as a whole.

2.2 New Zealand primary schools

The national education system in NZ was established under the Education Act 1877 (Swarbrick, 2008). In the colonial days, only churches and some private secular organisations provided limited support and resources for education. The NZ Education Act 1877 stated that children aged from 7 to 13 years old must attend schools. In the 2000s, the compulsory enrolment age was reduced to 5, and the minimum leaving school age was increased to 16 (Ministry of Education, 2018a). Every child living in a school's geographical zone must be allowed to attend the school, regardless of the school's capacity (Ministry of Education, 2017b). This section describes the types of NZ primary school buildings, the number of NZ primary schools, and insulation and airtightness of NZ primary school buildings.

2.2.1 Types of New Zealand primary school buildings

Table 2-2 shows changes of types in NZ primary school buildings over time.

Table 2-2 Changes of New Zealand primary schools over time

Time	Classroom characteristics
Before 1900 	• 6 m * 3.7 or 4.2 m (22 m^2 to 26 m^2); • Construction included "Wattle and daub", light timber-framed or stone buildings; • Few of these schools are still in use today.
1900 – 1950 	• 8 m * 7.5 m (60 m^2); • Light timber-framed structure; • Coal fire for space heating (central heating) in winter; No insulation; • Very large single glazed windows were used for daylighting and natural ventilation; • Use the adjacent corridor for the cloakroom.
1950 – 2000 	• 10 m * 7.5 m (75 m^2); • Uninsulated or low levels of insulation (introduced in 1978); • Natural ventilation; • School block, Dominion Basic Plan; • Many relocatable classrooms deployed and shifted between schools to accommodate fluctuations in school rolls.
2000 – now 	• Total 85 m^2, 65 m^2 for teaching and learning, 20 m^2 for the cloakroom and toilets; • Modern learning environment concepts, large open plan spaces with flexible breakout spaces; • Light timber-framed structure, carpet on the floor; • Thermal insulation is compulsory; • The sustainable design and mechanical ventilation system are recommended.

Source: (McLintock, 1996; Ministry of Education, 2011, 2015; Swarbrick, 2012a, 2012b)]. Images in this table were adapted from (Ministry of Education, 2011, 2013)

Table 2-2 shows that the size of NZ classrooms has been gradually increasing in the area from 26 m^2 in 1900 to 85 m^2 in 2000. These light timber-framed buildings constructed before 2002 were uninsulated or lightly insulated. Since 2002, for the newly built and retrofitted buildings, the thermal insulation is compulsory, while the mechanical ventilation and the sustainable design are recommended (Ministry of Education, 2017a).

Ninety-five percent of current primary schools in NZ were built between the 1950s and 1960s (Swarbrick, 2012a). School buildings built during this period were naturally ventilated timber-framed single story structures. They were built with large single glazed openable windows to permit the ventilation and daylighting and no insulation. Extending the life of these existing buildings and building new classrooms are two ways to meet the growth in student rolls and overcome the shortage of school buildings (Ministry of Education, 2017c).

2.2.2 The number of New Zealand primary schools

In NZ, there are three types of primary schools, namely full primary schools (students aged from 5 to 13 years old, which corresponds to academic years 1 to 8), contributing primary schools (students aged from 5 to 10 years old, which corresponds to academic years 1 to 6) and intermediate schools (students aged from 11 to 13 years old, which corresponds to academic years 7 to 8). Figure 2-2 shows the number of primary schools (including all three types) and the number of students (from Year 1 to Year 8) from 1875 to 2017 in NZ (Ministry of Education, 2018b). From 1875 to 2000, the data was recorded every five years. After 2000, the school census was conducted annually.

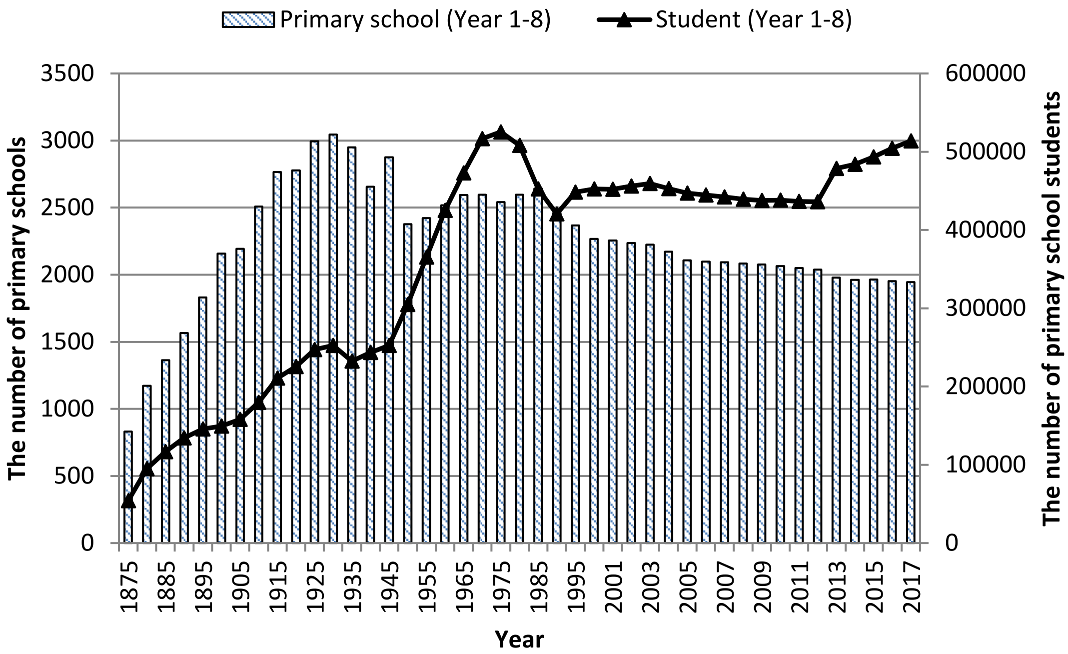

Figure 2-2 The number of New Zealand primary schools and students from 1875 to 2017 Source: (Ministry of Education, 2018b)

Figure 2-2 showed a significant increase in the number of schools between the years 1877 and 1930. This was followed by a drop of 25% over the next two decades, as many of the smaller schools that had been built during the post-war period were closed. Since 2000, the number of primary schools has stayed around 2000, while the number of students has increased from 452300 in 2000 to 513657 in 2017. There were 1945 primary schools in NZ in 2017. This was comprised of 1064 full primary schools, 764 contributing schools and 117 intermediate schools (Ministry of Education, 2018b).

2.2.3 Insulation in New Zealand primary school buildings

The climatic variations significantly affect the required building insulation levels. NZ is divided into three climate zones for making the building energy efficient purposes (Standards New Zealand, 2009). Climate zone 1 includes Northland, Auckland, Franklin Counties and the Coromandel Peninsula. Climate zone 2 is the rest of the North Island but excluding the Volcanic Plateau. Climate zone 3 covers all of the South Island and the North Island Volcanic Plateau. Figure 2-3 shows these climate zones in NZ, including the name of some major cities in each climate zone (Ministry of Education, 2017a).

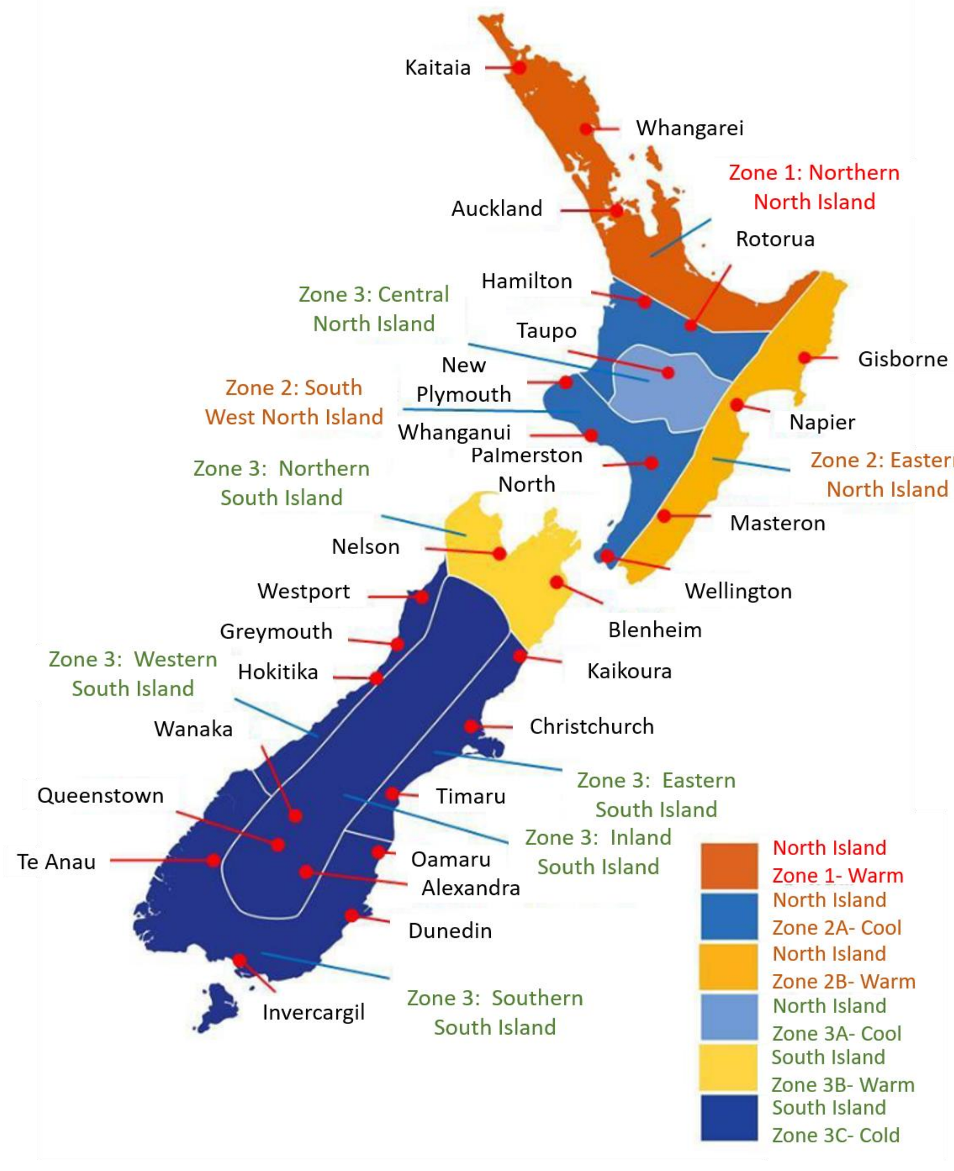

Figure 2-3 New Zealand climate zones and sub-zones

Source: (Ministry of Education, 2017a)

The first mandated insulation requirement for NZ low rise buildings came into force in 1978. In NZ, the current insulation requirements for houses are stipulated in two NZBC clauses, namely H1 Energy Efficiency and E3 Internal Moisture (Department of Building and Housing, 2004, 2011b). NZS 4218 Thermal Insulation – Housing and small buildings (set out by NZBC) requires thermal resistance (R-value, m^2K/W) for residential buildings (Standards New Zealand, 2009). However, there are no specific insulation requirements from these two NZBC clauses and NZS 4218 regarding the insulation in school buildings. Consequently, standards for residential buildings are normally used for schools.

In 2017, NZMoE released the document – Designing Quality Learning Spaces: Indoor Air Quality and Thermal Comfort (DQLS 2017) (Ministry of Education, 2017a). The aim of this document is to ensure the school environment fully supports teaching and learning and does not negatively affect occupants' health and wellbeing. DQLS 2017 states it is compulsory to have insulation for newly built school buildings and upgraded existing school buildings. All school buildings built after 1st January 2018 must meet DQLS 2017 requirements.

Table 2-3 shows thermal resistance requirements for school buildings from DQLS 2017 (Ministry of Education, 2017a), and for residential buildings from NZS 4218 (Standards New Zealand, 2009) in different climatic zones.

Table 2-3 Thermal resistance (R-value, m^2K/W) requirements for school buildings from Design Quality Learning Space 2017, and for residential buildings from New Zealand Standard 4218

Climate zones	Building components	Insulation requirements	
		DQLS 2017	NZS 4218
Zone 1	Roof	R 3.4	R 2.9
	Wall	R 2.2	R 1.9
	Floor	R 1.3	R 1.3
	Windows	R 0.15 (Single glazing)	R 0.26
Zone 2	Roof	R 3.4	R 2.9
	Wall	R 2.2	R 1.9
	Floor	R 1.3	R 1.3
	Windows	R 0.26 (insulated glazing units)	R 0.26
Zone 3	Roof	R 3.6	R 3.3
	Wall	R 2.6	R 2.0
	Floor	R 1.9	R 1.3
	Windows	R 0.26 (insulated glazing units)	R 0.26

Source: DQLS 2017 (Ministry of Education, 2017a), NZS 4218 (Standards New Zealand, 2009).

Table 2-3 shows, except for windows in climatic zone 1, the insulation requirements from DQLS 2017 for school buildings meet or exceed the insulation requirement specified by NZS 4218 for residential buildings. To slow the flow of heat inwards in hot weather and heat outwards in cold weather, school buildings are required to have sufficient thermal insulation in different building components (roof, wall, floor and windows), as shown in Table 2-3 (Ministry of Education, 2017a). However, NZ schools built prior to the 1990s are most likely to have a minimum insulation or have no insulation in walls or ceilings (Ministry of Education, 2013). Poor thermal insulation cannot prevent heat loss during cold weather nor reduce heat gains in hot weather. In a typical uninsulated NZ classroom, 40% of the heat in winter escapes from the ceiling, 30% escapes from walls, 20% and 10% are lost from windows and floors respectively (BRANZ, 2007a). To achieve the same temperature, poorly insulated school buildings may require twice as much energy as well insulated school buildings (EECA *et al.*, 2008).

To make the building more energy efficient, a series of methods for improving the insulation of existing school buildings are recommended. For example, placing fibreglass batts, polystyrene or wool insulation in the ceiling cavity and the wall cavity, and replacing single glazed windows with double glazed windows (EECA *et al.*, 2008). Besides, insulation inspections are needed to make sure the insulation materials have not deteriorated over time or been installed incorrectly. The typical R-value of some common building insulating materials, the thickness of some common building insulating materials, and the methods of adding insulation to different building components (roof, wall and floors) have been illustrated elsewhere (BRANZ, 2007a). Figure 2-4 shows an example of the installation of thermal insulation into a flexible learning space during the construction phase.

Figure 2-4 Installation of thermal insulation into a learning space

Source: (Ministry of Education, 2017a)

2.2.4 Airtightness of New Zealand primary school buildings

Airtightness is the resistance to air movements through the building fabric unintentional openings, like cracks or gaps. Airtightness influences the building energy efficient (Overton, 2013). NZBC Clause H1 Energy Efficiency states airtightness should be considered when a building is built (Department of Building and Housing, 2011b) but without any specific requirements.

Table 2-4 shows the airtightness of NZ residential buildings @ 50 Pa, and the classification based on the house type (Bassett, 2001). The airtightness was measured according to the European Standard EN13829:2000[1] (CEN, 2011) by the use of the blower door. The measurement was expressed as air changes per hour (ACH) @ 50 Pa.

Table 2-4 New Zealand house infiltration rates (air changes per hours @ 50 Pa)

House type	Airtightness @ 50 Pa (Air changes per hour, ACH @ 50 Pa)	Classification
Post-1960 houses with a simple rectangular single story floor plan of less than 120m^2 and airtight joinery (windows with airtight seals)	5 ACH	Airtight house
Post-1960 houses of larger simple designs with airtight joinery	10 ACH	Average house
Post-1960 houses of more complex building shapes and with unsealed windows	15 ACH	Leaky house
All pre-1960 houses with strip flooring and timber windows	20 ACH	Draughty house

Source: (Bassett, 2001)

The ACH (@ 50 Pa) of NZ residential buildings decreased from 20 ACH for buildings built before the 1960s, to 10 ACH for buildings built between 1960 and 1980, and to 4.5 ACH for buildings built since 2000 (Overton *et al.*, 2013). The increase in building airtightness over time was caused by the use of more airtight window joinery (shifting from timber-framed windows to aluminium-framed windows), the use of sheet lining materials, and the replacement of suspended tongue-and-groove floors with slab-on-ground floors (Overton *et al.*, 2013).

[1] EN 13829:2000: Thermal performance of buildings "Determination of air permeability of buildings – fan pressurisation method" (ISO 9972:1996, modified).

The airtightness of NZ school buildings can be estimated from residential buildings (Bassett *et al.*, 1999), as school buildings and residential buildings built during the same periods used similar construction methods, construction materials and followed the same building codes. Therefore, it is inferred that new school buildings are becoming increasingly airtight.

The increased airtightness benefits energy savings. However, it can reduce the building ventilation rate (Ridley *et al.*, 2016). Consequently, it could negatively impact building IAQ and occupants' health, unless an adequate ventilation rate is achieved by other means. In some European countries, to achieve an acceptable IAQ, the regulations for airtightness of building envelopes are connected to the minimum required ventilation rate to establish the "build tight – ventilate right" strategy (Kunkel *et al.*, 2015).

2.2.5 Section summary

In conclusion, the majority of current NZ primary school buildings were built during the 1950s and 1960s. These buildings are light timber-framed, with extensive single glazed windows, with ceilings, walls and floors uninsulated or insulated to a low level. Besides, these school buildings are naturally ventilated by manual opening/closing of windows and doors. From the airtightness of residential buildings, it is inferred that school buildings built during the 1950s and the 1960s had an airtightness of 10 to 20 ACH (@50 Pa). More recently constructed schools are becoming more airtight.

2.3 Review methods

The literature review aims to evaluate (1) temperature, humidity and CO_2 levels in primary schools in winter, (2) ventilation rate in primary schools in winter and the methods to increase the ventilation rate, and (3) the solar energy application used for ventilation and space heating.

To conduct the literature review, journal paper published in the relevant areas were searched through the search engines (Google Scholar) using keywords. The search string was the different combination of temperature, humidity, CO_2, ventilation, IAQ, primary schools (elementary schools), winter, naturally ventilated, mechanically ventilated, solar chimney, Trombe wall, solar wall, SAH, solar energy application. No restrictions were applied to the year of the publication or the location of the study.

After the initial search, if the title looked relevant to the research topic or in the field of the research topic, the abstract of the paper was read. The full paper would be downloaded and read if the abstract indicated that this paper might be relevant to the research topic. The paper was decided to be included according to the criteria. The inclusion criteria are (1) the study was carried out in winter in schools with the data reporting the temperature, humidity, CO_2 and ventilation rate during school hours, (2) the number of the classrooms involved in the study was two or more, and (3) the study was published in English.

Conference proceedings, report and thesis (both the master and doctoral) in the relevant area were searched and included, because there are limited journal paper published about the school IAQ in winters in some regions or countries, such as NZ. For the similar reason, the report on the solar applications in schools was included. Standards and guidelines were included with no limitation of the date of the publication. Some selected papers were summarised using the table to show the information of the study (sample size, location, and monitoring sensors) and the result. For the studies which were not described in the table, they were discussed to reflect the consistency or inconsistency of the research findings. In total, the literature review includes 87 journal papers, 26 reports, 13 standards and guidelines, 10 conference proceedings and four book sections. These publications were published between 1989 and 2018.

2.4 Temperature, humidity and carbon dioxide in primary schools

ASHRAE (2007, p. 3) defined acceptable IAQ as "*air in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction*".

Temperature, humidity and ventilation are the three main monitored parameters for IAQ in schools (Nielsen, 2004). These three parameters are interdependent and must be considered together (BRANZ, 2007a). Due to a combination of a high density of occupants and the reliance on natural ventilation, it is challenging to provide an acceptable IAQ (temperature, humidity and ventilation) during the winter months in the school environment (Jurelionis and Seduikyte, 2008).

In addition to temperature, humidity and ventilation, school IAQ includes many other parameters, namely formaldehyde, particulate matter ($PM_{2.5}$, PM_{10}), nitrogen dioxide, sulphur dioxide, volatile organic compounds (VOCs), moulds, fungi and allergens to name a few. As this project aims to investigate the impacts of operating a SAH on classroom temperature, humidity and ventilation, studies about other IAQ parameters are outside the scope of this project and are not reviewed in the literature.

The following section reviews the level of temperature, humidity and CO_2 in NZ and overseas schools in winter. CO_2 is an indicator to approximate to the ventilation rate. In each section, firstly, the existing recommended guidelines by different organisations are reported. Then it is followed by reviewing studies that investigate levels of temperature, humidity and CO_2 in primary schools during the winter seasons in different countries. The effects of temperature, humidity and CO_2 on students' health and school absenteeism rate are briefly reviewed at the end of each section.

2.4.1 Temperature level in primary schools

The indoor temperature in an occupied building is the result of heat gains and heat losses. The heat gains include heater use (either central heating or local room heating), the heat emitted from occupants' bodies, lights, computers and equipment, and solar gains (BRANZ, 2007a). The heat losses include the heat that escapes from the building roof cavity, windows and doors, external walls, floors and infiltration/exfiltration. The amount of heat gains and heat losses are influenced by the building orientation, insulation, airtightness, ventilation, types of windows and doors, and the ambient weather conditions. The colder the indoor environment compared to the ambient, the higher the heat transfer. The higher the thermal resistance of the building materials, the lower the heat transfer.

The WHO recommends an indoor temperature between 18 °C and 24 °C for occupants' wellbeing (WHO, 1987). Chatzidiakou *et al.* (2012) reported that the acceptable thermal comfort (evaluated through predicted mean vote and predicted percentage dissatisfied) was achieved when the temperature in classrooms ranged from 20 ± 1 °C and 24.5 ± 2.5 °C in different seasons. Pierse *et al.* (2011) found that the indoor temperature was significantly associated with the lung function in children with asthma, especially when the temperature dropped below 11 °C.

In addition to WHO recommendations, Chartered Institution of Building Services Engineers (CIBSE) guidelines – Environmental design suggests the temperature of teaching spaces should be between 19 °C and 21 °C in the winter (CIBSE, 2006). Another guideline – Building Bulletin 101 specifies that during the winter season, the temperature in the teaching and learning environment should be maintained at 20 °C and should not exceed 25 °C (BB101, 2018). In some European countries[1], the recommended temperature in classrooms in winter is consistent with the WHO recommended levels (from 18 °C to 24 °C) (Brelih and Seppänen, 2011).

[1] These countries include the Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Lithuania, Netherlands, Norway, Poland, Portugal, Slovenia and the United Kingdom.

Based on the WHO recommendation, NZMoE document "Designing Quality Learning Spaces: Indoor Air Quality and Thermal Comfort" (DQLS 2017) outlines temperature requirements for both learning and non-learning spaces in schools, as shown in Figure 2-5 (Ministry of Education, 2017a). The temperature focuses on NZ school hours (from 9 am to 3 pm).

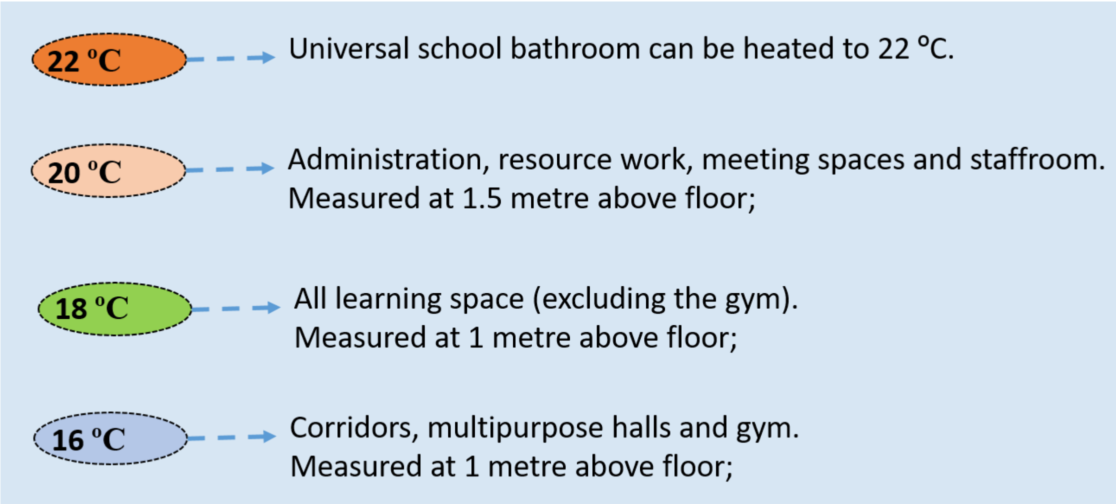

Figure 2-5 Minimum mandatory requirements of temperature levels for school buildings built after 1st January 2018 and updated existing school buildings.
Source: (Ministry of Education, 2017a)

DQLS 2017 (Ministry of Education, 2017a) recommends a minimum temperature of 18 °C in school teaching spaces in winter. DQLS 2017 specifies the minimum temperatures in school corridors, administration spaces and bathrooms as well.

The temperature in classrooms in winter has been researched in many countries, including NZ. These studies are discussed and summarised in Table 2-5.

In NZ, McIntosh (2011) (Study A, Table 2-5) found that for 9 out of 35 Wellington (NZ) primary classrooms, the mean temperature was below the WHO recommended minimum value (18 °C), with a range from 13.4 °C to 17.7 °C during school hours. 14 classrooms had temperature levels below 18 °C for more than 50% of the school day. A low temperature level (mean = 13.4 °C, minimum–maximum: 10.3–15.2 °C) was found in a special language class which was only occupied sporadically by a small number of students. This result was consistent with another NZ study undertaken in two Christchurch naturally ventilated classrooms in winter (Cutler-Welsh, 2006). This study showed 3 out of 4 measured days had a mean temperature below 18 °C between 7 am and 4 pm. Cutler-Welsh (2006) did not report the percentage of school days with a temperature less than 18 °C. Both studies showed a low level of indoor temperature in NZ naturally ventilated classrooms in winter.

Similarly, overseas studies have shown consistent temperature levels in naturally ventilated schools in winter (Elbayoumi *et al.*, 2013; Mi *et al.*, 2006). Table 2-5 Study B found similar results to a Gaza Strip (Palestinian) study, with a mean indoor temperature of 14 °C in 12 naturally ventilated primary schools (24-hour average ambient temperature of 13 °C) in winter (Elbayoumi *et al.*, 2013). While the climate and the school construction in Gaza Strip are different from in NZ and other locations, the low temperature level was also obtained in the naturally ventilated schools in winter. Results in Table 2-5 Study B were only one hour averaged data and may be inaccurate compared with the whole day monitoring. Classrooms participating in Table 2-5 Study B had no heating system, while Elbayoumi *et al.* (2013) did not report any information on the classroom heater use.

In contrast, Study C, Study D and Study E in Table 2-5 showed an acceptable temperature level in primary schools in winter. Study D on Los Angeles, the USA schools found that with the use of the heating, ventilation, and air conditioning (HVAC) system, during school hours the temperature in portable classrooms and traditional classrooms met the WHO recommendation (18 °C). However, without the use of the HVAC system, the minimum overnight temperature level in portable classrooms was lower than in traditional classrooms (-1.7 °C vs 1.9 °C). This is due to the low thermal resistance of building components (e.g. walls, ceilings and windows) or the low building airtightness of the portable classrooms. Study E on New South Wales, Australian schools concluded that temperature levels in classrooms with either an unflued gas heater or a flued gas heater achieved acceptable levels. However, the unflued gas heater will cause higher levels of pollutants in classrooms and adversely impact on student's respiratory symptoms (Pilotto *et al.*, 1997).

Among these studies, Study C gave no information on the classroom heater use and ventilation systems, while Study D and Study E reported the heater use.

Fromme *et al.* (2007) found a similar result to Study D and Study E (Table 2-5), namely with the use of a central heating system, a mean school hours temperature of 22 °C (minimum–maximum: 18–25 °C) was obtained in 92 German classrooms (from 64 schools).

From 2010 to 2012, a European project called Schools Indoor Pollution and Health: Observatory Network in Europe (SINPHONIE) was undertaken in 114 primary schools (340 classrooms in total) from 54 cities in 23 European countries. Eighty-six percent of the participating classrooms were naturally ventilated. The full school week temperature measurements showed that the mean temperature among all participating schools was 20.8 °C (minimum–maximum: 11.7–30.0 °C; standard deviation, SD = 2.0 °C) (Csobod *et al.*, 2014). However, the SINPHONIE project report did not give the percentage of time that classroom occupants experienced temperatures below 18 °C or above 24 °C.

Overall, classrooms temperature varies according to the ambient temperature and heater uses. Without heater use, it is difficult to achieve an acceptable temperature in naturally ventilated classrooms in winter. Studies reported in this literature review showed that 12 out of 39 investigated NZ naturally ventilated classrooms failed to meet WHO recommended temperature levels (between 18 °C and 24 °C), even with the heating systems. Similar results were found in overseas naturally ventilated classrooms.

As indoor temperatures affected the humidity levels, humidity levels in classrooms in winter are reviewed in the following section.

Table 2-5 Summary of studies on temperature (°C) and relative humidity (%) levels in primary schools

Study	Sample size and classroom description	Study location and design	Monitoring sensors and location	Temperature and relative humidity levels in classroom (°C; %); Mean (SD) / range	Main observation	Reference
A	35 classrooms; Naturally ventilated; Have the heating system.	Wellington, New Zealand; 13 classrooms: August to October 2003; 22 classrooms: July to August 2005; School hours; 5-min intervals.	Temperature: thermistor; Relative humidity: thin-film capacitive.	18.7 (1.6); [10.3–24.1]; 56.9 (7.8); [38.7–85.8].	Low indoor temperatures (around 11 °C) during the morning was common in most of the classrooms. Very high RH levels (85%) were found in the morning.	(McIntosh, 2011)
B	30 classrooms (10 schools); Naturally ventilated; No heating systems.	Shanghai, China; November and December, 2000; Only 1 hour monitoring during a full class.	Temperature: thermistor; Relative humidity: thin-film capacitive; 0.9 m above the floor.	17.4 (1.8) [13.0–21.0]; 56.0 (12.0) [36.0–82.0].	Indoor temperature was connected with outdoor temperature for naturally ventilated classrooms without heating systems.	(Mi *et al.*, 2006)

<table>
<tr><th>Study</th><th>Sample size and classroom description</th><th>Study location and design</th><th>Monitoring sensors and location</th><th>Temperature and relative humidity levels in classroom (°C; %); Mean (SD) / range</th><th>Main observation</th><th>Reference</th></tr>
<tr><td>C</td><td>73 primary classrooms from 20 public schools.</td><td>Porto, Portugal;

November to March, 2011 to 2013;

School hours.</td><td>Temperature: thermistor;

Relative humidity: thin-film capacitive;

1.0–1.5 m above the floor.</td><td>20.5 (2.6) [14.3–24.6];

55.0 (10.0) [34.0–74.0].</td><td>Mean levels of temperature and humidity were within the recommended range.

The difference in IAQ between schools varied more than within schools.</td><td>(Madureira, Paciencia, Pereira, et al., 2015)</td></tr>
<tr><td>D</td><td>Eight portables and four traditional classrooms;

Mechanically ventilated (wall-mounted HVAC).</td><td>Los Angeles Country, USA;

One week (occupied);

Winter 2001.</td><td>Temperature: battery-operated HOBO H8 Family data loggers with internal sensors.</td><td><table>
<tr><th>Parameters</th><th>Type of classrooms</th><th>Mean</th><th>Median</th></tr>
<tr><td rowspan="2">Temperature (°C)</td><td>Portable classroom</td><td>20.2</td><td>20.3</td></tr>
<tr><td>Traditional classroom</td><td>20.1</td><td>20.2</td></tr>
<tr><td rowspan="2">Relative humidity (%)</td><td>Portable classroom</td><td>53.4</td><td>53.5</td></tr>
<tr><td>Traditional classroom</td><td>51.4</td><td>51.5</td></tr>
</table></td><td>During school hours, with the use of HVAC, no significant differences in levels of temperature and RH between portable and traditional classrooms.

Without the use of HVAC, the minimum overnight temperature levels in portable classrooms were lower than in traditional classrooms.</td><td>(Shendell, Winer, et al., 2004)</td></tr>
</table>

Study	Sample size and classroom description	Study location and design	Monitoring sensors and location	Temperature and relative humidity levels in classroom (°C; %); Mean (SD) / range	Main observation	Reference
E	22 primary schools; Unflued gas heater versus flued gas heater;	New South Wales, Australia; June to August, 2009 (6 weeks research focus on winter); Double blind, cluster randomized, crossover study; School hours (9 am to 3 pm); 2-min intervals.	Heater: HOBO H8 series data loggers (changes in temperature were used to identify the time when heaters were turned on-off); Temperature: HOBO H8 series data loggers.	Mean daily temperature: 20.9 (unflued gas heater); 20.5 (flued gas heater); No RH data.	Formaldehyde and nitrogen dioxide concentrations were higher when the classroom exposed to the unflued gas heater.	(Marks *et al.*, 2010)

2.4.2 Humidity level in primary schools

Moisture in the indoor environment comes from three primary sources: building materials, indoor sources and outdoor sources (Christian, 1994). The moisture from building materials is different from the indoor and outdoor sources. During building materials drying out periods, they released moisture into the indoor environment. However, after the drying out period, though hygroscopic building materials might absorb moisture from the environment and then dry out, they are no longer the source of moisture.

In school buildings, the indoor moisture sources include the moisture from occupants' respiration, wet clothes and wet footwear. The outdoor moisture sources are rain, the low air temperatures during night times, and the subfloor dampness. Subfloor dampness can lead to an increase in the indoor moisture. As classrooms often have an attached cloakroom, there is an undirected pathway for moisture to enter the classroom from wet raincoats or sports gear. Controlling the moisture ingress into the indoor environment and removing the moisture from the indoor environment could reduce the indoor moisture level. In NZ schools, controlling the ambient moisture ingress into classrooms is important to achieve acceptable indoor RH levels, as the yearly round ambient RH levels are between 70% and 90%, with the mean of 80% (NIWA, 2018).

Levels of RH and humidity ratio (HR) are widely used to describe humidity levels in the environment (Gatley, 2005, p. 6). RH refers to the ratio of the amount of water vapour in the air to the maximum amount of the water vapour that the air could hold under the same temperature, as a percentage (%). HR refers to the ratio of the mass of water vapour to the mass of the dry air, with the units of $kg_{\text{water vapour}}/kg_{\text{dry air}}$ or $g_{\text{water vapour}}/kg_{\text{dry air}}$. A psychometric chart can be used to describe relationships between RH, HR and temperature. The WHO (2009, p. 35) gave examples and explanations of the interrelationships between these three parameters.

HR levels in the indoor environment are more affected by the hygroscopic materials inside buildings rather than the ventilation and temperature (McNeil *et al.*, 2014). ASHRAE 55 recommends HR levels not above 12.0 g/kg to achieve a comfortable occupied condition (ASHRAE, 2017). This HR level corresponds to a level of RH of 80% at a temperature of 21.5 °C[1].

ASHRAE (1989) recommends "*Relative humidity in habitable spaces preferably should be maintained between 30% and 60% to minimise growth of allergenic or pathogenic organisms*". Since 2004, ASHRAE has increased the upper RH level to 65% for an acceptable IAQ (ASHRAE, 2004). ASHRAE (2016) recommends RH levels between 30% and 65% in occupied spaces to reduce the likelihood of the growth of microbial matter. The United States Environmental Protection Agency (US EPA) recommends that the indoor RH should be kept below 60%, ideally between 30% and 50% (Indoor Environments Division, 2008). US EPA states that 80% or more of averagely dressed occupants feel comfortable at an RH level of 50%, with a corresponding temperature between 20 °C and 25 °C.

An RH level below 30% makes occupants' skin and eyes dry (Mendell and Heath, 2005; Wan and Li, 1999). In reverse, an RH level above 70% benefits the survival and the growth of indoor allergens, like dust mites, moulds and bacteria (Munir *et al.*, 1995). The recommended RH level in classrooms, complying with comfort and minimising the growth of allergens (moulds and bacteria), should be between 40% and 60% at a temperature range of 18 °C to 24 °C (Sterling *et al.*, 1985). A comparative study showed that exposure to RH levels between 40% and 50% were more comfortable for occupants than exposure to either 20% to 40% or 50% to 70% at the same temperature of 23 °C (McIntyre, 1978).

Table 2-5 (Studies A, B, C and D) shows a summary of some studies that investigated RH levels in primary schools in winter. Studies A, B and C showed that the mean RH level in classrooms during school hours was between 50% and 60%. However, the maximum RH levels were all above 65% (ASHRAE maximum levels for the good IAQ) in these studied classrooms. McIntosh (2011) found that in 11 out of 35 Wellington (NZ) classrooms, RH levels exceeding 65% were present for more than half of the school days.

[1] There is no lower humidity requirement in ASHRAE 55 "Thermal Environmental Conditions for Human Occupancy" (ASHRAE, 2017).

A German study, involved 92 classrooms from 64 schools, found a mean RH of 38% (from 22% to 60%), with a corresponding mean temperature of 22 °C (Fromme *et al.*, 2007) during school hours in winter. Among these 64 schools, only two schools had mechanical ventilation systems. The remaining schools were naturally ventilated. Ramachandran *et al.* (2005) found the mean school hours RH levels in two American (Minnesota) mechanically ventilated primary schools were 38.1% (SD = 0.3%, 108 classrooms) and 39.9% (SD = 0.3%, 86 classrooms) respectively in winter. In these two schools, there were 68% and 30% of daily average RH levels outside the range of 30% to 60%. In contrast to RH levels in NZ schools, 97% of these outside daily RH levels were below 30%.

Concerning RH levels in European schools, the SINPHONIE project found mean RH levels of 43% (SD = 12%, minimum–maximum: 6–80%, median = 42%) in all participating schools (Csobod *et al.*, 2014). The SINPHONIE project clustered all participating schools according to their geographic locations. The lowest and highest mean RH levels were found in Northern Europe (33.4%, minimum–maximum: 6.0–56.1%) and in Southern Europe (51.4%, minimum–maximum: 25.5–80.4%) respectively. RH levels in schools located in Central Eastern Europe (mean = 38.7%, minimum–maximum: 20.4–64.2%) and Western Europe (mean = 42.7%, minimum–maximum: 23.0–67.8%) were in the middle. This project did not report the percentage of school hours experiencing RH levels outside the range of 30% to 60%. However, from the RH range (minimum–maximum) in different regions, it can be assumed that schools in all regions experienced RH levels either below 30% or above 60% during school hours (Csobod *et al.*, 2014).

Overall, due to the high level of ambient RH in NZ[1], levels of RH above 60% were found in NZ primary schools during the winter months. Acceptable RH levels were obtained in schools located in countries with a cold winter. Since increasing ventilation by bringing dry air into the indoor environment could reduce the indoor humidity level, the following section reviews levels of a ventilation indicator, CO_2, in schools in winter.

[1] In NZ, the yearly round ambient RH levels are between 70% and 90%, with a mean of 80% (NIWA, 2018).

2.4.3 Carbon dioxide level in primary schools

CO_2 is colourless, odourless and non-flammable gas. It is generated from fuel combustion and respiration. The WHO (2006) classifies CO_2 as a pollutant that current evidence is uncertain about or is not sufficient for guidelines. The lowest CO_2 level that can cause adverse health effects (acidosis) is 7000 ppm (Health Canada, 1989). After several weeks' continuous exposure to CO_2 levels at 7000 ppm, acidosis could occur. This can happen in a submarine environment. To protect from the adverse health effects and provide an adequate safety environment for sensitive occupants, the maximum CO_2 exposure level for residential IAQ is required to be below 3500 ppm (Health Canada, 1989).

Due to the non-toxicity of CO_2 at levels found in the indoor environment, exposure to CO_2 does not constitute a health risk per se (Lugg and Batty, 1999). However, CO_2 level can be used to indicate the acceptability of human body odour in a space and the ventilation rate of a building, where there are significant metabolic or combustion sources (Health Canada, 1989) or when the indoor CO_2 level is above the outdoor CO_2 level (Persily, 1997).

Figure 2-6 shows the ventilation conditions and the corresponding IAQ under different CO_2 levels (BRANZ, 2007b). It can be seen that a CO_2 level above 1600 ppm will result in odours and make people uncomfortable.

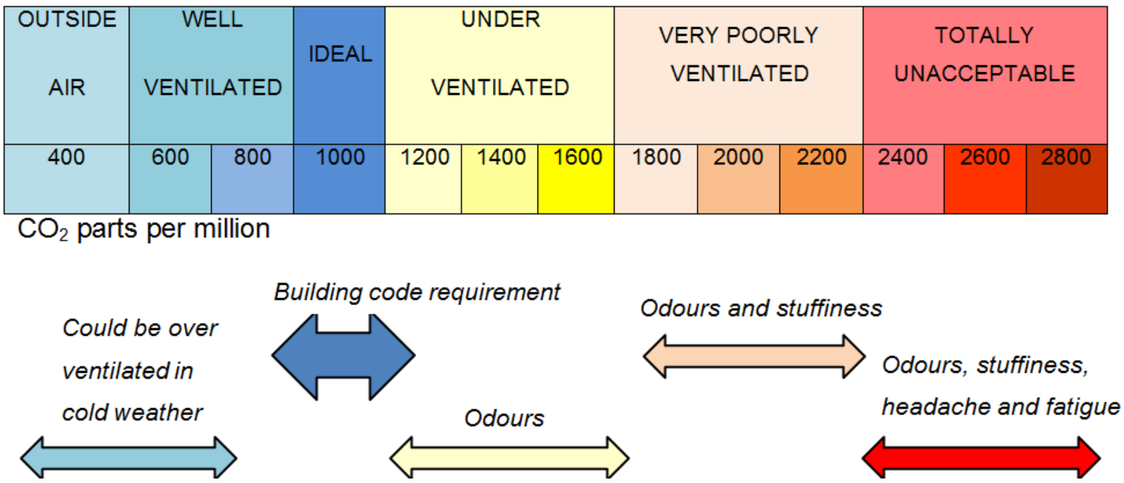

Figure 2-6 Ventilation conditions and the relative air quality under different carbon dioxide levels
Source: (BRANZ, 2007b)

Table 2-6 shows a summary of the guidelines for CO_2 levels and their corresponding ventilation rates in school teaching and learning spaces (classrooms).

Table 2-6 Guidelines for carbon dioxide (ppm) and ventilation rates (l/s/ person) in classrooms

Documents and reference		Indoor CO_2 (ppm) during teaching periods	Ventilation rate (litres of fresh air per second per person, l/s/person)
ASHRAE 62 (ASHRAE, 2016)		1000 (continuous)	8 (minimum required)
NZS 4303:1990 (Standards New Zealand, 1990)		1000 (continuous)	8 (minimum required)
AS 1668 (Standards Australia, 2012)		600-800	10-12
REHVA Guidebook 13 (REHVA, 2010)		1500[a]	3 (minimum)
EN 15251 (CEN, 2006)	IAQ[b] I	350[c]	10 (10% of visitor unsatisfied with the IAQ)
	IAQ II	500[c]	7 (20% of visitor unsatisfied with the IAQ)
	IAQ III	800[c]	4 (30% of visitor unsatisfied with the IAQ)
	IAQ IV	>800[c]	< 4 (> 30% of visitor unsatisfied with the IAQ)
EN 13779 (CEN, 2007)	Low IAQ	> 1400	< 6
	Moderate IAQ	1000–1400	6–10
	Medium IAQ	800–1000	10–15
	High IAQ	< 800	> 15
Building Bulletin 101 (BB101, 2018)	Naturally ventilated teaching spaces	1500[a] 2000[d]	8 or 2.3 l/s/m^2, [g]
	Mechanically ventilated teaching spaces	1000[a] 1500[d]	
	Hybrid systems design requirements	1200[e] 1750[f]	
Ministry of Education (2017a)	Best practice recommendations	800[h]	8 (minimum required)
	Minimum mandatory requirements	1000[i] 1200[j] 1500[k] 3000[l]	

[a] daily mean level; [b] IAQ, indoor air quality; [c] CO_2 level above the ambient (dCO_2: difference of CO_2 levels between indoor and ambient).; [d] maximum daily CO_2 level should not exceed this level for more than 20 consecutive minutes; [e] for the new building; [f] for refurbished building; [g] whichever is the greater; [h] at any occupied time, CO_2 level can reduce to 800 ppm, within 10 minutes; [i] at any occupied time, CO_2 level can reduce to 1000 ppm, within 10 minutes; [j] an average daily CO_2 level; [k] the maximum daily average CO_2 level; l the maximum CO_2 level.

These standards include ASHRAE 62, NZ Standard (NZS) 4303, Australian Standard (AS 1668), European Standards (REHVA handbook, EN 15251, EN 13779) and British guideline Building Bulletin 101 (BB101). CO_2 requirements set by NZMoE (Ministry of Education, 2017a) were also included.

An indoor CO_2 concentration below 1000 ppm is required to achieve the minimum ventilation rate (ASHRAE, 2016). Based on ASHRAE 62, NZS 4303:1990 "Ventilation for Acceptable Indoor Air Quality" states 8 litres of fresh air per second per person (l/s/person) in a classroom should be provided with an assumed maximum occupant density of 0.5 users/m^2, to result in a CO_2 level below 1000 ppm (Standards New Zealand, 1990). The same occupant density (0.5 users/m^2) was required by ASHRAE (ASHRAE, 2016) and EN 15251 (CEN, 2006). Australian Standard (AS 1668) recommends the ventilation rate in schools should not be below 10 l/s/person, corresponding to CO_2 levels of 800 ppm (Standards Australia, 2012). ASTM (2012) states that the CO_2 level in classrooms below 1000 ppm indicates a comfortable environment for occupants is achieved provided that there are no high levels of contaminants created by occupant activities.

Table 2-6 shows EN 15251 categorises IAQ into four groups, according to the proportion of visitors unsatisfied with the IAQ. EN 13779 divides indoor air into four categories based on indoor CO_2 levels; low IAQ, moderate IAQ, medium IAQ and high IAQ. BB101 states the daily mean CO_2 level (1500 ppm vs 1000 ppm) and the daily maximum CO_2 level for less than 20 consecutive minutes (2000 ppm vs 1500 ppm) in naturally ventilated and mechanically ventilated classrooms respectively. In addition, BB101 specifies ventilation systems should have the capability to keep CO_2 levels at 1200 ppm in newly-built schools and at 1750 ppm in refurbished schools for the majority of the school day.

CO_2 requirements set by NZMoE for NZ school buildings built or refurbished after January 2018 (Ministry of Education, 2017a) specify that during the occupied school hours (from 9 am to 3 pm), the average daily CO_2 level should not exceed 1200 ppm, and the maximum CO_2 level should be below 3000 ppm (Ministry of Education, 2017a). The minimum required ventilation rate should be equivalent to 8 l/s/person and 4 ACH.

The CO_2 level in classrooms in winter has been researched in many countries, including NZ. These studies are discussed and summarised in Table 2-7.

McIntosh (2011) (Table 2-7, Study A) found a mean CO_2 level above 1000 ppm in 13 out of 35 NZ classrooms for more than 50% (between 51% and 85%) of school hours (from 9 am to 3 pm). This result was supported by another NZ study (Cutler-Welsh, 2006). Cutler-Welsh (2006) undertook two-day monitoring in three Christchurch classrooms in winter. Results of this study were shown on a daily basis, and it was found that the mean CO_2 level was above 1000 ppm from 7.30 am to 4 pm in 4 out of 5 measured days (one room was excluded because it was unoccupied for most time during the CO_2 measurement). Cutler-Welsh (2006) did not report the percentage of school days that had a CO_2 level above 1000 ppm. Another NZ study was conducted in the Wellington (NZ) and involved 18 naturally ventilated classrooms (Bassett *et al.*, 1999). This study measured one full week of CO_2 levels during school hours. The results showed a mean CO_2 level above 1000 ppm in winter with a peak of 1400 ppm (10^{th} and 90^{th} percentile: 500 ppm, 2500 ppm) around 10.30 am (Bassett *et al.*, 1999). All these studies showed a CO_2 level above 1000 ppm in NZ naturally ventilated classrooms during the winter.

Studies B and C in Table 2-7 have shown CO_2 levels above 1000 ppm in overseas naturally ventilated classrooms. In addition, Stabile *et al.* (2017) found median CO_2 levels in 5 naturally ventilated central Italian classrooms (from 3 different schools) ranged from 1400 ppm to 3000 ppm during the winter seasons. Canha *et al.* (2016) reported a mean CO_2 level of 1290 ppm in 50 French primary classrooms during school hours (median = 1250 ppm, maximum: 2220 ppm). Chatzidiakou *et al.* (2012) analysed the results of CO_2 levels in 312 classrooms from 80 schools and found that 30% of the investigated classrooms had median CO_2 levels above 1500 ppm.

In contrast to CO_2 levels above 1000 ppm in naturally ventilated classrooms, some studies have found levels of CO_2 below 1000 ppm in mechanically ventilated classrooms. Studies D, E and F (Table 2-7) stated that with the operation of mechanical ventilation, the CO_2 level in classrooms was around 1000 ppm. This outcome was consistent with the results found in a one-year German study, which showed the mean level of CO_2 during school hours was 1759 ppm in 90 naturally ventilated classrooms in winter while it was respectively 701 ppm and 598 ppm in two mechanical ventilation classrooms (Fromme *et al.*, 2007). A UK study showed similar results with a CO_2 level above 1000 ppm (minimum–maximum: 1020–1938 ppm) during school hours in eight naturally ventilated classrooms, whereas two mechanically ventilated classrooms showed a CO_2 level below 1000 ppm (672 ppm and 907ppm) (Mahyuddin *et al.*, 2013).

Overall, all studies agree that the CO_2 levels in naturally ventilated classrooms, during the winter, are above the recommended levels from different organisations (normally 1000 ppm). An acceptable CO_2 level was achieved in some mechanically ventilated classrooms during the winter.

Table 2-7 Summary of studies on carbon dioxide levels (ppm) and ventilation rates (l/s/ person or ACH) in primary schools

Study	Sample size and classroom description	Study location and design	Monitoring sensors and location	CO_2 levels (ppm); Mean (SD) / range	Ventilation rate (l/s/person) or air change per hour (ACH, h^{-1})	Main observation	Reference
A	35 classrooms; Naturally ventilated; With the heating system.	Wellington, New Zealand; 13 classrooms: August to October 2003; 22 classrooms: July to August 2005; School hours; 5-min intervals.	Non-dispersive infrared sensors.	1006 (419) [552, 2178].	No data	13 classrooms (38%) were with a CO_2 above 1000 ppm for more than 50% of the school day.	(McIntosh, 2011)
B	30 classrooms (10 schools); Naturally ventilated; No heating.	Shanghai, China; November and December, 2000; Only 1 hour monitoring during a full class.	Non-dispersive infrared sensors; 0.9 m above the floor.	> 1000 ppm: 55% of the classrooms; 1000-2000 ppm: 45% of the classrooms.	ACH: Mean (SD): 9.1 (5.8) h^{-1}; Minimum–maximum: 2.9–29.4 h^{-1}	Inadequate ventilation rate in classrooms negatively affects asthma and asthmatic symptoms among students. The wide range of the ACH was due to the variability of natural ventilation (windows or doors open).	(Mi *et al.*, 2006)

Study	Sample size and classroom description	Study location and design	Monitoring sensors and location	CO_2 levels (ppm); Mean (SD) / range	Ventilation rate (l/s/person) or air change per hour (ACH, h^{-1})	Main observation	Reference
C	73 classrooms from 20 public primary schools.	Porto, Portugal; Winter seasons; November to March; 2011 to 2013; School hours; Ventilation rates were derived from the CO_2 and occupancy data.	Non-dispersive infrared sensors; 1–1.5 m above the floor.	1669 (601) [829–3111].	0.87 (1.38) [0.11–7.21].	85% of the classrooms had a median CO_2 level above 1000ppm.	(Madureira, Paciencia, Pereira, *et al.*, 2015)
D	22 mechanically ventilated classrooms from seven schools; one naturally ventilated classroom.	Uppsala city, Sweden; 2000; Tracer gas technique to calculate the ventilation rate.	Non-dispersive infrared sensors; 1-min intervals.	815 (216) [540–1275].	ACH: 4.5 (2.0) [0.5–8.1]	Either increasing the ventilation rate or reducing the CO_2 level can reduce the formaldehyde level. Increase ACH from 0.5 h^{-1} to 4.4 h^{-1} significantly reduced the symptom of wheeze and nocturnal breathlessness, but no associations were found when it was increased from 4.4 h^{-1} to 8.1 h^{-1}.	(Kim *et al.*, 2007)

Study	Sample size and classroom description	Study location and design	Monitoring sensors and location	CO_2 levels (ppm); Mean (SD) / range	Ventilation rate (l/s/person) or air change per hour (ACH, h^{-1})	Main observation	Reference
E	199 classrooms from 39 schools (28 primary schools, 5 secondary schools and 6 combined schools); 12% of the classrooms were installed with a mechanical ventilation system (the intervention group) between 1993 and 1995.	Sweden; March to May 1993 (98 classrooms) and January to March 1995 (101 classrooms); 51 of the 199 classrooms participated in the two years; CO_2 measured twice at the end of each lesson.	Non-dispersive infrared sensors; Data recorded at 15-min intervals.	In 1993: 1050 ppm (intervention group later); 930 ppm (control group); In 1995: 780 ppm (intervention group); 1050 ppm (control group).	In 1993: 0.5 h^{-1} (intervention group later); 3.1 h^{-1} (control group); In 1995: 4.5 h^{-1} (intervention group); 3.0 h^{-1} (control group).	There were no significant differences in the pollution exposure level between the two group classrooms in 1993. After installing the ventilation system, levels of CO_2 (1050 vs 780 ppm), RH (42 vs 32%), formaldehyde (6 vs 2 µg/m^3), VOCs (40 vs 2 µg/m^3) and respirable dust (24 vs 11 µg/m^3) were significantly lower in the classrooms with a mechanical ventilation system (intervention group) than in the classrooms without mechanical ventilation systems (control group).	(Smedje *et al.*, 2000)

Study	Sample size and classroom description	Study location and design	Monitoring sensors and location	CO_2 levels (ppm); Mean (SD) / range	Ventilation rate (l/s/person) or air change per hour (ACH, h^{-1})	Main observation	Reference
F	Two Portugal naturally ventilated classrooms; Six Finnish mechanically ventilated classrooms.	Heating seasons; 1.2 m above the floor; Tracer gas technique (CO_2) to calculate the ventilation rate.	Non-dispersive infrared sensors; One day continue monitoring at either 15-sec or 1-min intervals.	Portugal: 384 ppm–1314 ppm; Finland: 368 ppm–1383 ppm.	Portugal: 2.4 l/s/person, 1.0 ACH; Finland: 13.0 (4.0) [7.0–20.0] l/s/person, 4.6 ACH.	In Finnish mechanically ventilated schools, although the ventilation rate meets the standard requirement, high levels of CO_2 were found. During the winter season, the naturally ventilated classrooms failed to provide a satisfying classroom environment.	(Canha *et al.*, 2013)

2.4.4 Impacts of the classroom temperature, moisture and carbon dioxide levels on the student health

Poor IAQ in classrooms can deteriorate students decision-making, respiratory symptoms and academic performance (Annesi-Maesano *et al.*, 2012; Apte *et al.*, 2000; Bakó-Biró *et al.*, 2007; Gaihre *et al.*, 2014; Haverinen-Shaughnessy *et al.*, 2011; Satish *et al.*, 2012). This section briefly summarises the impact of temperature, moisture and CO_2 on students' health.

2.4.4.1 Impacts of temperature on student health

Temperature levels in classrooms impact student respiratory symptoms. There were respectively 15.2%, 24.8% and 28.6% of students reporting the daytime breathlessness when the classroom temperature in the 13.4–16.0 °C, 16.1–18.0 °C and 18.1–19.5 °C ranges. Students in classrooms with a high level of temperature (from 13 °C to 21 °C, mean =17 °C) had the daytime breathlessness more often (OR = 1.26, 95% CI: 1.14–1.38) (Mi *et al.*, 2006). This is the subjective data collected by filling the questionnaire. The results need to be supported by the measured data. An NZ home study (309 children over 12049 days) found that children's respiratory health was strongly impacted by bedroom temperatures under 11 °C (Pierse *et al.*, 2011). All these studies showed the impact of indoor temperatures (either classrooms or homes) on children's respiratory symptoms.

2.4.4.2 Impacts of moisture on student health

Moisture level can affect students' health directly and indirectly, as damp areas have a high probability for mould growth. Taskinen *et al.* (2007) found frequencies of coughing (21% vs 9%) and wheezing (16% vs 6%) were significantly higher in moisture damaged classrooms than in non-moisture damaged classrooms. The moisture damaged schools refer to schools with visible moulds and potential leaks in classrooms. Follow-up research showed after retrofitting the moisture damaged classrooms, all prevalence of the respiratory symptom in previous moisture damaged classrooms was reduced, and there were no statistically significant differences in coughing and wheezing between the students in the retrofitted classrooms and the non-moisture damaged classrooms (Savilahti *et al.*, 2000). The results are supported by two other studies (Borras-Santos *et al.*, 2013; Meklin *et al.*, 2002).

Meklin *et al.* (2002) undertook a comparative study in 24 moisture damaged and eight non-moisture damaged central Finnish schools and showed that coughing in the moisture damaged schools was significantly higher than in the non-moisture damaged schools (33% vs 25%). Borras-Santos *et al.* (2013) reported that a nocturnal dry cough was associated with high moisture levels in schools (OR = 1.2, 95% CI: 1.0–1.3) in a study undertaken in Spain, Finland and the Netherlands including 9271 children from 29 moisture damaged schools and 27 non-moisture damaged schools. These studies agree that a high level of moisture in classrooms is associated with a prevalence of children's respiratory symptoms.

2.4.4.3 Impacts of carbon dioxide on student health

Due to the non-toxicity of CO_2 at levels found in the indoor environment, exposure to CO_2 does not constitute a health risk per se (Lugg *et al.*, 1999). However, when CO_2 levels are used as a surrogate to estimate the ventilation rate, it can indicate levels of other pollutants generated by people due to a lack of ventilation. Impacts of high CO_2 levels (above 1000 ppm) caused by an inadequate ventilation rate on respiratory symptoms have been investigated. A Chinese study, undertaken in 30 naturally ventilated classrooms during the winter (1414 participants, 10 naturally ventilated school) showed that there was an association between indoor CO_2 concentration (a surrogate for estimating the ventilation rate) and asthmatic symptoms with an OR of 1.18 (95% CI: 1.04–1.35) for per 100 ppm CO_2 concentration increase from 1000 ppm to 1555 ppm (Mi *et al.*, 2006). Similar results were found where respiratory symptoms (sore throat, cough, wheezing) were significantly associated with daily average dCO_2 concentration (the difference between the indoor and outside CO_2 levels), with the OR ranging from 1.2 to 1.5 for per 100 ppm dCO_2 increase (dCO_2 ranged from 6 ppm to 418 ppm) (Rosbach *et al.*, 2013).

Overall, an unacceptable level of temperature, moisture and CO_2 (an indicator of ventilation rate) adversely affects students' health, especially the respiratory symptoms related health. The following section will review the impacts of these three IAQ parameters (temperature, moisture and CO_2) on school absenteeism rate.

2.4.5 Impacts of temperature, moisture and carbon dioxide on absenteeism rate

School attendance is a critical factor for students' academic performance (Shendell, Prill, *et al.*, 2004). The benefit of improving school attendance is considerably higher than the cost of improving the school IAQ (Mendell *et al.*, 2013). Wargocki *et al.* (2014) used a Danish official financial model to evaluate the financial output that could result from increasing the Danish school environment to the compulsory requirements, and found that this action would yield a 173 million Euro increase in the Gross Domestic Product and a 37 million Euro increase in public finances per year. Therefore, improving the school environment is necessary for both the student health and local economy.

2.4.5.1 Impacts of temperature on school absenteeism rate

Gaihre *et al.* (2014) found no statistically significant relationship between the student's absenteeism rate and the indoor temperature (median = 22 °C, the 1st–3rd quartile: 21–23 °C) in 60 naturally ventilated Scotland primary classrooms. This result supports WHO recommendations for a temperature range of 18 °C to 24 °C.

Studies on relationships between temperatures and the student's absenteeism rate are also focused on the ambient temperature. An American (Nevada) elementary school study showed a negative association between the absenteeism rate and ambient temperature (school hours averaged ambient temperature was 8.2 °C) (Chen *et al.*, 2000). This result was supported by a one-year Finnish study that found significant relationships between the ambient temperature (school hours averaged temperature was 3.1 °C) and student absenteeism rate (Pönkä, 1990), regardless of the fact that Finnish children have better protective measures (warm clothes) against the cold ambient temperature (The Eurowinter Group, 1997). Additionally, an NZ home study showed that increasing home temperatures (from 16.0 °C to 17.1 °C) significantly reduced children's school absences for medical reasons (Free *et al.*, 2010).

2.4.5.2 Impacts of moisture on school absenteeism rate

Green (1975) found the absenteeism rate in 12 public schools decreased by 20% when the indoor average RH was increased from 22% to 35%, as the low level

RH can dry out the mucous membrane. Simons *et al.* (2010) found the student absenteeism rate was associated with the visible mould in classrooms (mean OR = 2.22, 95% CI: 1.34–3.68). Simons *et al.* (2010) did not measure classroom moisture levels, but categorised classrooms into “visible water damaged classrooms”, “active roof leaky classrooms”, “condensation in classrooms” and “poor humidity rating classrooms”. Borras-Santos *et al.* (2013) undertook a study in 29 moisture damaged schools and 27 non-moisture damaged schools from Spain, Finland and the Netherlands including 9271 children. They found that Finnish schools’ absenteeism rate (due to respiratory symptoms) in moisture damaged schools was significantly higher than in non-moisture damaged schools, with the mean OR of 1.50 (95% CI: 1.10–2.03).

Gaihre *et al.* (2014) found no statistically significant relationship between the student’s absenteeism rate and the RH level, which ranged from 38% to 48% in 60 naturally ventilated Scottish primary classrooms. This result supports the ASHRAE recommendation for RH within 30% to 60%. These studies suggest that moisture damaged classrooms or classrooms having an RH level outside the ASHRAE recommended levels could have an impact on students’ absenteeism rate.

2.4.5.3 Impacts of carbon dioxide on school absenteeism rate

Similar to the impacts of CO_2 on student health, impacts of high levels of CO_2 on student absenteeism rate could be an indicator of the impact of inadequate ventilation on students’ absenteeism rate. An American study of 409 traditional and 25 portable classrooms (Shendell, Prill*, et al.*, 2004) found that the absenteeism rate increased by 10% to 20% with an increase in 1000 ppm dCO_2 concentration. A further short-term study (focused on three to five teaching days) that involved 60 naturally ventilated Scottish primary classrooms supported this result with the annual attendance reduced by 0.2% for per 100 ppm CO_2 concentration increase ($p = 0.014$) (Gaihre *et al.*, 2014). In conclusion, both studies showed the impact of an increased CO_2 concentration on school absenteeism rate.

2.4.6 Section summary

This section reviewed the literature on temperature, RH and CO_2 levels in schools in winter, and their impacts on students' respiratory health and school absenteeism rate. This section also reported the recommended levels of temperature, RH and CO_2 from different organisations to achieve an acceptable IAQ in schools.

The reviewed studies showed that naturally ventilated NZ schools had low levels of temperature, high levels of RH and high levels of CO_2 in winter. The acceptable levels of these three IAQ parameters (temperature, RH and CO_2) were obtained in some overseas mechanically ventilated schools in winter. Low levels of temperature, high levels of RH and high levels of CO_2 can adversely impact students' respiratory symptoms and school attendance. Therefore, students need to be provided with a learning environment that has acceptable levels of temperature, RH and CO_2.

CO_2 levels are an indicator of ventilation. Temperature and RH levels are affected by ventilation. The next section reviews the level of ventilation and the method used to increase ventilation in schools.

2.5 Ventilation in primary schools

Natural ventilation is defined as the exchange of outdoor air and indoor air, which is driven by wind or buoyancy through open windows, doors and vents. Mechanical ventilation requires a fan to drive the air exchange. The total ventilation rate of a building or a room is the sum of natural ventilation, mechanical ventilation and infiltration/exfiltration (air moving through the leakage of a building envelop). The total ventilation rate can be expressed in air changes per hour (ACH, h^{-1}).

This section reviews the level of ventilation in NZ and overseas schools during the winter. Firstly, the existing recommended ventilation guidelines by different organisations are reported. This is followed by a review of studies that investigate levels of ventilation rate in primary schools during the winter. The third part of this section reviews some methods that can be used to increase the ventilation rate in schools in winter. This section is closed by briefly reviewing the effect of the ventilation rate on students' health and school absenteeism rate.

2.5.1 Ventilation guidelines in schools

Table 2-6 (Section 2.3.3) shows the required ventilation rate in classrooms according to ASHRAE 62, REHVA handbook, EN 15251, EN13779, BB101, AS 1668, NZS 4303 and NZMoE document DQLS 2017. When the minimum ventilation rate is achieved, the pollutants generated by occupants (odour and bio-effluents) and buildings (emissions from building materials and furniture) are generally diluted (ASHRAE, 2016). ASHRAE specifies a minimum ventilation rate of 7.4 litres per second per person (l/s/person) for pupils aged between 5 and 8, and 6.7 l/s/person for those aged 9 and above (ASHRAE, 2016). The European Committee for Standardisation (CEN) recommends an 8 l/s/person ventilation rate in classrooms (CEN, 2007). The ventilation rate specified by ASHRAE 62 is based on adapted occupants (occupants have been in the room for 10 to 15 minutes), while the ventilation rate recommended by EN 13779 is based on non adapted occupants (visitors or occupants first entering the room).

Based on ASHRAE (1989), the NZS 4303:1990 "Ventilation for Acceptable Indoor Air Quality" recommends a minimum ventilation rate of 8 l/s/person, with an assumed maximum occupant density of 0.5 users/m^2 (50 people per 100 m^2 floor area), and it results in a CO_2 concentration below 1000 ppm (Standards New Zealand, 1990). At this ventilation rate, a classroom will have an average ACH of 4 h^{-1} (BRANZ, 2007b).

In addition to the ventilation rate required by NZS 4303:1990, the NZBC Clause G4 Ventilation requires that the area of openable windows in classrooms is in excess of 5% of the floor area to achieve sufficient ventilation (Department of Building and Housing, 2011a). However, a survey undertaken in 40 Auckland (NZ) primary schools in 2015 showed that only 40% of teachers open windows during their teaching in winter (Gully, 2015; Liaw, 2015). This figure dropped to 15% in a survey of 33 teachers from nine schools located in three NZ regions, namely Christchurch (N=4), Dunedin (N=3) and Hawke's Bay (N=2) (unpublished data[1]). Security was the main issue in Auckland studies preventing teachers opening windows, while the outside noise deterred teachers from opening the windows in the study carried out in other three above-mentioned NZ regions. This means that when an NZ classroom is dependent on natural ventilation, an acceptable ventilation rate might not be achieved in winter, even if the school is designed according to the NZBC requirements.

2.5.2 Studies on ventilation rates in schools

The ventilation rate can be estimated using the tracer gas technique, under a well mixed, single zone and homogeneity assumption (Persily, 1997; Sherman, 1990). In a well mixed zone, any outside air or injected tracer gas becomes instantaneously (and homogeneously) dispersed within the zone. A single zone means the space only communicates with the outside, and a space whose concentration of tracer gas is unaffected by the zone. The fluid properties (i.e. density and tracer gas concentration) are assumed to be the same at every point within the zone (homogeneity).

Table 2-7 summarises some studies that investigated ventilation rates in schools in winter. Study C (Table 2-7) showed an inadequate ventilation rate in 73

[1] This data was collected by the PhD candidate Yu Wang in a sequel school project.

classrooms in 20 naturally ventilated primary schools in Portugal, with the CO_2 levels between 829 ppm and 3111 ppm, which corresponds to a ventilation rate in the range of 7.21 l/s/person to 0.11 l/s/person (Madureira, Paciencia, Pereira, *et al.*, 2015). Similarity, unacceptable ventilation rates (CO_2 levels above 1000 ppm) were found in naturally ventilated Australian schools, American schools and the UK schools in winter (Coley and Beisteiner, 2016; Luther, Horan, *et al.*, 2014; Shendell, Winer, *et al.*, 2004). Luther and Horan (2014) undertook a study in 24 classrooms from four naturally ventilated schools in Victoria, Australia. It was found that levels of CO_2 were up to 1450 ppm and 2700 ppm when windows were opened partly and closed respectively. Shendell, Winer, *et al.* (2004) undertook a study in Los Angeles, USA, in winter 2001, investigating the ventilation rate in eight portable classrooms and four traditional classrooms. This study found inadequate ventilation rates in both portable classrooms (mean = 0.7 h^{-1}, SD = 1.1 h^{-1}, minimum–maximum: 0.2–2.9 h^{-1}) and traditional classrooms (mean = 0.9 h^{-1}, SD = 0.4 h^{-1}, minimum–maximum: 0.6–1.2 h^{-1}). Coley *et al.* (2016) measured levels of CO_2 in seven classrooms from four naturally ventilated schools in the UK, and found that the average ventilation rate during school hours was far below REHVA required minimum levels (1.38 l/s/person vs 3 l/s/person), which resulted in an average CO_2 level of 1957 ppm. In conclusion, all studies agree with an unacceptable ventilation rate (CO_2 levels above 1000 ppm) in naturally ventilated schools during the winter.

Fisk (2017) summarised the ventilation rates found during occupied school hours in 3494 classrooms from 1242 schools in 14 countries. These samples consisted of 550 naturally ventilated classrooms, 1182 mechanically ventilated classrooms, 866 mixed ventilated classrooms and 731 classrooms where the types of ventilation were not specified. The remainder 165 classrooms were from 62 naturally ventilated and two mechanically ventilated schools. This review showed maximum CO_2 concentrations in these 3494 classrooms ranged from 3000 ppm to 6000 ppm during school hours. The averaged school hours CO_2 concentration during the measurements exceeded 1000 ppm in the majority of schools, with the maximum averaged levels between 1400 ppm and 5200 ppm. The levels of CO_2 in naturally ventilated classrooms were not systematically higher or lower than in the mechanically ventilated classrooms. Overall, Fisk (2017) has reported that inadequate ventilation rates in school buildings are a worldwide issue. Therefore, methods that increase ventilation rates in schools are needed. Methods used to increase ventilation rates in schools are reviewed in the following section.

2.5.3 Methods to increase ventilation rates in schools

Table 2-8 shows studies that have investigated the performance of different ventilation interventions in schools. Study A supplied a constant volume of fresh air into classrooms using a fan controller (Bakó-Biró *et al.*, 2012). The ventilation rate was initially 1 l/s/person (before intervention), and this was increased to 8 l/s/person (with intervention). Study B used demand controlled mechanical ventilation to increase the ventilation rate in schools. The levels of CO_2 were the indicator of ventilation rates. Results of Study B showed that levels of CO_2 were 1335 ppm (minimum–maximum: 763–2000 ppm) in the control classrooms, and 841 ppm (minimum–maximum: 743–925 ppm) and 975 ppm (minimum–maximum: 887–1077 ppm) in the treatment classrooms respectively (Rosbach *et al.*, 2013).

A temperature and CO_2 controlled ventilation system has been installed in a Porto (Portugal) school (Almeida and de Freitas, 2015). The performance of this demand controlled ventilation system was tested during two months in two refurbished classrooms. Results showed that mean (SD) levels of CO_2 were 898 (588) ppm and 1082 (663) ppm respectively in the two control classrooms (naturally ventilated). These levels were reduced to 612 (269) ppm and 735 (312) ppm respectively in the two intervention classrooms (with the installation of the ventilation system). In control classrooms, for 20% of the school hours, CO_2 levels were between 1500 ppm and 2500 ppm. In the intervention classrooms, CO_2 levels were below 1500 ppm for almost all school hours.

These studies showed that it was possible to achieve acceptable ventilation rates (CO_2 levels) in schools in winter, with the use of mechanical ventilation systems. However, mechanical ventilation systems have both a high capital cost and operational cost (Almeida and de Freitas, 2014).

In contrast, low cost solutions to increase the ventilation rate were applied in some schools. Study C (Table 2-8) showed the influence of occupant behaviours on ventilation rates (Geelen *et al.*, 2008). Results of this study found that ventilation advice combined with a teaching package was the most effective method to reduce the levels of CO_2 in classrooms, compared with ventilation advice only and ventilation advice combined with a CO_2 warning device. In classrooms that had the ventilation advice combined with a teaching package, percentage of school hours with CO_2 levels above 1000 ppm reduced from 65% (before intervention) to 40% (after intervention).

Study D (Table 2-8) showed the CO_2 levels in classrooms with four types of ventilation methods (Gao *et al.*, 2014), namely manually openable windows, automatically openable windows, automatically openable windows with an exhaust fan installed in classrooms, and a balanced mechanical ventilation system. Results showed that the highest and the lowest mean (SD) CO_2 levels were 1458 (436) ppm and 757 (147) ppm respectively in the classrooms with manually operable windows, and with the balanced mechanically operable windows (Gao *et al.*, 2014).

A similar study was undertaken in an Italian naturally ventilated school in winter, to investigate the effects of a manual airing strategy on the school IAQ (Stabile *et al.*, 2017). This study was composed of six tests. Two of them were the control conditions. Under the control conditions, teachers and students were allowed to use windows and doors based on their schedule. Four of the tests were operating the windows for 5-min, 10-min, 15-min and 20-min respectively every hour. During the intervention, doors were not allowed to be used for ventilation. Results showed that under the two control conditions, mean (SD) levels of CO_2 were 1339 (340) ppm and 1869 (564) ppm. Teachers preferred to use doors to improve the IAQ in classrooms. During the intervention, mean (SD) levels of CO_2 in classrooms were 1656 (375) ppm, 1447 (351) ppm, 1305 (240) ppm and 1104 (238) ppm respectively, when the classroom had open windows for 5-min, 10-min, 15-min and 20-min every hour respectively. Overall, changes in ventilation behaviours can increase ventilation rates in schools, but it is hard to achieve to an acceptable level.

In addition to change ventilation behaviours, other studies investigated the ventilation performance of making changes to the building structure and the using sustainable energy applications in schools (Chen, 2013; Jones and Kirby, 2012; Mysen *et al.*, 2005). Study E (Table 2-8) conducted a study in a Norway school by taking unconditioned supply air from the building facade at the ceiling level into classrooms in winter (Mysen *et al.*, 2005). This was a demand controlled ventilation system to make the classroom CO_2 levels below 800 ppm. Results of this study showed that with the use of this ventilation system, although students were satisfied with the classroom IAQ, the classroom temperature deteriorated due to the supply of cold air directly into classrooms. However, taking the facade air directly into classrooms during the winter is not applicable in NZ. As compared with Norway, NZ had very humid ambient air in winter.

Study F (Table 2-8) showed the ventilation performance of a roof-mounted split-duct windcatcher (Jones *et al.*, 2012). This study was carried out in nine classrooms from five naturally ventilated schools that were located in the south of England. The temperature controlled windcatcher did not work when the classroom temperature was below 22 °C. Results of this study showed the windcatcher was closed for 92% of the school hours, as the classroom temperature was unable to reach 22 °C. The median CO_2 levels in six out of nine classrooms were above 1500 ppm during school hours. Only one of the nine classrooms had a ventilation rate up to 3 l/s/person (Jones *et al.*, 2012).

Study G (Table 2-8) showed the performance of using a solar wall (a transpired solar air collector) to preheat and ventilate the classrooms in one Canadian school. This solar air collector was installed at the time of the school was built. Results showed that during the winter months (December, January and February), the difference between the outlet air temperature and the ambient air temperature of the solar wall ranged from 0.1 °C to 8.5 °C, with the mean (SD) level of 3.9 (1.9) °C. There were no ventilation results reported in this study. It was inferred that, with the use of the solar wall, the ventilation rate in classrooms should be increased, as warm air was taken into the classroom. This solar wall encountered partial shading problems, which partially adversely affected its efficiency.

Overall, the reviewed studies showed that three types of methods were used to increase ventilation rates in schools in winter, namely the traditional mechanical ventilation, changing ventilation behaviours and using sustainable energy applications. Even though ventilation rates were increased, they were still below the recommended levels in some schools.

Table 2-8 Research investigating methods to increase the ventilation rate in schools in winter

Study	Sample size and classroom description	Interventions	Ventilation measurement or calculation	Ventilation rate (or CO_2 levels)	Main observation	Reference
A	England; 16 classrooms from 8 primary schools; Three weeks of monitoring.	Portable mechanical ventilation system (an exterior fan with 200 mm diameter duct); Supply the air into building through windows openings.	Tracer gas technique; sulphur hexafluoride.	Before intervention: 1 l/s/person; After intervention: 8 l/s/person.	At a higher ventilation rate, students' academic performance was increased as follows: Choice reaction (by 22%); Colour word vigilance (by 27%); Picture memory (by 8%); Word recognition (by 15%).	(Bakó-Biró *et al.*, 2012)

<table>
<tr><th>Study</th><th>Sample size and classroom description</th><th>Interventions</th><th>Ventilation measurement or calculation</th><th>Ventilation rate (or CO_2 levels)</th><th>Main observation</th><th>Reference</th></tr>
<tr><td>B</td><td>A longitude crossover designed study;

18 classrooms from 17 schools (12 treatment 6 control);

The Netherlands;

Winter months during 2010-2012;

Three consecutive weeks of monitoring.</td><td>A custom-designed CO_2 controlled mechanical ventilation system;

Indoor CO_2 levels were targeted at 800 and 1200 ppm respectively.</td><td>Use CO_2 levels as the indicator of the ventilation rate.</td><td>The control group: 1335 ppm (range:763–2000ppm);

The treatment group:
<table><tr><td>CO_2 targets (ppm)</td><td>Classroom CO_2 levels (ppm);

mean (minimum–maximum)</td></tr><tr><td>a) 800</td><td>841 (743–925)</td></tr><tr><td>b) 1200</td><td>975 (887–1077)</td></tr></table></td><td>CO_2 levels in classrooms were significantly reduced, with the use of the mechanical ventilation.</td><td>(Rosbach et al., 2013)</td></tr>
</table>

<table>
<tr><th>Study</th><th>Sample size and classroom description</th><th>Interventions</th><th>Ventilation measurement or calculation</th><th>Ventilation rate (or CO_2 levels)</th><th>Main observation</th><th>Reference</th></tr>
<tr><td>C</td><td>81 classrooms from 20 Dutch primary schools;

October to December 2004, 24 classrooms;

January to March 2005, 57 classrooms;

The effectiveness of interventions was measured 6 weeks later.</td><td>Three types of ventilation behaviours plus a control group:

a) classroom specific ventilation advice (n = 20);

b) classroom specific ventilation advice, combined with a CO_2 warning device (n = 20);

c) classroom specific ventilation advice, combined with a teaching package (n = 21);

d) a control group (n = 20).</td><td>Use percentage of CO_2 levels above 1000 ppm as the indicator of the effectiveness of the intervention.</td><td><table>
<tr><th>Ventilation intervention</th><th>T_0^*</th><th>T_1^{**}</th><th>T_2^{***}</th></tr>
<tr><td>a) Advice only</td><td>65%</td><td>55%</td><td>62%</td></tr>
<tr><td>b) Advice & warning device</td><td>65%</td><td>38%</td><td>57%</td></tr>
<tr><td>c) Advice & teaching package</td><td>65%</td><td>58%</td><td>40%</td></tr>
<tr><td>d) Control group</td><td>65%</td><td>63%</td><td>69%</td></tr>
</table>
*percentage of daily CO_2 levels above 1000 ppm before the intervention;
**percentage of daily CO_2 levels above 1000 ppm directly after the intervention;
***percentage of daily CO_2 levels above 1000 ppm 6 weeks after the intervention;</td><td>Providing ventilation advice only was not effective enough to increase ventilation in schools.

CO_2 results measured after 6 weeks of the intervention showed that ventilation advice combined with the teaching package was the most effective.</td><td>(Geelen et al., 2008)</td></tr>
</table>

<table>
<tr><th>Study</th><th>Sample size and classroom description</th><th>Interventions</th><th>Ventilation measurement or calculation</th><th>Ventilation rate (or CO_2 levels)</th><th>Main observation</th><th>Reference</th></tr>
<tr><td>D</td><td>4 classrooms from 1 school;

Suburban Denmark;

Classrooms buildings: bricks and concrete built in the early 1970s;

Have a central heating system.</td><td>Four types of ventilation systems:

a) Manually openable windows (MW);

b) Automatically openable windows (AW);

c) Automatically openable windows with an exhaust fan (AW/EF);

d) A balanced mechanical ventilation system (MV).</td><td>Tracer gas (CO_2) technique</td><td><table>
<tr><td>Ventilation intervention</td><td>CO_2 level (ppm) (mean, SD)</td><td>Ventilation rate (l/s/person) (mean, SD)</td></tr>
<tr><td>a) MV</td><td>1458 (436)</td><td>2.3 (0.6)</td></tr>
<tr><td>b) AW</td><td>1079 (248)</td><td>4.2 (0.9)</td></tr>
<tr><td>c) AW/EF</td><td>942 (185)</td><td>4.5 (1.3)</td></tr>
<tr><td>d) MV</td><td>757 (147)</td><td>7.3 (1.8)</td></tr>
</table></td><td>Windows were seldom open in winter.

The highest CO_2 levels were found in naturally ventilated classrooms with manually openable windows.

Automatically openable windows had remarkable impacts on the classroom ventilation rate.

Pupil's perception in classrooms with automatically openable windows and the exhaust fan was the best.</td><td>(Gao et al., 2014)</td></tr>
</table>

Study	Sample size and classroom description	Interventions	Ventilation measurement or calculation	Ventilation rate (or CO_2 levels)	Main observation	Reference
E	Norway; One refurbished school; January 2003; Two-day monitoring.	Taking unconditioned supply air from the facade into classrooms at the ceiling level; Demand controlled ventilation: indoor CO_2 below 800 ppm; No supplied air when the indoor temperature was below 19 °C.	Air velocity, air velocity turbulence intensity were measured at three heights: 3 cm above the floor; 3 cm above the desk; 1.2 m above the floor (averaged seated height); 3-min intervals.	No CO_2 data; No ventilation rate data;	Classroom temperature was deteriorated due to the supply of the cold air. On cold days, it has an unpleasant draughtiness problem. The indoor climate is satisfactory and no extra energy was consumed, compared with previous annual consumption A temperature compensated CO_2 set-point fan is recommended for future research	(Mysen *et al.*, 2005)

Study	Sample size and classroom description	Interventions	Ventilation measurement or calculation	Ventilation rate (or CO_2 levels)	Main observation	Reference
F	South of England; Nine classrooms from 5 schools; Winter; All naturally ventilated classrooms; Focus on school hours (9 am to 3.30 pm).	Use a roof-mounted single (top-down) split-duct windcatcher; The windcatcher was automatically controlled by the classroom temperature; The windcatcher did not work when classroom temperature was below 22 °C.	Standard single zone tracer gas technique; Sulphur hexafluoride.	Six out of nine classrooms had the median CO_2 levels below 1500 ppm; It was estimated that only one of the nine classrooms had the ventilation rate up to 3 l/s/person.	The windcatcher was closed for 92% of the school hours, as the temperature in classrooms was hard to reach 22 °C.	(Jones *et al.*, 2012)

Study	Sample size and classroom description	Interventions	Ventilation measurement or calculation	Ventilation rate (or CO_2 levels)	Main observation	Reference
G	Yellowknife, Northwest Territory, Canada; One school; Arctic Energy Alliance monitored the system to calculate the energy savings from April 2013 to March 2014.	Use a surface area of 192 m^2 solar wall (transpired) to preheat the ambient air to increase the ventilation rate and save energy; The solar wall was installed at the time of the building being constructed; Oriented 15° west of the south.	There was a monitoring of the ambient air temperature and outlet air temperature of the solar wall; No monitoring of CO_2 levels or ventilation rates.	No CO_2 data; No ventilation rate data.	The solar wall was partially shaded in shoulder seasons. Shading partially adversely affected the efficiency of the solar wall.	(Arctic Energy Alliance, 2014; Chen, 2013)

2.5.4 Impacts of the classroom ventilation rates on students health and absenteeism rate

An adequate ventilation rate will expel moisture, bacteria and other pollutants from the indoor environment, and benefit the occupants' health and school attendance (Canha *et al.*, 2013; Kim *et al.*, 2007; Smedje *et al.*, 2000).

A low ventilation rate increases the prevalence of respiratory symptoms. Smedje *et al.* (2000) studied the influence of the ventilation rate on students' respiratory symptoms. The fieldwork was undertaken in approximately 100 classrooms from 39 randomly selected schools in 1993 and 1995 in Sweden. In between, the mechanical ventilation system was installed in 12% of the classrooms that increased the ventilation rate from 0.5 to 4.0 ACH. While the other classrooms had the ventilation rate of 3.1 ACH at both years. In classrooms with the newly installed mechanical ventilation system, the pupils reported the less occurrence of "at least one asthmatic symptom", and there was a reduce in reporting the asthmatic symptoms from 1993 to 1995. This study showed a negative relationship between asthmatic symptoms (cough, wheeze, shortness of breath) and the ventilation rate in classrooms, with the mean OR of 0.30 (95% CI: 0.10–0.80).

The ventilation rate is associated with the school attendance (Mendell *et al.*, 2013; Simons *et al.*, 2010). An American (California) study involved 162 classrooms (3^{rd} to 5^{th} grade) in three school districts over two school years showed that the absenteeism rate (due to medical reasons) was reduced by 1.6% ($p < 0.05$) for per 1 l/s/person ventilation rate increase (from 4 l/s/person to 7 l/s/person) (Mendell *et al.*, 2013). Simons *et al.* (2010) combined the results of school building conditions survey[1] and school absenteeism report in 2751 New York schools, found the similar results that student's absenteeism rate was associated with the ventilation problems in classrooms with the mean OR of 3.10

[1] Information on the ventilation problems was gathered by questionnaire. The building conditions questionnaire regarding ventilation problems in Simons *et al.* (2010) study included 11 questions, namely (1) Any ventilation problem; (2) Air intake near bus loading; (3) Air intake near truck delivery; (4) Air intake near garbage storage; (5) Dirt, dust, or debris around intake; (6) Fresh air intake blockage; (7) Dirt, dust or debris in ductwork; (8) Damper malfunction; (9) Air filter condition; (10) Inadequate outside air; (11) Poor ventilation and indoor air quality rating.

(95% CI: 1.79–5.37). In conclusion, inadequate ventilation rates in schools adversely affect students' health and the school attendance.

2.5.5 Section summary

This section reviewed guidelines of ventilation rate in schools, and some studies investigating ventilation rates in schools in winter. The ventilation rate in naturally ventilated schools during the winter was found to be lower than the recommended levels. However, the acceptable ventilation rates were obtained in mechanically ventilated schools in winter. Following the guidelines and ventilation studies, approaches that can increase the ventilation rate in schools were reviewed.

Overall, operating the mechanical ventilation can provide schools with an acceptable ventilation rate, but at a high capital and operational cost. Changing behaviours can increase the ventilation rate, but not enough to reach the minimum requirement. Taking unconditioned ambient air directly into classrooms during the winter is not applicable in NZ. Therefore, to increase the ventilation rate in NZ schools in winter, an affordable method that can heat the fresh air first and then bring the warmed air into classrooms is needed.

The school hours in NZ are between 9 am and 3 pm, which are well aligned with the optimum solar radiation. Consequently, schools are the ideal environment to use free solar energy for space heating and ventilation. The following section will review the solar energy applications used for space heating and ventilation in winter.

2.6 Solar energy: an alternative solution to ventilate and heat school buildings

Solar energy could be passively and actively used for building space heating and ventilation. Passively applied solar energy requires proper construction design and uses natural processes, like the stack effect and the thermal lag effect, to circulate air. Actively applied solar energy uses some systems, such as solar walls or solar air collectors, to convert solar energy into thermal energy, and uses a powered fan to move the air. This section reviews some studies reporting passive solar energy applications (solar chimney, Trombe wall) and active solar energy applications (solar wall, SAH). The advantages and disadvantages of adapting each application under NZ conditions are discussed.

2.6.1 Solar chimney

A solar chimney is a vertical construction element that is installed on the building sun-facing facade. Figure 2-7 shows a diagram of a solar chimney used for space heating.

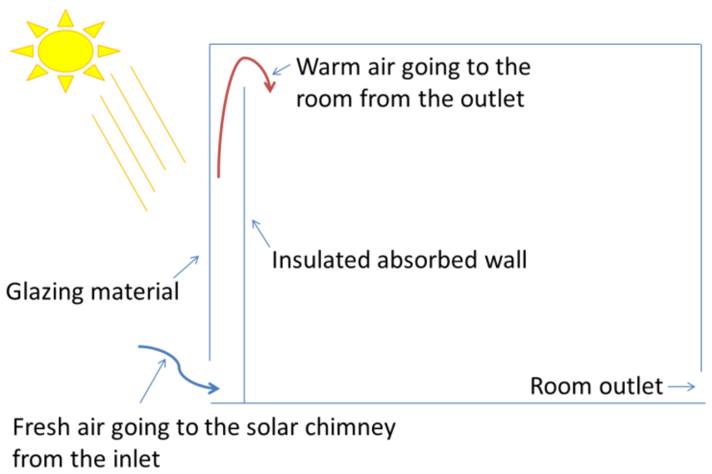

Figure 2-7 Diagram of solar chimney

Source: Chan *et al.* (2010)

A solar chimney includes an external glazed layer (glass) and an insulated absorber wall. Air flows through the solar chimney due to the difference of the air density or temperature between the solar chimney inlet (bottom section of the wall) and the solar chimney outlet (high section of the wall). The heated air is pushed into the room by thermal buoyancy, increasing the room temperature and ventilation rate. The efficiency of a solar chimney depends on the configuration, including the size of the inlet and outlet opening, the distance between the glazing layer and the insulated wall, as well as the weather conditions (solar radiation and ambient temperature) (Haghighi and Maerefat, 2014).

Adding a solar chimney to an existing building will require extensive wall retrofitting and incur significant costs. The solar chimney is more efficient when it is used in a two- or three- storey building, due to the stack effect (Tan and Wong, 2012). The insulation level of the attached absorbed wall will influence the outlet air temperature. Further, it reduces the available glazing area for the daylighting. Thus, the solar chimney is not a suitable solution for space heating and ventilation in NZ primary schools, as most schools are single storey buildings with no or minimum insulated walls.

2.6.2 Trombe wall

Trombe walls were invented by the American engineer Edward Morse in 1880s and was popularised by the French engineer Felix Trombe and architect Jacques Michel in 1960s (Saadatian *et al.*, 2012). There are many variations of Trombe walls, including the classic Trombe wall, the Zigzag Trombe wall, the Water Trombe wall, the Solar transwall, solar hybrid wall, Trombe wall with phase change material, composite Trombe wall, Fluidised Trombe wall and photovoltaic Trombe wall (Saadatian *et al.*, 2012). The classical Trombe wall is of a large sized wall, which comprised a sun-facing glazing layer (like glass), an air channel behind the exterior glazing layer and a blackened high thermal mass wall (normally concrete).

Figure 2-8 shows a diagram of the adjusted Trombe wall (left) and the composite Trombe-Michel wall (right). Compared with the adjusted Trombe wall, the classical Trombe wall only has a dark coloured wall of high thermal mass without Damper A and Damper B. The classical Trombe wall is used for increasing the room temperature in winter by conduction, as there is no fresh air coming into the building. The indoor air circulates through the lower and upper vent can increase the room temperature.

The adjusted Trombe wall has an upper damper (Damper B) and a lower damper (Damper A), and upper and lower vents for air circulation. The dampers and vents can be adjusted for winter heating and summer cooling. The adjustable Trombe wall is equivalent to a solar chimney, when Damper A and the upper vent are open, and Damper B and lower vent are closed (Gan, 1998; Jie *et al.*, 2007).

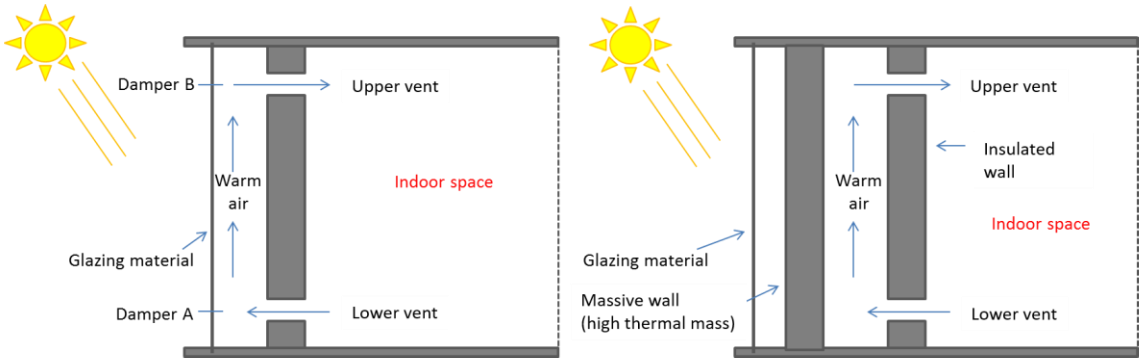

Figure 2-8 Diagram of the adjusted Trombe wall (left) and composite Trombe-Michel wall (right)
Source: Chan *et al.* (2010)

The composite Trombe-Michel wall has an additional massive wall with the high thermal mass between the insulated wall (absorbed wall) and the exterior glazing layer. The solar energy is absorbed by the massive wall, and then the absorbed heat goes through the air channel (plenum) between the massive wall and the insulated wall by conduction. This is followed by a similar process to the adjusted Trombe wall. During a sunny winter day, solar radiation is absorbed into the thermal mass wall. The absorbed energy transferred to the indoor environment by the heat radiation and the air movement through the lower and upper vents. At the night time, the absorbed wall release heat into the building by radiation. During a cloudy day (day time and night time), the inverse thermosyphon phenomenon was observed: the thermal mass wall absorbed heat from the indoor environment (Saadatian *et al.*, 2012).

High thermal mass wall and extensive changes in the building facade are required for retrofitting of a Trombe wall. As the same for the solar chimney, the use of Trombe wall in an existing NZ school building requires extensive retrofitting and reduce building daylighting availability. Thus, the Trombe wall technique is not appropriate for space heating and ventilation in NZ primary schools.

2.6.3 Solar wall

Solar wall (also called transpired solar collector) was invented in the mid-1980s (Hollick, 1994). The solar wall can be used as a stand-alone wall (Hall *et al.*, 2011) or mounted on the building sun-facing facade (Dymond and Kutscher, 1997). Figure 2-9 shows a diagram of a vertically installed glazed solar wall (left) and an unglazed solar wall (right).

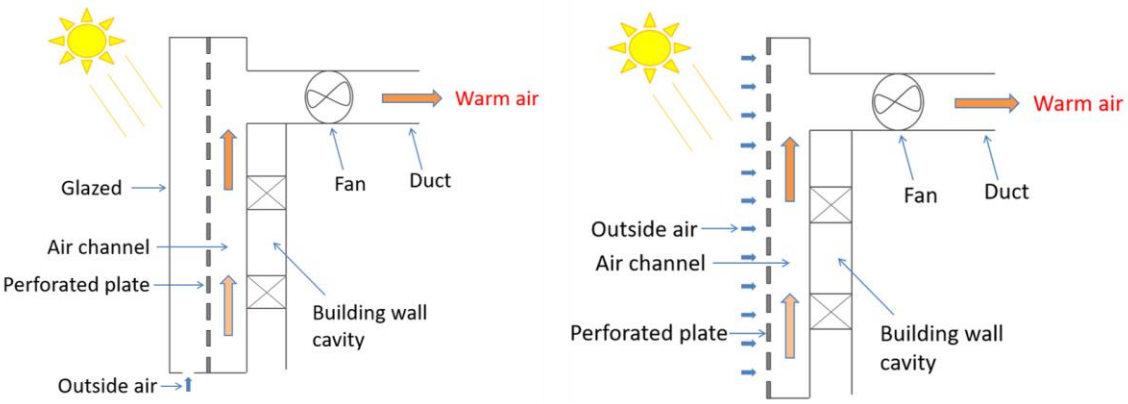

Figure 2-9 Diagram of a vertically installed glazed solar wall (left) and an unglazed solar wall (right)
Source: Heinrich (2007)

The solar wall consists of a cover, which is optional, a perforated plate, a back plate and a fan. Solar radiation enters through the glazed cover (optional) or the perforated plate. The glazed cover is typically a glazing layer of class. The perforated plate is a metal plate, usually steel or aluminium with thousands of small holes per square metre (also known as porosity). Dymond *et al.* (1997) reported that the porosity of the solar wall perforated plate typically ranged from 0.5% to 2.0%. The back plate is usually the wall of the building. The space between the perforated plate and the back plate is sealed to create the air channel (also known as a plenum) (Shukla *et al.*, 2012). The heated warm air is blown into the building by the fan.

The energy efficiency of the solar wall depends on the local weather conditions, specifically the solar radiation, ambient temperature and wind speed. The configurations of the solar wall include the size of the collector, the air channel configuration, the porosity, shape and thickness of the perforated plate, the glazing materials, and the insulation levels of building walls (or back plate) The speed of the fan influences the efficiency of the solar wall as well. Hall *et al.* (2011) summarised applications of the solar wall for building space heating and ventilation projects in the UK and the USA. Hall *et al.* (2011) have reported that with the use of solar walls, the building energy demand can be decreased between 10% and 20%. The amount of contribution depends on the size of the solar wall, the configuration of the solar wall and the weather conditions.

Jaques *et al.* (2010) conducted a study in three NZ secondary schools (one classroom per school in Auckland North Shore, Hamilton and Invercargill) and in one newly built house (located in Hamilton), to investigate the performance of both the unglazed solar wall and the glazed solar wall (1% porosity). Results showed that there was no statistically significant difference in the performance between these two types of solar walls. The insulation levels of the air duct affect the outlet air temperature, as the maximum temperature of the air inside the insulated duct was 58 °C, and it dropped to 36 °C and 40 °C in the uninsulated air duct (Jaques et al., 2010).

Heinrich (2007) installed six unglazed solar walls on different locations of a three-storey residential building during the building construction period. Two of these six unglazed solar walls were installed on the first floor of the building, while the other four were installed on the second floor. The fieldwork was carried out in the NZ winter month of August in Wellington. During the fieldwork, the solar radiation on the surface of the perforated plate (1% porosity), the temperature within the air channel, the ambient air temperature, the outlet air temperature and the room temperature were measured. Heinrich (2007) found that the shading on the surface of the perforated plate adversely influenced the performance of the solar wall. The maximum temperature inside the air channel of two solar walls that encountered the shading problems was close to the temperature around the building (between 20 °C and 25 °C). However, for the other solar walls without the shading problems, the temperature inside the air channel was around 35 °C. The shading problems were caused by surrounding trees or building itself. Besides, the length of the duct negatively affected the energy output, as the efficiency was 15% and 54% respectively, when the length of the duct was 2.2 m and 0.5 m (Heinrich, 2007).

In conclusion, both studies showed the space heating performance of solar walls under NZ climate conditions (Heinrich, 2007; Jaques *et al.*, 2010). Solar wall played a positive role in building space heating under NZ climate conditions. However, as the solar chimney and Trombe walls, solar walls constrain the building daylight availability. The performance of the solar wall is determined by the shadings and the building wall insulation levels.

2.6.4 Solar air heater

SAHs have been widely used in agricultural drying and building space heating (Kalogirou, 2004; Oztop *et al.*, 2013) in Australia, Canada, Switzerland and the USA, but not in NZ (Mauthner *et al.*, 2016). There are two basic types of SAHs, namely the conventional SAH with the air flowing over or under the absorber plate, and the matrix SAH with the air flowing through the absorber matrix (Kolb *et al.*, 1999). Figure 2-10 shows the diagram of a conventional flat plate SAH (left) and a matrix SAH (right).

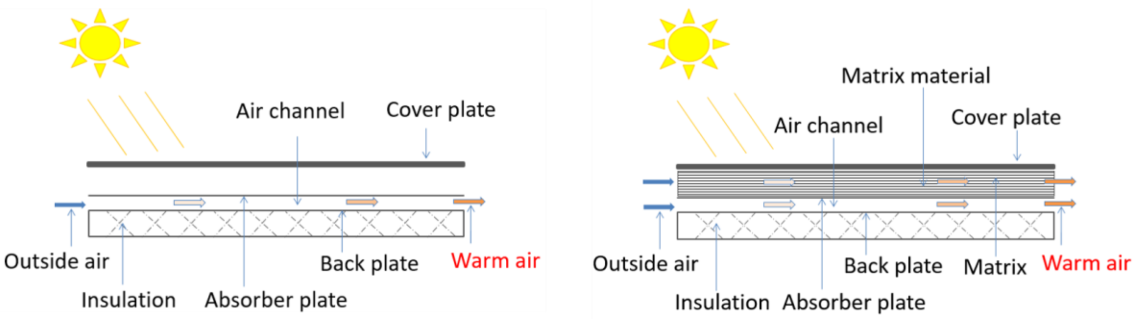

Figure 2-10 Diagram of a conventional flat plate solar air heater (left) and a matrix solar air heater (right)
Source: (Rajarajeswari and Sreekumar, 2016) & (Dhiman *et al.*, 2012)

Figure 2-10 (left) shows that, from top to bottom, a conventional flat plate SAH consists of a glass or plastic cover plate, an absorber plate, a back plate and a bottom insulation plate. The space between the absorber plate and the back plate forms the air channel. The cold outside air is heated when it goes through the air channel. The heated warm air is blown out the SAH from the end of the air channel (Omojaro and Aldabbagh, 2010). Figure 2-10 (right) shows the diagram of a matrix SAH. The components of a matrix SAH are similar to the flat plate SAH, except for the matrix material inside the air channel. For the matrix SAH, air flows through the absorber matrix.

The thermal efficiency of a SAH is defined as the ratio of the energy converted to the solar energy incident on the absorber plate (Esen *et al.*, 2009). Mohamad (1997) conducted sets of experiment and found that the SAH with matrix materials inside the air channel was between 5% and 40% more efficient than SAHs without matrix materials inside the air channel. Naphon (2005a) mathematically predicted that the thermal efficiency of a SAH with matrix material inside the air channel was 26% more efficienct than the similar SAH but without the matrix material. The similar result was found by (Languri *et al.*, 2011). The thermal efficiency of a SAH with the matrix materials inside the air channel increased by 30% compared with the SAH without the matrix materials (Languri *et al.*, 2011).

Some research has focused on modifying the configurations of SAHs to increase the heat transfer. These modifications include changing shapes and materials of the absorber plate (Akpinar and Kocyigit, 2010; El-Sebaii *et al.*, 2007; Jaurker *et al.*, 2006; Promvonge *et al.*, 2011; Skullong *et al.*, 2014; Sopian *et al.*, 1999), increasing the flow turbulence inside the air channel (Bahrehmand *et al.*, 2015; Chabane *et al.*, 2014; Naphon, 2005b; Yang *et al.*, 2014), modifying the flow type (Dhiman *et al.*, 2012; Hernández and Quiñonez, 2013; Yeh and Lin, 1996) and changing the material of the cover plate (El-Sebaii *et al.*, 2011b). The efficiency of different types of SAHs operated at different mass flow rates is reviewed in Chapter 3. Limit research has investigated the SAHs fieldwork performance, though they are designed for working under the real ambient environment.

2.6.5 Section summary

In NZ, the free solar energy could be the alternative energy for creating a healthy school environment, as the school hours are well aligned with the optimum solar radiation. Solar chimneys and Trombe walls are seldom used for space heating and ventilation in single storey buildings and would need major retrofitting to add to an existing building. They would deteriorate building daylighting availability. Solar walls have been studied in NZ buildings (such as built-in house and retrofitted schools). Most studies have modified the SAH configurations to increase the heat transfer, and limit studies on the ventilation and space heating performance of SAHs in schools has been conducted in NZ.

2.7 Summary of the literature review

This review of the literature highlighted some important issues:

- **Levels of temperature, RH, CO_2 and ventilation rate in NZ primary schools in winter were outside the recommended guidelines.**
    - The temperature in naturally ventilated NZ primary schools in winter was unable to meet the WHO recommended guidelines of 18 °C for 50% of school hours (Cutler-Welsh, 2006; McIntosh, 2011).
    - The RH level was above the ASHRAE recommended guideline in NZ naturally ventilated primary schools in winter for 60% of school hours in 11 out of 35 classrooms (McIntosh, 2011).
    - The CO_2 level was above 1000 ppm (ASHRAE recommendation) in naturally ventilated NZ primary schools in winter for 50% of school hours in 13 out of 35 classrooms (McIntosh, 2011).
    - The ventilation rate was less than 8 l/s/person (ASHRAE recommendation) in 2 out of 18 naturally ventilated NZ primary schools in winter (Bassett *et al.*, 1999; Cutler-Welsh, 2006; McIntosh, 2011).

- **A low level of temperature, a high level of moisture and a low level of ventilation rate can adversely affect student respiratory symptoms.**
    - A low level of temperature in classrooms was associated with a high prevalence of the student's asthma (Mi *et al.*, 2006; Smedje *et al.*, 1997).
    - Significant associations were found between the moisture levels and students' respiratory symptoms (repeated coughing and wheezing) (Meklin *et al.*, 2002; Savilahti *et al.*, 2000; Taskinen *et al.*, 2007).
    - Studies showed a negative relationship between the student's respiratory symptoms (cough, wheeze, shortness of breath) and the ventilation rate (Mi *et al.*, 2006; Smedje *et al.*, 2000).

- **A low level of temperature, a high level of moisture and a low level of ventilation rate can increase students' absenteeism rate (due to medical reasons).**
    - A negative association between the absenteeism rate and the ambient temperature was found (Chen *et al.*, 2000).
    - An RH level below 30% and above 60% in classrooms was significantly associated with students' absenteeism rate (Borras-Santos *et al.*, 2013; Green, 1975; Simons *et al.*, 2010).
    - Both long-term (over two years) and short-term (focus on three to five teaching days) studies reported a negative relationship between the ventilation rate in classrooms and students' absenteeism rate (Mendell *et al.*, 2013; Shendell, Prill*, et al.*, 2004).

Therefore, there is a need to improve the IAQ in naturally ventilated NZ primary schools in winter, to provide children with a healthy environment. Mechanical ventilation provides a healthy environment but at a high capital and operational cost.

In NZ, the optimum solar radiation levels are well aligned with school hours from 9 am to 3 pm. Consequently, free solar energy seems to be a good alternative solution for improving the IAQ in schools in winter, which could be used directly without any need for the thermal storage.

The solar chimney, Trombe wall, solar wall and SAHs can be used for ventilation and space heating in winter. Solar chimneys and Trombe wall can be viewed as a special case of a SAH with the building wall being the absorber. They require very little maintenance throughout their lifetime. However, they are seldom used for space heating in single storey buildings and would need extensive retrofitting to add to an existing building. Solar walls have been studied in NZ buildings, including the built-in house and retrofitted schools. Roof-mounted SAHs have been proved better than a solar wall due to the minimising of shading and no deterioration in building daylighting availability (Stasinopoulos, 2002). However, majority research on SAHs have focused on the efficiency of SAHs themselves, and have not investigated the fieldwork performance of the SAHs, neither the effects of operating a roof-mounted SAH on the IAQ parameters (such as temperature, RH, CO_2) in NZ schools in winter.

This study is proposed to fill the gap of knowledge by investigating the change in the temperature, RH, CO_2 and ventilation rate in NZ schools in winter, from when a roof-mounted SAH is operating (treatment group) and not operating (control group).

2.8 Outline of the thesis

This thesis comprises of seven chapters: Chapter 1 was the introduction; Chapter 2 was the literature review; Chapters 3 to 5 are presented in the journal paper format and cover three stages of the study. Chapter 6 is the general discussion. Chapter 7 is the conclusion and recommendation. Chapter 3 has been published. Chapter 4 and Chapter 5 are close to being submitted. Since chapters 3 to 5 are in the journal format and are all reporting the result of this project, there are some inevitable repetitions of these chapters in the introduction and method sections, also between these chapters (chapters 3 to 5) and the thesis Chapter 2. To avoid the duplication, the cross-reference is applied.

In Chapter 3, the experimental performance of the SAH was investigated when it was operated under different air mass flow rates.

In Chapter 4, the fieldwork performance of the SAH in the unoccupied classrooms over two winters was investigated, focusing on the SAH outlet air temperature, volumetric flow rate and efficiency.

In Chapter 5, the change in the classroom temperature, humidity, CO_2 and ventilation rate from when the SAH was operating and not operating was investigated.

In Chapter 6, the study was discussed.

In Chapter 7, the contribution of this study, the limitations of this study and the suggestion for future research were concluded.

3 Solar Air Heater Experimental Performance

Experimental performance of a solar air collector with a perforated back plate in New Zealand

Chapter reference:

Y. Wang, M. Boulic, R. Phipps, M. Plagmann, C. Cunningham. Experimental performance of a solar air collector with a perforated back plate in New Zealand. *Energies* **2020**, *13 (6)*, 1415.

Abstract

This study investigates the thermal efficiency of a solar air heater (SAH), when it was mounted on a custom-made support frame, and was operated under different air mass flow rates. This SAH is composed of a transparent polycarbonate cover plate, a felt absorber layer, a perforated aluminium back plate and an aluminium frame. The ambient inlet air of this SAH is heated as it passes through the perforated back plate and over the felt absorber layer. The heated air is blown out through the outlet. Studies of SAHs with a similar design to this SAH were not found in the literature. The experiment was carried out at Massey University, Auckland campus, New Zealand (36.7° S, 174.7° E). The global horizontal solar irradiance, the ambient temperature and the wind speed were recorded using an onsite weather station. Temperature and velocity of the air at the outlet were measured using a hot wire anemometer. During the experiment, the mean (SD) air mass flow rate was between 0.022 (0.001) kg/s and 0.056 (0.005) kg/s. Results showed that when the SAH was operated at the airflow between 0.054 kg/s and 0.058 kg/s, the inlet air temperature and the wind speed (between 0 m/s and 6.0 m/s) did not impact the temperature difference between the outlet air and the inlet air.

The mean (SD) thermal efficiency of the SAH increased from 34 (5) % at the airflow between 0.021 kg/s and 0.023 kg/s, to 47 (6) % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, to 71 (4) % at the airflow between 0.054 kg/s and 0.058 kg/s. The maximum thermal efficiency of 75% was obtained at the airflow of 0.057 kg/s. The mean (SD) effective efficiency of the SAH was 32 (5) % at the airflow between 0.021 kg/s and 0.023 kg/s, 42 (6) % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, and 46 (11) % at the airflow between 0.054 kg/s and 0.058 kg/s.

3.1 Introduction

The thermal efficiency of a solar air heater (SAH) is defined as the ratio of the energy converted to the solar energy incident on the SAH collector panel (Esen *et al.*, 2009). The design and operation conditions are the main factors that influence the efficiency of a SAH. The main components for the design include the cover, flow types and the absorber layer. Operation conditions include the air mass flow rate and the weather conditions (solar radiation, ambient temperature and wind speed).

Several research projects have focused on modifying the configurations of the SAH to increase the heat transfer. These modifications include changing shapes and materials of the absorber layer (Akpinar *et al.*, 2010; El-Sebaii *et al.*, 2007; Jaurker *et al.*, 2006; Promvonge *et al.*, 2011; Skullong *et al.*, 2014; Sopian *et al.*, 1999), increasing the air channel turbulence (Bahrehmand *et al.*, 2015; Chabane *et al.*, 2014; Naphon, 2005b; Yang *et al.*, 2014), and modifying the flow type (Dhiman *et al.*, 2012; Hernández *et al.*, 2013; Yeh *et al.*, 1996) and the cover plate (El-Sebaii *et al.*, 2011b). Table 3-1 shows the efficiencies of several types of SAHs, when they were operated at different air mass flow rates.

Table 3-1 Efficiencies of several types of solar air heaters operated at different air mass flow rates

Study	Air mass flow rate (kg/s)	Cover	Flow type	Absorber layer	Efficiency (%)	Reference
1	0.010 kg/s; 0.020 kg/s; 0.030 kg/s; 0.040 kg/s; 0.050 kg/s; 0.060 kg/s.	Double glazed.	Double parallel pass; Placing the absorber plate in the middle of the air channel forming the equal upper and lower flow channel.	Type 1: flat plate; Type 2: longitudinal fins below and above the absorber layer; Type 3: V-corrugated shaped absorber layer.	Type 3 was 11% to 14% more efficiency than Type 1; Type 3 was 9% to 12% more efficient than Type 2; Maximum efficiencies at air mass flow rate of 0.060 kg/s: Type 1: 58%; Type 2: 56%; Type 3: 65%.	(El-Sebaii *et al.*, 2011a, 2011b)

Study	Air mass flow rate (kg/s)	Cover	Flow type	Absorber layer	Efficiency (%)	Reference
2	0.010 kg/s; 0.020 kg/s; 0.030 kg/s; 0.040 kg/s; 0.050 kg/s; 0.060 kg/s.	Single glazed.	Type 1, 2, 3 single pass under the absorber layer; Type 4, 5, 6 double counter pass. First channel was formed by the glass cover and the absorber layer. Second channel was formed by the absorber layer and the insulation layer.	Type 1 and Type 4: flat plate; Type 2 and Type 5: longitudinal fins below the absorber layer; Type 3 and Type 6: V-corrugated shape absorber layer.	Maximum efficiencies at air mass flow rate of 0.060 kg/s: Type 1: 65%; Type 2: 69%; Type 3: 75%; Type 4: 78%; Type 5: 79%; Type 6: 82%.	(Karim and Hawlader, 2006)
3	0.012 kg/s; 0.016 kg/s.	Single glazed.	Single pass.	Type 1: galvanized iron sheet with 0.5 mm thick black chrome selective coating, without fins; Type 2: five longitudinal and hollow semi-cylindrical fins located below the absorber layer.	Maximum efficiencies at air mass flow rate of 0.012 kg/s and 0.016 kg/s: Type 1: 35% and 44% respectively; Type 2: 40% and 52% respectively.	(Chabane *et al.*, 2014)
4	0.030 kg/s; 0.050 kg/s.	Single glazed.	Double parallel pass; Placing the absorber layer in the middle of the air channel forming the upper and lower flow channel.	Absorber layer was formed by aluminium cans. Type 1: flat aluminium plate with zag-zig staggered arranged aluminium cans on both sides; Type 2: flat aluminium plate with orderly arranged aluminium cans on both side; Type 3: flat aluminium plate with no cans on both sides.	The maximum efficiency (73%) was found in Type 1 SAH at air mass flow rate of 0.050 kg/s. Mean efficiencies at air mass flow rate 0.030 kg/s and 0.050 kg/s respectively: Type 1: 41% and 55%; Type 2: 36% and 47%; Type 3: 31% and 43%.	(Ozgen *et al.*, 2009)
5	0.012 kg/s to 0.038 kg/s	Double glazed.	Type 1: Single pass through wire mesh; Type 2: Double counter pass through wire mesh.	A steel wire mesh with fins.	Maximum efficiencies at air mass flow rate of 0.038 kg/s: Type 1: 60%; Type 2: 64%.	(Omojaro *et al.*, 2010)

Study	Air mass flow rate (kg/s)	Cover	Flow type	Absorber layer	Efficiency (%)	Reference
6	0.012 kg/s to 0.042 kg/s.	Double glazed.	Double pass; First flow channel was formed by the two glass layers; Second flow channel was formed by the lower glass cover and the absorber layer.	Wire mesh layers between the fins: Type 1: With 2 fins attached; Type 2: With 4 fins attached; Type 3: With 6 fins attached.	Maximum efficiencies at air mass flow rate of 0.042 kg/s: Type 1: 75%; Type 2: 82%; Type 3: 86%.	(El-khawajah *et al.*, 2011)

Among all the reported SAHs in Table 3-1, efficiencies ranged from 35% to 86% when they were operated at the mass flow rates from 0.010 kg/s to 0.060 kg/s. Study 6 Type 3 SAH showed the maximum efficiency of 86% at the air mass flow rate of 0.042 kg/s.

Study 1 (Table 3-1) to Study 4 (Table 3-1) showed artificially roughening the absorber layer can increase the efficiency of the SAH (Chabane *et al.*, 2014; El-Sebaii *et al.*, 2011a, 2011b; Karim *et al.*, 2006; Ozgen *et al.*, 2009). Study 1 (El-Sebaii *et al.*, 2011a, 2011b) showed that the double pass SAH with a V-corrugated shape absorber layer was from 11% to 14% and from 9% to 12% more efficient than the double pass SAH with a flat and finned absorber layer respectively. Karim *et al.* (2006) (Table 3-1, Study 2) found a single pass SAH with a finned absorber layer was 4% more efficient than the flat plate SAH. The single pass SAH with a V-corrugated shape absorber layer was 10% more efficient than the flat plate SAH. Chabane *et al.* (2014) (Table 3-1, Study 3) reported that the maximum efficiency of a single pass SAH with fins below the absorber layer was 5% and 8% more efficient than the one without fins, when they were operated at air mass flow rates of 0.012 kg/s and 0.016 kg/s respectively. Ozgen *et al.* (2009) (Table 3-1, Study 4) compared a parallel double flow SAH with zigzag arranged aluminium cans on the absorber layer, orderly arranged aluminium cans on the absorber layer, and a smooth absorber layer at air mass flow rates of 0.030 kg/s and 0.050 kg/s. The maximum efficiency of 73% was found for the SAH with zigzag-arranged cans on the absorber layer at the air mass flow rate of 0.050 kg/s. In short, artificially roughening the SAH absorber layer can increase the SAH efficiency.

Modifying the airflow type is another way to increase the heat transfer of the SAH (Dhiman *et al.*, 2012; Hernández *et al.*, 2013; Yeh *et al.*, 1996). Airflow types can be categorised as (i) single flow (with only one flow channel over or under the absorber layer); (ii) double flows (double pass parallel flow or double pass counter flow); and (iii) air flow through a matrix absorber layer (Hernández *et al.*, 2013). There are two ways to create a double flow. One uses the space between the two glass covers (double glazed SAH) forming the upper channel, with the lower glass cover and the absorber layer forming the lower channel. Another double flow SAH is designed by placing the absorber layer inside the air channel to form a double air passage around the absorber layer. The maximum thermal efficiency was achieved by placing the absorber layer in the middle of the air channel, with the upper and lower channels of equal size (Esen, 2008). Omojaro *et al.* (2010) (Table 3-1, Study 5) showed a 4% increase in the thermal efficiency when the SAH was modified from single flow to double flow. Karim *et al.* (2006) (Table 3-1, Study 2) reported 13%, 10% and 7% thermal efficiency increases for SAHs with V-corrugated shape, finned and flat plate absorber layers respectively when changing the airflow type from single flow to double flow. Dhiman *et al.* (2012) found that the thermal efficiency of a counter flow SAH was from 11% to 17% higher than the same SAH with the parallel flow, when they were operated at air mass flow rates from 0.012 kg/s to 0.038 kg/s. In conclusion, modifying the airflow type can increase the thermal efficiency of a SAH.

The thermal performance of six types of SAHs was investigated (Aldabbagh *et al.*, 2010; El-khawajah *et al.*, 2011; Mahmood *et al.*, 2015; Nowzari *et al.*, 2014; Omojaro *et al.*, 2010). The first SAH had a steel wire mesh absorber layer (Aldabbagh *et al.*, 2010). The second SAH had a steel wire mesh absorber layer and longitude fins attached (Omojaro *et al.*, 2010). The third one had a steel wire mesh absorber layer with transverse fins attached and an S-shape airflow (Table 3-1, Study 6) (El-khawajah *et al.*, 2011). The fourth one had a steel wire mesh absorber layer with transverse fins attached and an 8-Shape airflow (Mahmood *et al.*, 2015). The fifth one had a steel wire mesh absorber layer and a partially perforated cover (Nowzari *et al.*, 2014). The performance of these five SAHs was compared with a similar SAH without any modifications (the sixth SAH).

The authors concluded that the SAH with the wire mesh absorber layer (matrix layer) was most efficient, as air passing through the wire mesh absorber layer can maximise heat extraction (El-Sebaii *et al.*, 2007). The SAH with modified rough air channels performed better than the SAH with a smooth air channel. The double pass SAH was more efficient than the single pass SAH. For the double pass SAH, the height of the upper channel negatively impacted the thermal efficiency. The narrower the upper channel, the more efficient was the SAH. When the SAH was operated at an air mass flow rate of 0.036 kg/s, thermal efficiencies were respectively 62%, 59% and 57% at upper channel heights of 30 mm, 50 mm and 70 mm respectively (Omojaro *et al.*, 2010). The maximum thermal efficiency (86%) was obtained from the third type SAH (the double pass counter flow SAH with six transverse fins and an S-shape airflow channel) at an air mass flow rate of 0.042 kg/s (El-khawajah *et al.*, 2011).

Our study aims to investigate the thermal efficiency of a SAH when it was operated at different air mass flow rates. The experiment was conducted under Auckland, New Zealand (NZ) weather conditions. The thermal efficiency of this SAH is compared with that of some of SAHs reported in the introduction of this chapter. This SAH has the inlet air coming from a perforated back plate and then passing through and over the absorber layer before it is ducted into a space. Results for investigating the thermal efficiency of this type of SAH have not yet been reported in the literature.

The chapter is organised as follows: materials and methods for investigating the SAH thermal efficiency are presented in Section 3.2, including the structure of the SAH, the experiment setup, test procedure and the efficiency calculation. Section 3.3 presents the experimental results. Section 3.4 introduces the findings along with suggestions for future research.

3.2 Materials and Methods

3.2.1 Structure of the solar air heater

Figure 3-1 shows the exploded view of the SAH.

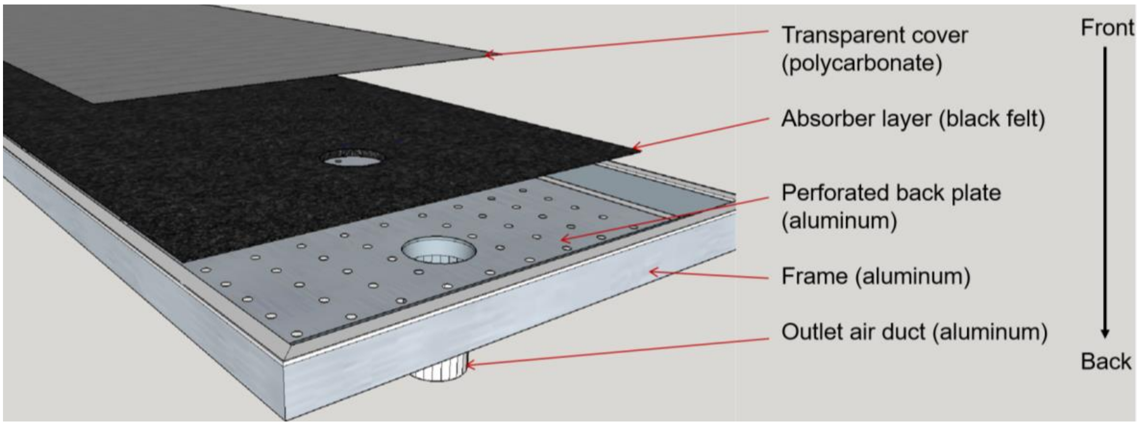

Figure 3-1 Exploded view of the solar air heater

Figure 3-1 shows that this SAH, from the front to the back, is composed of a transparent cover (double layer polycarbonate with the solar transmission of 0.77 and visible transmission of 0.85), an absorber layer (black felt), a perforated back plate (aluminium) and an aluminium frame. The diameter of the outlet air duct is 125 mm. The diameter of the air inlet holes in the perforated back plate is 1.5 mm. These holes are evenly distributed in a grid, spaced 15 mm apart (approximately 4300 holes/m^2).

Figure 3-2 shows the schematic view of the SAH.

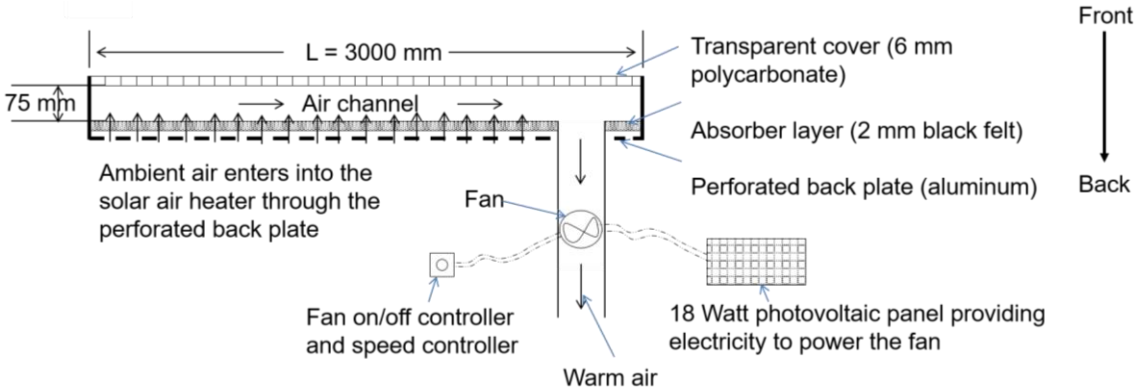

Figure 3-2 Schematic view of the solar air heater

The length, width, and air channel depth of this SAH are 3000 mm, 1020 mm and 75 mm respectively. The collector gross area and the absorber layer effective area are both 3 m^2. The SAH has a fan with the power consumption of 5.1 Watt, a fan speed and on-off controller, and an outlet duct. The fan is powered by an 18 Watt photovoltaic panel. The ambient air enters into the SAH through the perforated back plate. The heated air is pushed in the outlet duct by the fan. The velocity of the outlet air is controlled by the fan speed controller (regulator).

3.2.2 Experiment setup and test procedure

During the experiment, the SAH was mounted on a custom-made support frame. Figure 3-3 shows the setup of the experiment.

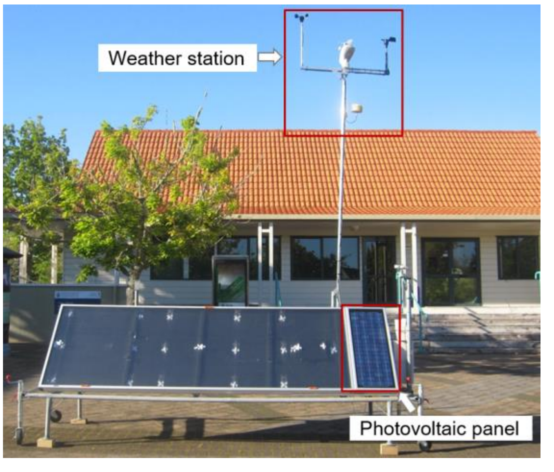

Figure 3-3 Setup of the experiment

The SAH panel was 52° off the horizontal surface (local latitude 37° plus 15°). The panel faced due north (at the azimuth angle of 0°). The global horizontal solar irradiance, the ambient temperature and the wind speed were recorded by an onsite weather station (HP2000 Wi-Fi Weather Station, Fine Offset Electronics Co., Ltd), as shown in Figure 3-3. The velocity and the temperature of the outlet air were monitored by a hot wire anemometer (AM4214SD, Lutron Electronic Enterprise Co. Ltd.).

Table 3-2 shows the characteristics of the monitoring devices.

Table 3-2 Characteristics of the monitoring device

Device	Monitored parameters	Range	Accuracy
HP2000 weather station	Solar irradiance (W/m^2)	0–3000 W/m^2	± 15%
	Ambient air temperature (°C)	-30–65 °C	± 1 °C
	Wind speed (m/s)	0–50 m/s	± 1 m/s (wind speed < 5 m/s); ± 10% (wind speed > 5 m/s)
AM4214SD hot wire anemometer	Outlet air velocity (m/s)	0.2–25 m/s	± 5% of reading
	Outlet air temperature (°C)	0–50 °C	± 0.8 °C

The experiment was carried out for 9 days[1] from the end of November to the middle of December at Massey University, Auckland campus, NZ (36.7° S, 174.7° E). This was the late spring and early summer season in NZ. The test began at 9 am and ended at 4 pm (New Zealand Daylight Time). On each day, the air was circulated through the panel for at least 10 minutes before commencing the measurement. During the test, the regulator was set at 50% the maximum speed of the fan from Day 1 to Day 4; at 75% the maximum speed of the fan from Day 5 to Day 8, and 100% the maximum speed of the fan on Day 9[2]. The 50% and 75% maximum speeds of the fan were set to investigate the SAH efficiency and the outlet air temperature rise (temperature between the outlet air and inlet air), when it was operated at different air mass flow rates.

[1] The dates of these 9 days were 28th, 29th, 30th November 2016, 7th, 12th, 13th, 14th, 15th and 16th December 2016.

[2] As explained in the introduction chapter, the experimental study was carried out after the fieldwork study to investigate the SAH performance differences from when it was operated in the experiment and fieldwork. SAH was operated at 75% the maximum fan speed in the fieldwork study. The emphasis of this experimental study was to investigate the SAH experimental performance at 75% the maximum fan speed. Besides, the SAH experimental performance at 50% the maximum fan speed was investigated. Only one day experiment of the SAH operated at 100% maximum fan speed was conducted, because this is a proprietary SAH, the SAH experimental performance at 100% maximum fan speed has been tested by the company. The maximum efficiency of 75% is reported. The similar result was obtained in this experimental study. So experiment of the SAH operated at 100% the maximum fan speed stopped. The SAH performance difference from when it was operated in the experiment and the fieldwork are estimated in Chapter 4 of this thesis.

3.2.3 Thermal efficiency calculation

The thermal efficiency of the SAH was calculated based on Equation 3-1.

$$\eta = \frac{Q_u}{A_c I_T} = \frac{\dot{m} C_P (T_o - T_i)}{A_c I_T} = \frac{\rho \vartheta A_d C_P (T_o - T_i)}{A_c I_T}$$ Equation 3-1

Where,

A_c	Solar air heater effective area (m^2)
A_d	Outlet duct cross section area (m^2)
C_P	Specific heat capacity of air [J/(kg*K)]
I_T	Solar radiation on the tilted solar air heater surface (W/m^2)
Q_u	Useful thermal energy gained by the solar air heater (W)
T_i	Inlet air temperature (K)
T_o	Outlet air temperature (K)
$\dot{m}$	Air mass flow rate (kg/s)
η	Efficiency (%)
ρ	Density of air (kg/m^3)
ϑ	Air velocity (m/s)

During the calculation, it was assumed that the monitored air velocity was the mean air velocity, and the ambient air temperature was the inlet air temperature. Equation 3-1 shows that the efficiency of the SAH depends on the air mass flow rate and the temperature difference between the outlet air and inlet air divided by the solar radiation on the tilted solar collector surface, as the specific heat capacity of air and solar collector effective area were constant. The air density and the air specific heat capacity were set according to the air temperature, as shown in Table 3-3 (Cengel and Boles, 2015).

Table 3-3 Air density (kg/m^3) and air specific heat capacity (J/(kg*K)) under different temperatures

Air temperature (K)	**Air density (kg/m^3)**	**Air specific heat capacity (J/(kg*K))**
(273.15, 283.15]	1.269	1006
(283.15, 293.15]	1.225	1007
(293.15, 303.15]	1.184	1007
(303.15, 313.15]	1.145	1007
(313.15, 323.15]	1.109	1007
(323.15, 333.15]	1.076	1007
(333.15, 343.15]	1.044	1007

Source: (Cengel *et al.*, 2015)

The solar radiation incident on the absorber layer was calculated using the computer program solaR (Lamigueiro, 2012). The Spencer model (Spencer, 1971) was chosen for calculating the declination angle and the extra-terrestrial radiation incident on the plane. The Boland-Ridley-Lauret model was used to calculate the horizontal diffuse solar radiation based on the measured global horizontal solar radiation (Ridley *et al.*, 2010). The Boland-Ridley-Lauret model performed well in both North and South Hemispheres (Ridley *et al.*, 2010). The Hay and McKay model was used to estimate the diffuse radiation on the inclined absorber plate (Hay and McKay, 1985). All equations for calculating the incident solar radiation are attached in Appendix A1.

3.2.4 Effective efficiency calculation

To evaluate the economic performance, the effective efficiency of the SAH is calculated according to Equation 3-2 (Cortés and Piacentini, 1990).

$$\eta_{eff} = \frac{Q_u - \frac{P_m}{C}}{A_c I_T} = \frac{\dot{m} C_P (T_o - T_i) - \frac{P_m}{C}}{A_c I_T} = \frac{\rho \vartheta A_d C_P (T_o - T_i) - \frac{P_m}{C}}{A_c I_T} \qquad \text{Equation 3-2}$$

Where,

A_c	Solar air heater effective area (m^2)
A_d	Outlet duct cross section area (m^2)
C_P	Specific heat capacity of air [J/(kg*K)]
C	Energy conversion factor
I_T	Solar radiation on the tilted solar air heater surface (W/m^2)
P_m	Mechanical power required to force the air through the solar air heater (W)
Q_u	Useful thermal energy gained by the solar air heater (W)
T_i	Inlet air temperature (K)
T_o	Outlet air temperature (K)
$\dot{m}$	Air mass flow rate (kg/s)
η_{eff}	Effective efficiency (%)
ρ	Density of air (kg/m^3)
ϑ	Air velocity (m/s)

The conversion factor (C) is the energy conversion efficiency from the primary energy to the mechanical energy, and a typical value of 0.18 is suggested to be considered (Cortés *et al.*, 1990; Mittal and Varshney, 2006). Equations for calculating the required mechanical power (P_m) are attached in Appendix A2. All calculations were conducted using the statistical computing and graphics platform programming language R version 3.4.3 (R Core Team, 2016).

3.3 Results and Discussion

3.3.1 Ambient weather conditions during the experiment

During the test, the weather data was monitored at the 1-min intervals from 9 am to 4 pm. It found that the solar radiation ranged from 104 W/m^2 (minimum) to 1298 W/m^2 (maximum), with the mean (standard deviation, SD) level of 544 (270) W/m^2. The ambient temperature ranged from 15.7 °C (minimum) to 22.8 °C (maximum), with the mean (SD) of 19.1 (1.7) °C. The wind speed ranged from 0 m/s to 9.6 m/s, with the mean (SD) level of 2.0 (1.3) m/s. 99.3% of the wind speed was between 0 m/s and 6.0 m/s, and 0.7% of the wind speed was above 6.0 m/s.

Figure 3-4 shows the hourly levels of the global horizontal solar radiation (top), ambient temperature (middle) and wind speed (bottom) on each test day.

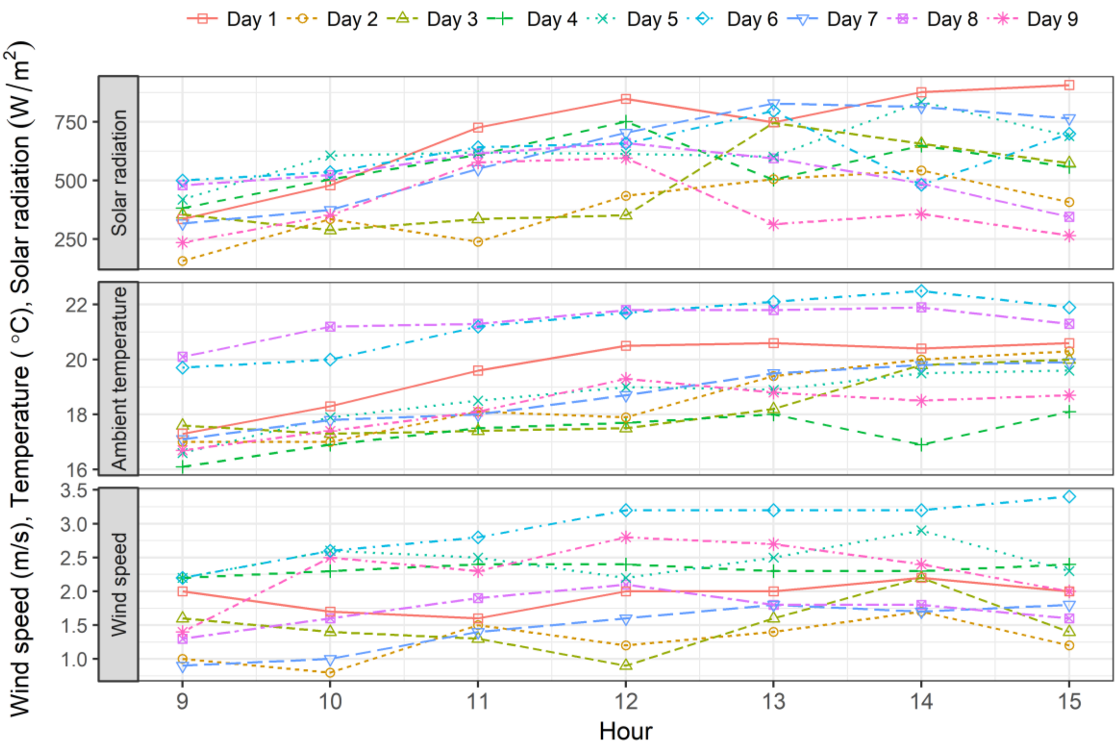

Figure 3-4 Hourly levels of the global horizontal solar radiation (W/m^2), ambient temperature (°C) and wind speed (m/s) on each test day

The hourly solar radiation ranged from 157 W/m^2 (minimum) to 908 W/m^2 (maximum). The hourly ambient temperature was from 16.1 °C to 22.5 °C. The hourly wind speed was between 0.8 m/s and 3.4 m/s. The daily mean (SD) values of the global horizontal solar radiation, ambient temperature and wind speed on each test day (from 9 am to 4 pm) are shown in Table 3-4.

Table 3-4 Mean (standard deviation) levels of the global horizontal solar radiation (W/m^2), ambient temperature (°C) and wind speed (m/s) on each test day

Test day	Solar radiation (W/m^2)	Ambient temperature (°C)	Wind speed (m/s)
Day 1	703.3 (286.6)	19.6 (1.3)	1.9 (1.1)
Day 2	374.8 (161.6)	18.5 (1.3)	1.3 (1.0)
Day 3	473.6 (255.8)	18.3 (1.1)	1.5 (1.1)
Day 4	566.7 (277.9)	17.3 (0.8)	2.3 (1.3)
Day 5	626.5 (299.2)	18.6 (1.0)	2.5 (1.4)
Day 6	616.5 (252.2)	21.3 (1.0)	3.0 (1.5)
Day 7	622.0 (314.3)	18.7 (1.0)	1.5 (1.0)
Day 8	529.6 (152.8)	21.3 (0.6)	1.7 (1.0)
Day 9	385.3 (180.3)	18.2 (0.9)	2.3 (1.3)

The highest and the lowest mean global horizontal solar radiation during the test days was 703.3 (286.6) W/m^2 on Day 1 and 374.8 (161.6) W/m^2 on Day 2. The mean (SD) ambient temperature ranged from 17.3 (0.8) °C on Day 4 to 21.3 (1.0) °C on Day 6. The highest and lowest mean wind speed was 3.0 (1.5) m/s on Day 6 and 1.3 (1.0) m/s on Day 2.

3.3.2 Outlet air temperature of the solar air heater

The air mass flow rate affects the SAH outlet air temperature. A higher air mass flow rate makes less time for air circulating inside the air channel and absorbing the heat. Consequently, it results in a lower outlet air temperature (Tyagi *et al.*, 2012). During the test, the air mass flow rate was between 0.022 (0.001) kg/s and 0.056 (0.005) kg/s. Table 3-5 shows mean (SD) values of the outlet air velocity (m/s), air mass flow rate (kg/s), solar radiation on the SAH absorber plate (W/m^2), the outlet air temperature (°C), and the temperature difference between the outlet air and the inlet air (ΔT, T_{outlet} - T_{inlet}) on each test day.

Table 3-5 Mean (standard deviation) values of velocity (m/s), air mass flow rate (kg/s), solar radiation on the collector surface (W/m²), outlet air temperature (°C), and the temperature difference (°C) between the outlet and inlet air on each test day

Percent of the maximum fan speed	Test day	Velocity (m/s)	Air mass flow rate (kg/s)	I_T[1] (W/m²)	T[2] outlet air (°C)	T difference[3] (°C)
50%	Day 1	1.5 (0.1)	0.014 (0.006)	552 (178)	45.2 (9.3)	25.5 (8.3)
	Day 2	1.5 (0.1)	0.021 (0.001)	297 (113)	31.6 (6.4)	13.1 (5.6)
	Day 3	1.6 (0.1)	0.021 (0.004)	376 (153)	34.6 (8.3)	16.3 (7.8)
	Day 4	1.7 (0.1)	0.019 (0.006)	451 (106)	39.5 (8.9)	22.2 (8.7)
75%	Day 5	2.6 (0.1)	0.034 (0.005)	490 (112)	37.1 (6.1)	18.6 (5.7)
	Day 6	2.7 (0.1)	0.035 (0.004)	478 (111)	39.1 (5.5)	17.8 (5.3)
	Day 7	2.7 (0.1)	0.036 (0.005)	494 (175)	36.9 (8.9)	18.3 (8.3)
	Day 8	2.7 (0.1)	0.036 (0.002)	414 (92)	36.9 (5.0)	15.5 (4.9)
100%	Day 9	4.0 (0.1)	0.056 (0.005)	304 (117)	29.7 (6.3)	11.5 (5.9)

[1] Solar radiation on the collector surface (W/m²). [2] Temperature of the outlet air. [3] Temperature difference between the outlet air and the inlet air, ΔT (T_{outlet} - T_{inlet}).

The outlet air temperature ranged from 19.9 °C to 59.8 °C, with a mean level of 36.7 °C (SD = 8.5 °C). Table 3-5 shows the mean (SD) daily values of the outlet air temperature ranged from 29.7 (6.3) °C (Day 9) to 45.2 (9.3) °C (Day 1). The mean level of the solar radiation on Day 1 was higher than on the other days with the same setting of the fan speed controller (Day 2 to Day 4, 50% the maximum speed of the fan). This resulted in the mean outlet air temperature on Day 1 being higher than for Day 2 to Day 4. Consequently, the air density and the mass flow rate on Day 1 were lower than on Day 2, Day 3 and Day 4 regardless of the similar air velocity. The mean air mass flow rate for Day 5 to Day 8 was between 0.032 kg/s and 0.038 kg/s, at 75% the maximum speed of the fan. The mean (SD) value of mass flow rate on Day 9 was 0.056 (0.005) kg/s.

Levels of ΔT (T_{outlet} - T_{inlet}) obtained during the experiment were from 3.2 °C (minimum) to 41.0 °C (maximum). The mean (SD) daily values of ΔT (T_{outlet} - T_{inlet}) ranged from 11.5 (5.9) °C (Day 9) to 25.5 (8.3) °C (Day 1). The maximum ΔT (T_{outlet} - T_{inlet}) was 41.0 °C. This was obtained on Day 4 at noon when the wind speed was 2.2 m/s, the inlet air temperature was 17.5 °C, and the solar radiation was 901 W/m^2. A multiple linear regression model was built to estimate ΔT (T_{outlet} - T_{inlet}), when the SAH was operated at different air mass flow rates. The model input variables include the solar radiation, air mass flow rate, inlet air temperature and the wind speed.

As expected, a positive relationship between ΔT (T_{outlet} - T_{inlet}) and the solar radiation, and a negative relationship between ΔT (T_{outlet} - T_{inlet}) and the air mass flow rate were observed in this study. When the SAH was operated at air mass flow rates between 0.021 kg/s and 0.023 kg/s, ΔT (T_{outlet} - T_{inlet}) was impacted by the solar radiation and mass flow rate. When the SAH was operated at flow rates between 0.032 kg/s and 0.038 kg/s, the solar radiation, the mass flow rate, the wind speed and the inlet air temperature all affected ΔT (T_{outlet} - T_{inlet}). When this SAH was operated at a flow rate between 0.054 kg/s and 0.058 kg/s, only the solar radiation affected ΔT (T_{outlet} - T_{inlet}) levels. This result was supported by Omojaro *et al.* (2010) and Aldabbagh *et al.* (2010), who found a negative relationship between ΔT (T_{outlet} - T_{inlet}) and the air mass flow rate, and a positive relationship between ΔT (T_{outlet} - T_{inlet}) and the solar radiation.

3.3.3 Efficiency of the solar air heater

Figure 3-5 shows the thermal efficiency versus values of the thermal efficiency function parameter (ΔT (T_{outlet} - T_{inlet}) / I_T) at different air mass flow rates. The regression models for efficiencies of the SAH under different mass flow rates have been added.

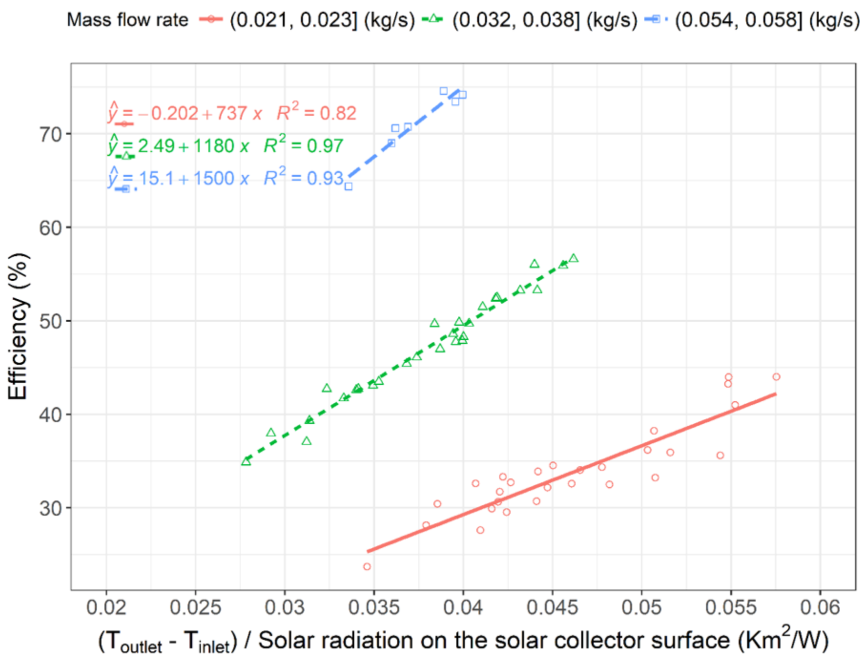

Figure 3-5 Thermal efficiency (%) of the solar air heater versus values of the thermal efficiency function at different air mass flow rates
The thermal efficiency function is the temperature difference between the outlet (T_{outlet}) and inlet air (T_{inlet}) divide the solar radiation on the collector panel (I_T).

Figure 3-5 shows that during the experiment, the ΔT (T_{outlet} - T_{inlet}) / I_T was between 0.027 Km²/W and 0.058 Km²/W. From the regression model, it can be estimated that when the value of (T_{outlet}-T_{inlet}) / I_T is ca. 0.04 Km²/W, the thermal efficiency of the SAH was ca. 29%, 50% and 75% at air mass flow rates of ca. 0.022 kg/s, 0.037 kg/s and 0.056 kg/s respectively. The efficiency is increasing when the value of ΔT (T_{outlet} - T_{inlet}) / I_T rises. This means the higher the air mass flow rate, the more heat is transferred.

Figure 3-6 shows the efficiency versus values of the efficiency function parameter (ΔT (T_{outlet} - T_{inlet}) / I_T) at different air mass flow rates. The solid line is the thermal efficiency, and the dashed line is the effective efficiency.

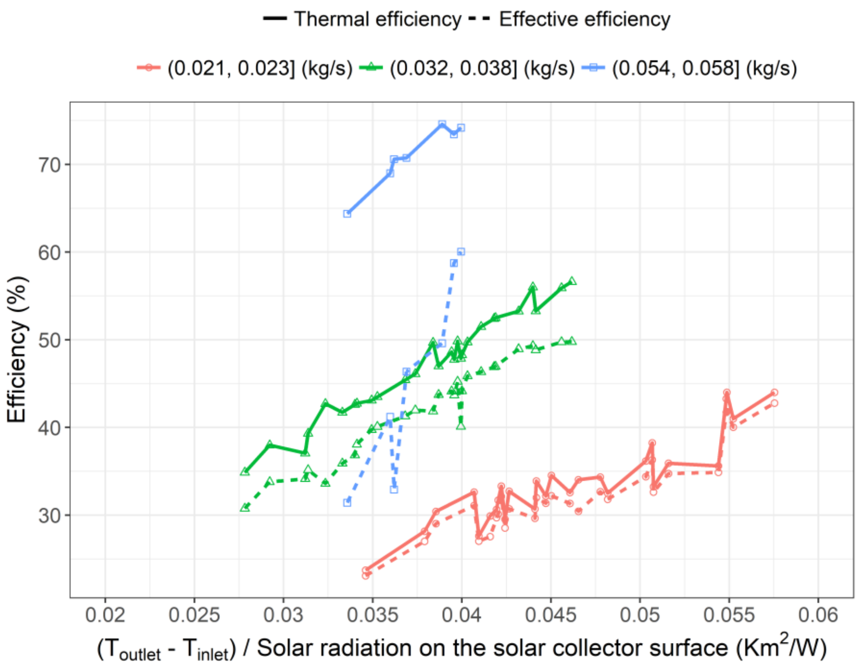

Figure 3-6 Thermal efficiency and effective efficiency (%) of the solar air heater versus the value of the efficiency function at different air mass flow rates
The efficiency function is the temperature difference between outlet air (T_{outlet}), and inlet air (T_{inlet}) divide the solar radiation on the collector panel (I_T).

Figure 3-6 shows that although the thermal efficiency increased with the increasing of the air mass flow rate, when considering the mechanic power consumed by the fan, the mean effective efficiency only had a 4% increase when the operating air mass flow rate increased from the range between 0.032 kg/s and 0.038 kg/s to the range from 0.054 kg/s to 0.058 kg/s. The mean (SD) effective efficiency of the SAH was 32 (5) % at the airflow between 0.021 kg/s and 0.023 kg/s, to 42 (6) % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, and 46 (11) % at the airflow in the 0.054–0.058 kg/s range.

3.3.4 Discussion

The mean (SD) efficiency of the SAH was 71 (4) % [minimum–maximum: 64–75%], at an air mass flow rate of 0.056 ± 0.005 kg/s. The maximum thermal efficiency of 75% was obtained at the mass flow rate of 0.057 kg/s. Karim *et al.* (2006) reported a double pass V-corrugated SAH with a maximum efficiency of 82% at an air mass flow rate of 0.056 kg/s. The maximum efficiency of 80% was found from a SAH with porous material between the absorber layer and the bottom plate, when it was operated at an air mass flow rate of 0.070 kg/s (Sopian *et al.*, 1999). Ozgen *et al.* (2009) found the maximum thermal efficiency of a double parallel flow SAH with zag-zig arranged aluminium cans on both sides of the aluminium absorber plate was 73% at an air mass flow rate of 0.055 kg/s. El-Sebaii *et al.* (2011a) found the thermal efficiency of a double parallel pass V-corrugated SAH was 67% at an air mass flow rate of 0.060 kg/s, and the thermal efficiency of a double parallel flat SAH was 59% at an air mass flow rate of 0.060 kg/s.

At an air mass flow rate between 0.032 kg/s and 0.038 kg/s, the mean (SD) efficiency of the SAH found in this study was 47 (6) % [minimum–maximum: 35–57%]. Prasad *et al.* (2009) found a single pass SAH with packed bed formed by wire mesh had the maximum efficiency of 59% at a mass flow rate of 0.035 kg/s. Omojaro *et al.* (2010) found the efficiency of a SAH with steel wire mesh was 60% (single pass SAH) and 64% (double pass SAH) when it was operated at a mass flow rate of 0.038 kg/s. El-Sebaii *et al.* (2011b) found a double parallel SAH had thermal efficiencies of 56% (flat absorber plate) and 65% (V-corrugated absorber plate) when they were operated at a mass flow rate of 0.040 kg/s.

At air mass flow rates between 0.021 kg/s and 0.023 kg/s, the mean (SD) thermal efficiency of this SAH was 34 (5) % [minimum–maximum: 24–44%]. Chabane *et al.* (2014) reported the thermal efficiency of two SAHs: one with longitudinal fins installed under the absorber layer and another one without fins installed. They reported that the thermal efficiencies of the SAH without fins were 35% and 44% at an air mass flow rate of 0.012 kg/s and 0.016 kg/s respectively. The thermal efficiency was increased to 40% and 52% for the SAH with the fins (Chabane *et al.*, 2014), because adding fins below the absorber layer increased the SAH heat transfer coefficient and the outlet air temperature. Consequently, the thermal efficiency of the SAH increases.

Overall, the efficiency of the SAH in the present study was higher than the efficiency of other SAHs reported in the literature, when it was operated at an air mass flow rate of 0.057 kg/s. However, when this SAH was operated at 50% and 75% the maximum fan capacity, its efficiency was lower than the efficiency of SAHs reported in the literature that were operated in a similar manner.

3.4 Conclusion

This chapter has investigated the experimental performance of a SAH under Auckland (NZ) weather conditions. This SAH had the inlet air passing through a perforated back plate and a felt absorber layer. This study found when the SAH was operated at 100% the maximum fan speed (mass flow rate in the 0.054–0.058 kg/s range), the wind speed and the inlet air temperature did not impact the ΔT (T_{outlet} - T_{inlet}) and the thermal efficiency. The maximum thermal efficiency of 75% was achieved when it was operated at an air mass flow rate of 0.057 kg/s.

Compared with the thermal efficiency of other SAHs reported in the literature, this SAH has a higher thermal efficiency when it was operated at the air mass flow rate of 0.057 kg/s, but has a lower thermal efficiency when it was operated at the air mass flow rates ranged from 0.021 kg/s to 0.023 kg/s, and from 0.032 kg/s to 0.038 kg/s. However, when considering the economic performance, the mean effective efficiency had a 4% increase when the operating air mass flow rate increased from the range between 0.032 kg/s and 0.038 kg/s to the range between 0.054 kg/s and 0.058 kg/s.

This study presented experimental results of the SAH thermal performance. Future studies could confirm the SAH optimum operational conditions by combining the theoretical analysis and experimental data. With results of the theoretical analysis, future modifications of this SAH, i.e. moving the outlet air duct to a central location, increasing the diameter of the holes on the perforated back plate, and changing the current downward outlet air duct to an upward duct, could be needed to enhance the SAH heat transfer.

Acknowledgements

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4 Solar Air Heater Fieldwork Performance

Performance of a solar air heater used for space heating and ventilation – a case study in New Zealand primary schools in winter

Chapter reference:

Y. Wang, M. Boulic, R. Phipps, M. Plagmann, C. Cunningham. Performance of a solar air heater used for space heating and ventilation – a case study in New Zealand primary schools in winter, paper to be submitted.

Abstract

This study investigated the space heating and ventilation performance of a solar air heater (SAH) for school buildings. The SAH was composed of a transparent double layer polycarbonate cover plate, a black felt absorber layer, a perforated aluminium back plate and an aluminium frame. The ambient air was heated as it entered through the perforated back plate and passed through the felt absorber layer. The heated air was delivered into the classrooms through the outlet duct.

The fieldwork was carried out in Palmerston North, New Zealand (NZ) during 2013 and 2014 winters. During the fieldwork, the SAH was installed on the sun-facing roof of four schools in 2013 and six schools in 2014 (four previous schools plus two new schools). In each school, two adjacent classrooms with very similar construction characteristics and population characteristics participated. The hourly levels of solar radiation, ambient air temperature, wind speed and rainfall were recorded by a local climate monitoring station. Levels of temperature and velocity of the SAH outlet air were measured at the end of the outlet duct (located inside the school buildings). The efficiency of this SAH was calculated. The SAH outlet air temperature drop between the temperature was measured in the duct 0.5 m and 5.0 m from the SAH back plate was estimated. A multiple linear regression model was built to investigate the impact of weather conditions on the SAH outlet air temperature.

It was found that the outlet air temperature was up to 50.2 °C, with the mean (SD) value of 28.9 (10.6) °C. The mean (SD) level of the temperature difference between the SAH outlet and inlet air was 16.6 (10.4) °C. The volumetric flow rate of the outlet air was around 34.0 (12.9) m^3/h, with a temperature of 28.9 (10.6) °C, at the velocity of 0.8 (0.3) m/s. The efficiency of this SAH was 16 (11) %. For every 100 W/m^2 increase in the solar radiation, the outlet air temperature dropped 2.8 °C between it was measured in the duct 0.5 m and 5.0 m from the SAH back plate. Results of this study showed that operating the SAH was a useful supplement to natural ventilation, but on its own was insufficient to achieve the ventilation rate required by the NZ Ministry of Education. Future research should focus on increasing the volumetric flow rate and keeping the outlet air temperature around 18 °C.

4.1 Introduction

The solar air heater (SAH) has been widely used in agriculture for drying and in buildings for space heating (Kalogirou, 2004; Oztop *et al.*, 2013) in Australia, Canada, Switzerland and the USA (Mauthner *et al.*, 2016). However, in New Zealand (NZ), the utilisation of a SAH for space heating has been sparse (Mauthner *et al.*, 2016). Hall *et al.* (2011) reported that operating a SAH significantly contributed to the building space heating in Canada, the USA and the UK. For example, incorporating 950 m^2 SAHs into a 60000 m^2 warehouse contributed 10% to 20% of the building heating energy demand under the UK weather conditions.

In NZ, two studies on solar walls were carried out by the Building Research Association of New Zealand (BRANZ) (Heinrich, 2007; Jaques *et al.*, 2010). Jaques *et al.* (2010) conducted a study in three NZ secondary schools (one classroom in schools in Auckland North Shore, Hamilton and Invercargill) and one newly built house (located in Hamilton), to investigate the performance of both perforated and non-perforated solar walls. Results showed no statistically significant difference in the performance of these two types of solar walls. The insulation level of the duct negatively affected the outlet air temperature. The maximum temperature between 36 °C and 40 °C was found in three schools where the duct was uninsulated, however it reached 58 °C in the newly built house with the insulated duct (Jaques et al., 2010).

Heinrich (2007) installed six perforated (1% porosity) solar walls in different locations on a three-storey residential building during the building construction period. Two of these six solar walls were located on the first floor of the building, while the other four were located on the second floor. The fieldwork was carried out in August (NZ winter month) in Wellington. The solar radiation on the surface of the perforated plate, the temperature inside the air channel, the ambient air temperature, the outlet air temperature and the room temperature were measured. Heinrich (2007) found that the length of the outlet air duct negatively affected the energy output, as the efficiency was 15% and 54% respectively, when the length of the duct was 2.2 m and 0.5 m. It was also found that shading reduced the efficiency of the solar walls, as a wall shaded for most of the day had no useful energy output.

Heinrich (2007) found the temperature inside two shaded solar wall air channels was close to the temperature around the building (between 20 °C and 25 °C). However, for the non shaded solar walls, the temperature inside the air channels was around 35 °C. The shading was caused by surrounding trees and the building itself. Stasinopoulos (2002) reported that a roof-mounted SAH performs better than a vertically wall-mounted SAH, as it is free from shading and is not affected by the building wall thermal resistance. Given the building wall is the back plate of the solar wall collector, the building wall with a higher thermal resistance would have the less heat loss, and vice versa (Stazi *et al.*, 2012).

Another NZ study reported a prototype SAH with thermal storage capacity. This SAH was designed and tested during March 2010 in Masterton (NZ). It was made of a double layer roof (clear corrugated polycarbonate sheet over the colour steel corrugated roof). There was a 12 mm foam spacer between the two layers to create an air channel. The ambient air entered the SAH at the lower edge of the roof. The heated air was collected at the roof ridge and was then blown into a gravel thermal storage bed under the concrete slab. Results showed that the maximum roof ridge temperature was around 70 °C (Duncan, 2010).

Similar overseas studies have been conducted to investigate the SAH space heating and ventilation performance. Cordeau and Barrington (2011) investigated the preheating performance of a SAH in Canada, and found that the wind speed significantly influenced the efficiency of the SAH. A linear model showed that for every 1 m/s wind speed increase (from 0 m/s to 9 m/s), the efficiency was reduced by 5.7%. When this SAH was operated at the same outlet air velocity and under the similar solar radiation conditions, the overall efficiency was reduced from 63% to 20% when the wind speed increased from 2.6 m/s to 7.2 m/s.

Although the SAH performance is constrained by some factors, such as shading, building wall thermal resistance and weather conditions, operating a SAH positively contributed to the energy demand of building space heating and ventilation. However, roof-mounted SAH space heating and ventilation fieldwork has not been performed in NZ. To fill the gap, this study investigates the space heating and ventilation performance of a roof-mounted SAH in NZ schools in winter.

The fieldwork was undertaken in Palmerston North (PN), NZ. In the fieldwork, the SAH was roof-mounted on four school buildings in 2013 and six school buildings in 2014 (four previous schools plus two new schools). This SAH was composed of a cover plate, a black felt absorber layer, a perforated aluminium back plate and an aluminium frame. The cover plate is a transparent double layer polycarbonate sheet with the solar transmission of 0.77 and visible transmission of 0.85 (McGowan, 2016). The diameter of air inlet holes on the perforated back plate is 1.5 mm. These holes are evenly distributed in a grid, spaced at 15 mm apart (approximately 4300 holes/m^2). The diameter of the outlet air duct is 125 mm. The length, width, and air channel depth of this SAH were 3000 mm, 1020 mm and 75 mm. The ambient air was heated as it passed through the perforated back plate and through the felt absorber layer. This heated air was then pushed into the outlet air duct by a fan. The outlet air velocity was controlled by a fan speed controller (regulator).

Experimental performance of this SAH was investigated under Auckland (NZ) weather conditions. Results of the experimental performance found that when the SAH was operated at the airflow between 0.054 kg/s and 0.058 kg/s, the inlet air temperature and the wind speed (between 0 m/s and 6.0 m/s) did not impact the temperature difference between the outlet and inlet air. The mean (SD) thermal efficiency of the SAH increased from 34 (5) % at the airflow between 0.021 kg/s and 0.023 kg/s, to 47 (6) % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, to 71 (4) % at the airflow between 0.054 kg/s and 0.058 kg/s. The maximum thermal efficiency of 75% was obtained at the airflow of 0.057 kg/s. The mean (SD) effective efficiency of the SAH was 32 (5) % at the airflow between 0.021 kg/s and 0.023 kg/s, 42 (6) % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, and 46 (11) % at the airflow between 0.054 kg/s and 0.058 kg/s.

This chapter reports the fieldwork performance of the SAH, when it was roof-mounted and operated in school buildings in PN, NZ. Results focused on the unoccupied classrooms over the school hours. It includes the outlet air temperature, the temperature difference between the outlet and inlet air, the volumetric flow rate of the outlet air, and the SAH efficiency. The SAH outlet air temperature drop was estimated between the outlet air temperature was measured in the duct 0.5 m from the SAH back plate and 5.0 m from the SAH back plate. The estimation was conducted via the regression model, using the data collected from the experimental study (Chapter 3) and the fieldwork (Chapter 4).

This chapter is organised as follows: Section 1 introduced the study. Section 2 presents materials and methods used to investigate the SAH fieldwork performance, including the study location, school recruitment and description, study design, data collection and data analysis. Section 3 presents the results and discussion. Section 4 concludes the study along with future research.

4.2 Materials and Methods

4.2.1 Structure of the solar air heater

The structure of the SAH was shown in Chapter 3, Section 3.2.1.

4.2.2 Study location

This project was conducted in PN, NZ in 2013 and 2014. Figure 4-1 shows the map of NZ and location of PN (left); Locations of the six participating schools in PN and the location of climate monitoring station in PN (right).

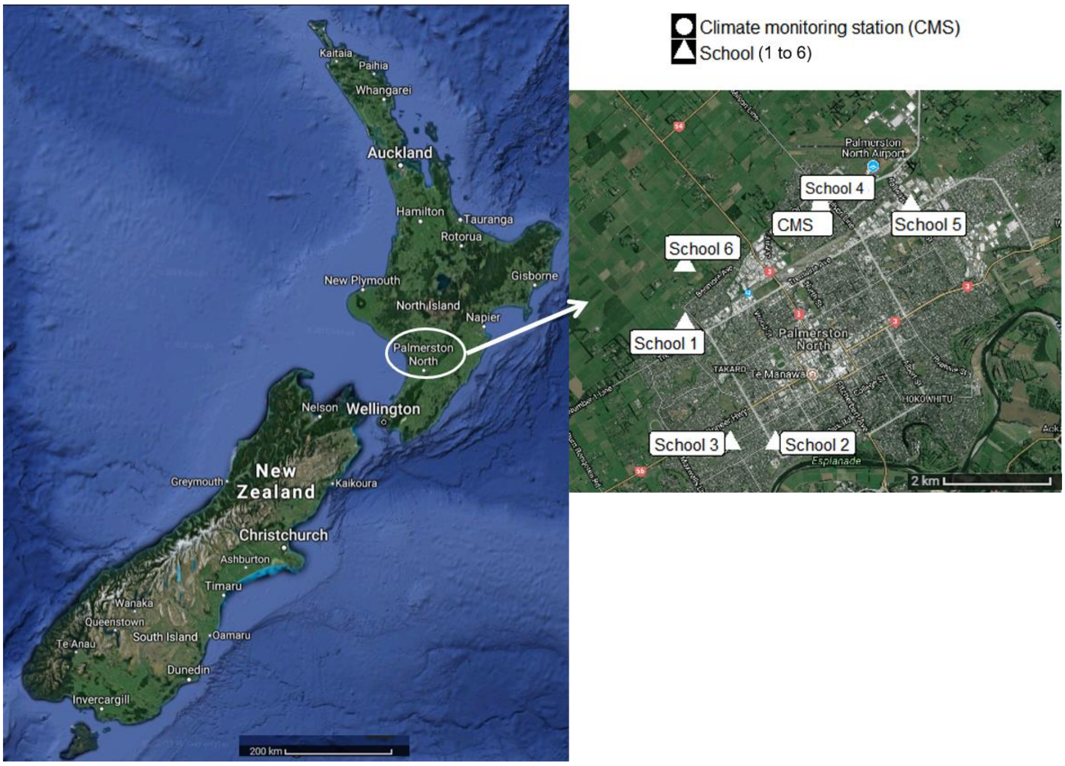

Figure 4-1 Map of New Zealand and location of Palmerston North (PN, left); Locations of the six participating schools in PN and the location of climate monitoring station in PN (right)

Source: Google Map Satellite.

As shown in Figure 4-1 (left), PN is located in the lower North Island of NZ. The location of PN (40 °S) is close to the midline of NZ (from 34 °S to 47 °S). During the winter months (June to August), the mean solar radiation levels in PN were close to the mean NZ solar radiation levels (77.2 vs 77.9 W/m^2). The mean daily sunshine hours in PN were 0.8 hours lower than the mean NZ sunshine hours (3.3 vs 4.1 hours). The mean ambient temperature levels in PN were 1.1 °C higher than the mean NZ ambient temperature (9.0 vs 7.9 °C) (NIWA, 2018). Overall, compared with the mean levels of NZ winter weather, PN has medium levels of solar radiation, sunshine hours and ambient temperature. This means performances of the SAH in PN could be assumed to be at the medium level compared to NZ as a whole.

4.2.3 School recruitment and description

The primary schools in NZ are decile rated from 1 to 10. The deciles relate to the socioeconomic status of the community living around the school and determine the level of government funding. Low decile rated schools have more government funding than high decile rated schools (Ministry of Education, 2019). At the time of this study, there were 31 primary schools in PN. To be selected in this study, schools were required to meet five criteria: (i) schools have a decile rating from 1 to 6, (ii) classrooms were not experiencing any weathertightness issues, (iii) classroom buildings were oriented within ± 30° of the north, (iv) two adjacent classrooms had the similar construction characteristics, and (v) no building alterations would be conducted during the time of this study. An invitation to participate in this study was sent to the school principals. The schools and classrooms were recruited based on principals' and teachers' willingness to participate.

Four schools were selected for the first year (2013) fieldwork and six schools were selected for the second year (2014) fieldwork. Figure 4-1 (right) shows the location of the participating schools in PN. Eight classrooms from four primary schools (School 1 to School 4) participated in 2013. Twelve classrooms from six primary schools (School 1 to School 6), consisting of four previous schools plus two additional schools, participated in 2014. The schools were all located within a 5 km radius around PN city centre.

Table 4-1 shows the construction characteristics for each classroom. To protect privacy and anonymise the data, the classrooms were named with the format "S1R1". The first number represents the school (S) identification number and was from 1 to 6. The second number represents the room (R) identification number and was 1 or 2.

Table 4-1 Construction characteristics for each classroom

Year	School (S) Room (R)	Volume (m^3)	Year of school open / school buildings	Roof	Windows (type and glazing)	Heaters
2013 & 2014	S1R1	221.0	1963	Skillion roof	Awning, single	Central radiator
	S1R2	221.0				
2013 & 2014	S2R1	212.5	1913[1]	Skillion roof	Awning, single	Inverter heat pump
	S2R2	230.6				
2013 & 2014	S3R1	227.7	1958	Skillion roof	Louvre, single	Unflued gas heater and Inverter heat pump
	S3R2	227.7				
2013 & 2014	S4R1	313.6	1928	Gable roof	Awning, single	Inverter heat pump
	S4R2	295.2				
2014	S5R1	175.8	1953	Skillion roof	Awning, sliding, single	Electric heater
	S5R2	175.8				
2014	S6R1	182.8	1975	Skillion roof	Awning, single	Central radiator
	S6R2	182.8				

[1] School 2 was open in 1913 with the brick structure building. In 1973, the classrooms and staff room were demolished. The new light timber-framed school buildings were replaced.

School 1 to School 4 participated in the fieldwork in both 2013 and 2014. School 5 and School 6 were added to the fieldwork in 2014. The classroom volume ranged from 175.8 m^3 to 313.6 m^3. These schools were open between 1913 and 1975. The two adjacent classrooms from the same school have the same roof, windows and heater. Expect for School 4 with the gable roof, the other five schools all had a skillion roof. All schools had single glazed awning windows, except for School 3 with louvre windows.

Among all participating classrooms, four types of heaters were found, namely central radiator, inverter heat pump, unflued gas heater and electric heater. School 1 and School 6 had the central radiator. School 2 and School 4 had the inverter heat pump. School 3 had both the inverter heat pump (primary heater) and unflued gas heater (secondary heater). School 5 had an electric heater. These classrooms were all light timber-framed single storey buildings, and were all naturally ventilated.

The population characteristics for each classroom is shown in Table 4-2.

Table 4-2 Population characteristics for each classroom

School (S)	Year	Room1		Room2	
		Student number	**Student age (years)**	**Student number**	**Student age (years)**
S1	2013	18	6–7	20	7–9
	2014	21	8–10	21	8–10
S2	2013	31	10–13	31	10–12
	2014	28	10–13	27	10–12
S3	2013	22	9–12	21	9–12
	2014	27	9–11	20	9–12
S4	2013	25	9–10	23	7–10
	2014	26	8–10	22	8–10
S5	2014	30	12–13	21	10–12
S6	2014	21	7–8	22	7–9

The student number per classroom was between 18 and 31. This is the enrollment number in each classroom. The student was in the 6–13 age range. The student age in the two adjacent classrooms from the same school was very similar, except for School 1 in 2013 and School 5 in 2014.

Figure 4-2 shows the layout of these 12 participating classrooms from the six schools. The position of the SAH outlet air duct was also included.

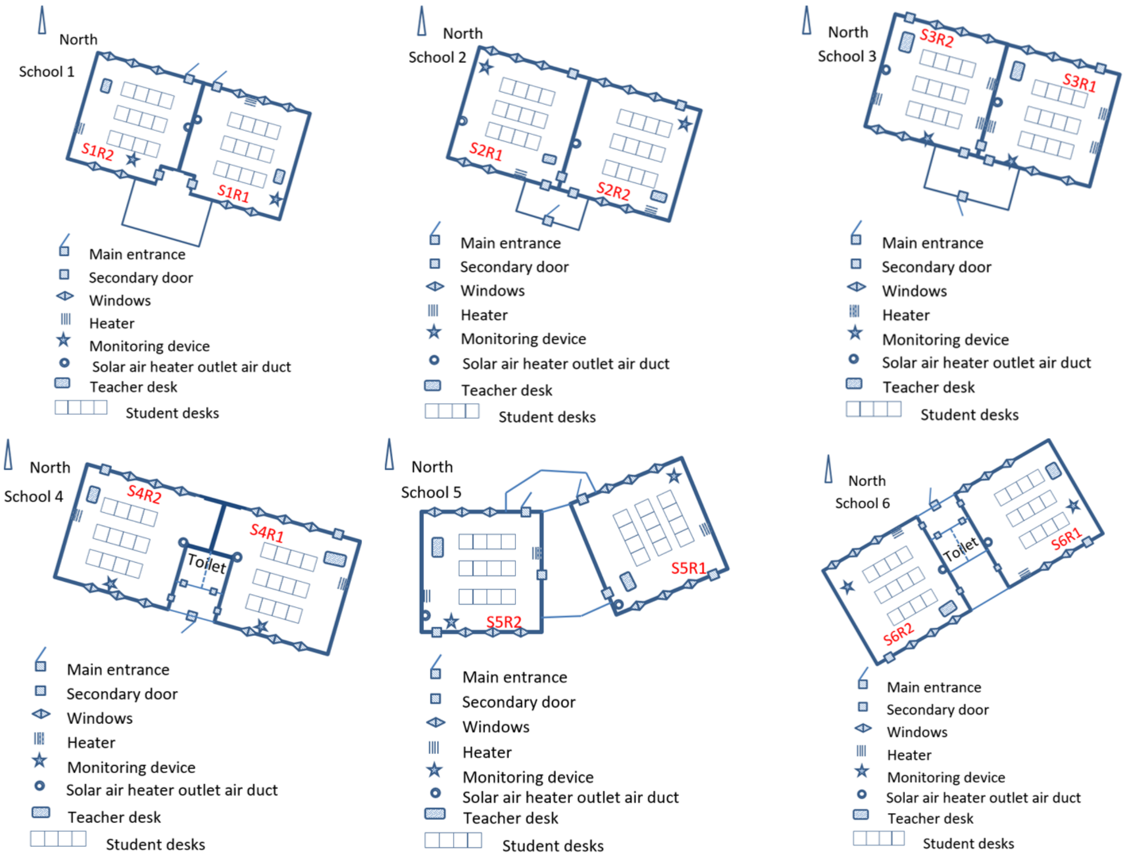

Figure 4-2 Layout of all participating classrooms

Figure 4-2 showed that the main entrance of the classrooms in School 1 and School 5 was directly connected to the outside. Whereas for the other four schools, there was a cloakroom between the main entrance and the main classroom door. The secondary doors in all classrooms were opened occasionally. Single glazed windows were installed on the northern and southern walls to provide daylighting and cross ventilation. Heaters were wall-mounted in all classrooms. During the fieldwork, no building alterations were conducted in all participating classrooms.

4.2.4 Study design

Prior to the fieldwork commencing, the SAH was installed on the sun-facing (north in the southern hemisphere) roof of all participating classrooms. Figure 4-3 shows the SAH located on the roof of the school building. There was one SAH installed for each participating classroom.

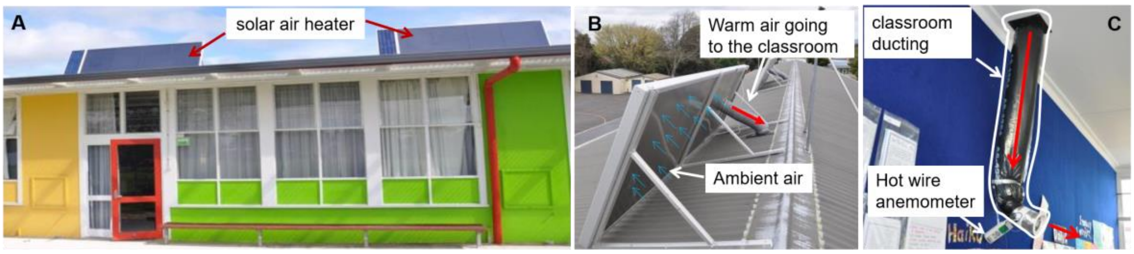

Figure 4-3 Solar air heater located on the roof of the school building (A) Solar air heater (SAH) front view; (B) SAH back plate; (C) Air duct inside the classroom and the location of a monitoring device (hot wire anemometer).

Figure 4-3 (A) shows the SAH installed on the roof of the school building. Figure 4-3 (B) shows the back of the SAH. Figure 4-3 (C) presents the indoor air duct and the hot wire anemometer position. The hot wire anemometer monitored the temperature and velocity of the outlet air. It was estimated the duct had a length of 5.0 m, measured from the SAH back plate to the endpoint in the classroom. 10 out of 12 participating classrooms had skillion ceilings, which meant the outlet air duct went straight into the classroom, and any heat that was lost through the duct was transferred into the classroom space. The outlet duct was attached to the wall surface in the classroom. The end of the outlet duct was located 2.0 m above the classroom floor level. A fan with the power consumption of 5.1 Watt was used. This fan was powered by an 18 Watt photovoltaic panel. The on-off status of the fan and the velocity of the outlet air were controlled by the fan speed controller (regulator). The fan speed was set at 75% the maximum fan speed in all classrooms. During the fieldwork, no building alterations were conducted in all participating classrooms, which was one of the recruiting criteria, to avoid confounding factors.

The performance of the SAH was affected by the SAH orientation angle and the inclination angle, as these two parameters determined the amount of the solar radiation falling on the tilted SAH surface (Yakup and Malik, 2001). Table 4-3 shows the SAH orientation angle and inclination angle for each classroom.

Table 4-3 Solar air heater panel orientation angle and inclination angle (°) for each classroom

Year	School (S) Room (R)	Panel orientation angle (°)	Panel inclination angle (°)
2013 & 2014	S1R1	13.5	60.1
	S1R2	13.5	60.1
2013 & 2014	S2R1	17.0	66.0
	S2R2	17.0	66.0
2013 & 2014	S3R1	19.0	58.2
	S3R2	19.0	58.2
2013 & 2014	S4R1	17.5	63.8
	S4R2	17.5	63.8
2014	S5R1	-18.5	65.0
	S5R2	0.0	65.0
2014	S6R1	-30.0	67.3
	S6R2	-30.0	67.3

The SAH orientation angles were the same as the building azimuth angle. The building azimuth angle of all these classrooms ranged from - 30.0° to 19.0°. This range met NZ Ministry of Education (NZMoE) recommended ideal orientation for school buildings (+/- 30.0° of the north) (Ministry of Education, 2017a). As buildings in different schools have different azimuth angles, the SAH panel orientation angle was different among these schools. However, the SAH panel orientation angle (building azimuth angle) was the same for every school, except for School 5, where there was an 18.5° difference.

The SAH inclined angles were the same for classrooms from the same school, ranging from 58.2° to 67.3°. This was the roof angle plus the support frame angle (50.0°). As roof angles are different among schools, the SAH panel inclination angle differs. Results of the analysis of variance test showed there were no statistically significant differences ($p = 0.885$) in the incident solar radiation on the SAH panel among different schools.

4.2.5 Data collection

The measured parameters consisted of three parts:

(i) the temperature and velocity of the SAH outlet air;
(ii) the weather data, including solar radiation, wind speed, ambient air temperature and rainfall;
(iii) the temperature, carbon dioxide (CO_2) and heater use in classrooms.

Levels of the temperature and velocity of the SAH outlet air were monitored by a hot wire anemometer (AM4214SD, Lutron electronic enterprise co. Ltd.), at 10-min intervals, 24 hours a day, 7 days a week (24/7). The hot wire anemometer was placed centrally at the end of the outlet duct, as shown in Figure 4-3 (C). The weather data (ambient temperature, solar radiation, wind speed and rainfall) were retrieved from a local climate monitoring station, as shown in Figure 4-1.

The classroom temperature and CO_2 were monitored at 2-min intervals, 24/7. The monitoring devices were either a BW Technologies IAQ3, Gas Probe IAQ monitor (BW Technologies Ltd, Canada) or a Model 7545 IAQ-Calc Meter (Trust Science Innovation, TSI Incorporated, Shoreview, USA) or a Model 8552 Q-Trak IAQ monitor (TSI Incorporated, Shoreview, USA). The characteristics of these monitoring devices are shown in Table 4-4.

As the classroom temperature was affected by the heater use. The heater use status (on-off) in classrooms was recorded by a type K thermocouple connected to a microvolt logger (French *et al.*, 2007). All devices were calibrated and checked before and after the fieldwork. This study protocol was approved by the Massey University Human Ethics Committee (MUHEC 12/49). The approval letter is attached in Appendix B.

Table 4-4 Characteristics of the fieldwork monitoring device

Device	Monitored parameters	Range	Accuracy
AM4214SD hot wire anemometer	Outlet air velocity (m/s)	0.2–25 m/s	± 5% of reading
	Outlet air temperature (°C)	0–50 °C	± 0.8 °C
The local climate monitoring station[1]	Solar radiation (W/m^2)	0–3000 W/m^2	± 1%
	Ambient air temperature (°C)	-80–60 °C	± 0.3 °C
	Wind speed (m/s)	0.15–75 m/s	± 1%
	Rainfall (mm)	No information	± 2%
BW Technologies IAQ3, Gas Probe IAQ monitor (BW Technologies Ltd, Canada);	Temperature (°C)	0–40 °C	± 0.1 °C
	Relative humidity (%)	0–95%	± 2%
	Carbon dioxide (ppm)	0–10000 ppm	± 3%
Model 7545 IAQ-Calc Meter; Trust Science Innovation, Incorporated, Shoreview, USA	Temperature (°C)	0–60 °C	± 0.6 °C
	Relative humidity (%)	5–95%	± 3%
	Carbon dioxide (ppm)	0–5000 ppm	± 50 ppm
Model 8552 Q-Trak IAQ monitor; Trust Science Innovation, Incorporated, Shoreview, USA	Temperature (°C)	0–50 °C	± 0.6 °C
	Relative humidity (%)	5–95%	± 3%
	Carbon dioxide (ppm)	0–5000 ppm	± 50 ppm

[1] The manufacturer and model of the sensors used at the local climate monitoring station were: Vaisala HMP 155D to measure the air temperature; Vector A101M to monitor the wind speed; LI-COR LI200 Pyranometer to record the solar radiation; and OTA 0.2 mm tipping bucket rain gauge to record the rainfall.

4.2.6 Data analysis

The hot wire anemometer was placed at the centre of the outlet air duct, to measure the maximum air velocity. To calculate the volume of the outlet air and the SAH efficiency, the average velocity of the outlet air is needed. The average air velocity was calculated using the Reynolds number. The process of calculating the Reynolds number and the average velocity is attached in Appendix C1.

The efficiency of the SAH was calculated using Equation 4-1.

$$\eta = \frac{\dot{m}C_P(T_o - T_i)}{A_c I_T} = \frac{\rho \vartheta A_d C_P(T_o - T_i)}{A_c I_T} \qquad \text{Equation 4-1}$$

Where,

A_c	Solar air heater effective area (m^2)
A_d	Outlet duct cross section area (m^2)
C_P	Specific heat capacity of air [J/(kg*K)]
I_T	Solar radiation on the tilted solar air heater surface (W/m^2)
T_i	Inlet air temperature (K)
T_o	Outlet air temperature (K)
$\dot{m}$	Air mass flow rate (kg/s)
η	Efficiency (%)
ρ	Density of air (kg/m^3)
ϑ	Average air velocity (m/s)

It was assumed that the ambient air temperature was equivalent to the inlet air temperature. Air specific heat capacity and SAH effective area were constant. Equation 4-1 shows the efficiency of the SAH is a function of the air mass flow rate and the temperature difference between the outlet and inlet air divided by the solar radiation on the tilted SAH surface. The air density and the air specific heat capacity were set according to the air temperature, as shown in Chapter 3 Table 3-3.

The solar radiation incident on the SAH absorber layer was calculated using the computer program solaR (Lamigueiro, 2012). The Spencer model (Spencer, 1971) was chosen to calculate the declination angle and the extra-terrestrial radiation incident on the plane. The Boland-Ridley-Lauret model was used to calculate the horizontal diffuse solar radiation based on the measured horizontal global solar radiation (Ridley *et al.*, 2010). The Boland-Ridley-Lauret model performed well in both North and South Hemispheres (Ridley *et al.*, 2010). The Hay and McKay model was used to estimate the diffuse radiation on the inclined absorber plate (Hay *et al.*, 1985). All equations for calculating the incident solar radiation are attached in Appendix A1. All calculations were conducted using the statistical computing and graphics platform programming language R version 3.4.3 (R Core Team, 2016).

4.3 Results and Discussion

Jaques et al. (2010) found classroom temperature affected the measurement of the outlet air temperature. The same result was also found in the present study. Figure 4-4 shows the measurement of the SAH outlet air temperature during a weekday and weekend.

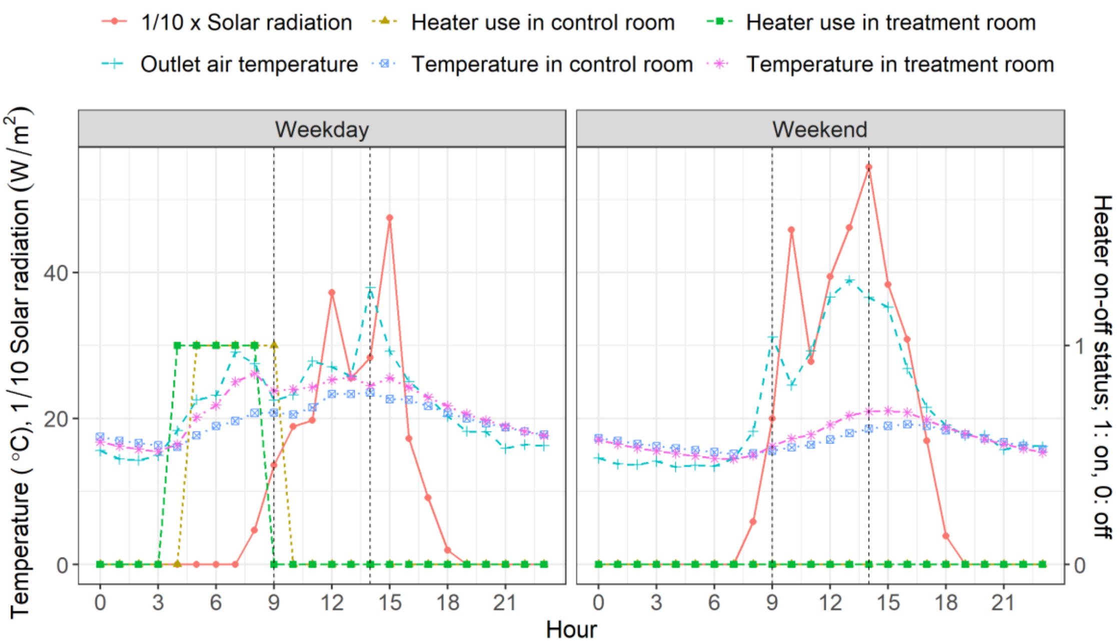

Figure 4-4 Solar air heater outlet air temperature (°C) during a weekday and weekend

As shown in Figure 4-4, for almost all weekdays, temperature of the outlet air had an increase before school hours, even before the sunrise. This is presumed to be from the heater use rather than the operation of the SAH, as in all classrooms, the heaters were turned on before school hours to preheat the classroom. However, during the weekend, when the classroom was unoccupied and without the heater use, the SAH outlet air temperature was well aligned with the solar radiation. It increased from 7 am, peaked around noon and decreased in the afternoon. Therefore, to eliminate the influence of classroom temperature on the measurement of SAH outlet air temperature, the analysis of the SAH fieldwork focused on the unoccupied school hours (from 9 am to 3 pm). This included the weekend (Saturday and Sunday) and the school term break.

To make sure the classroom was not occupied, the CO_2 levels were used as a surrogate of the occupancy. During the data analysis period, the level of CO_2 was below 450 ppm at all time, which confirmed the classroom was unoccupied. Heater use was also checked. It was confirmed that none of the classrooms had heaters in use both during and outside the school hours. This removed the influence of the classroom temperature on the measurement of the SAH outlet air temperature. Table 4-5 shows the number of unoccupied school days in different schools in 2013 and 2014.

Table 4-5 Number of unoccupied school days in different schools, months and years

School (S)	2013				2014				
	July	August	September	Total	June	July	August	September	Total
S1	1	3	4	8	3	0	8	5	16
S2	0	4	7	11	3	8	1	3	15
S3	1	6	5	12	2	5	3	2	12
S4	1	2	1	4	1	2	0	1	4
S5	NA	NA	NA	NA	3	6	4	2	15
S6	NA	NA	NA	NA	3	2	7	6	18

The total number of unoccupied school days ranged from 4 to 18 in different schools and years, based on the classroom had both CO_2 levels below 450 ppm and no heaters in use.

4.3.1 Performance of the solar air heater in fieldwork

Solar radiation, ambient air temperature and wind speed influence the performance of the SAH, as these factors determine the heat gain, the heat loss by convection and the latent energy (Anderson *et al.*, 2006). Table 4-6 shows levels of solar radiation, ambient air temperature and wind speed during the fieldwork unoccupied days in 2013 and 2014. It includes the mean (standard deviation, SD), 95% confidence interval (95% CI), the minimum, median and maximum levels.

Table 4-6 Weather conditions in 2013 and 2014 fieldwork (unoccupied school hours)

Year	2013		2014	
Parameters	**Mean (SD) [95% CI]**	**Median (minimum–maximum)**	**Mean (SD) [95% CI]**	**Median (minimum–maximum)**
Solar radiation ($W*m^{-2}$)	315 (185) [277–353]	283 (14–722)	280 (160) [257–303]	278 (6–667)
Temperature (°C)	13.2 (2.2) [12.7–13.7]	13.1 (8.0–18.7)	12.0 (2.6) [11.6–12.4]	11.9 (3.5–19.4)
Wind speed ($m*s^{-1}$)	18.5 (8.1) [16.8–20.2]	20.4 (1.9–35.2)	18.4 (9.6) [17.0–19.8]	16.7 (1.9–50.0)

Source: (National Climate Database, https://cliflo.niwa.co.nz/)

During the unoccupied school hours, the mean solar radiation was 315 W/m^2 and 280 W/m^2 in 2013 and in 2014 respectively. The mean ambient temperature was 13.2 °C and 12.0 °C in 2013 and in 2014 respectively. The mean wind speeds in 2013 and 2014 were 18.5 m/s and 18.4 m/s respectively.

4.3.1.1 Solar air heater outlet air temperature

Levels of the mean (SD) and 95% CI of the SAH outlet air temperature in different schools and different years are shown in Table 4-7. Among all schools and across the two years, the mean (SD) outlet air temperature was 28.9 (10.6) °C.

Table 4-7 Solar air heater outlet air temperature (°C), mean (standard deviation) and 95% confidence interval

Year	2013		2014	
School (S)	**Mean (SD) [95% CI]**	**% of the time with temperatures above 18 °C**	**Mean (SD) [95% CI]**	**% of the time with temperatures above 18 °C**
S1	28.4 (10.3) [25.5–31.4]	80.9%	32.2 (10.4) [30.0–34.3]	85.4%
S2	30.2 (9.1) [27.6–32.7]	93.8%	28.9 (10.8) [26.7–31.1]	75.6%
S3	27.5 (10.1) [24.1–30.8]	80.0%	29.2 (11.4) [26.5–31.9]	76.1%
S4	28.4 (9.3) [24.6–32.2]	91.3%	27.3 (11.7) [22.6–32.0]	62.5%
S5	NA	NA	26.4 (9.8) [23.7–29.0]	68.5%
S6	NA	NA	27.9 (10.8) [25.8–29.9]	73.8%

In 2013, the mean outlet air temperature was from 27.5 °C to 30.2 °C in all the four schools. The minimum temperature was 14.6 °C, which occurred at 2 pm, when the solar radiation was 125 W/m^2, the ambient temperature was 11.8 °C, and the wind speed was 9.3 m/s. The maximum outlet air temperature was 50.2 °C, which occurred at noon (12 pm) with a solar radiation of 631 W/m^2, the ambient temperature of 16.2 °C, and the wind speed of 14.8 m/s. The outlet air temperature was above 18 °C (WHO minimum recommended temperature) for more than 80% (minimum–maximum: 80–94%) of school hours in each school.

In 2014, the mean outlet air temperature in the six schools ranged from 26.4 °C to 32.2 °C. The minimum level of 11.3 °C was obtained at 9 am, when solar radiation was 92 W/m^2, ambient temperature was 5.6 °C, and wind speed was 1.9 m/s. The maximum outlet air temperature of 50.2 °C was achieved at 11 am, when the solar radiation was 656 W/m^2, the ambient temperature was 11.4 °C, and the wind speed was 11.1 m/s. The outlet air temperature was above 18 °C for at least 62% (minimum–maximum: 62–85%) of school hours in each school.

4.3.1.2 Temperature difference between the outlet and inlet air

In both years, among all schools, the mean (SD) temperature difference between the outlet air and the inlet air (ΔT, T_{outlet} - T_{inlet}) was 16.6 (10.4) °C. At least 78.6% of the school hours had the outlet air temperature 6 °C above the ambient temperature. The threshold of a 6 °C increase in temperature was selected, this is because the outlet air temperature of 18 °C (WHO recommended minimum temperature) should be achieved when the temperature increase was at 6 °C, as the mean level of SAH inlet air temperature (ambient temperature) during the fieldwork was between 12 °C and 13 °C (as shown in Table 4-6).

Levels of the mean (SD) and 95% CI of the ΔT (T_{outlet} - T_{inlet}) in different schools and different years are shown in Table 4-8.

Table 4-8 Temperature (°C) difference between the solar air heater outlet and inlet air (ΔT, T_{outlet} - T_{inlet})

Year	2013		2014	
School (S)	**Mean ΔT (SD) [95% CI]**	**% of time having ΔT (T_{outlet} - T_{inlet}) above 6 °C**	**Mean ΔT (SD) [95% CI]**	**% of time having ΔT (T_{outlet} - T_{inlet}) above 6 °C**
S1	14.4 (9.9) [11.6–17.3]	70.2%	20.6 (10.3) [18.5–22.7]	92.1%
S2	17.0 (10.0) [14.2–19.8]	81.3%	17.2 (11.0) [14.9–19.4]	74.4%
S3	14.3 (9.5) [11.1–17.4]	77.2%	16.4 (10.7) [13.9–18.9]	74.6%
S4	16.3 (9.4) [12.4–20.1]	95.7%	16.3 (11.6) [11.6–20.9]	75.0%
S5	NA	NA	14.7 (9.3) [12.2–17.2]	72.2%
S6	NA	NA	15.8 (10.1) [13.9–17.7]	76.6%

In 2013, the mean ΔT (T_{outlet} - T_{inlet}) level in all four schools ranged from 14.3 °C to 17.0 °C. All four schools had a ΔT (T_{outlet} - T_{inlet}) level above 2 °C for 100% of the school hours, and above 6 °C for at least 70% of the school hours. In 2014, the mean ΔT (T_{outlet} - T_{inlet}) levels in all six schools ranged from 14.7 °C to 20.6 °C. For at least 72% of the school hours, all six schools had ΔT (T_{outlet} - T_{inlet}) levels above 6 °C. School 5 and School 6 had 11% and 3% of the school hours with ΔT (T_{outlet} - T_{inlet}) levels below 2 °C respectively. Jaques *et al.* (2010) found that using the solar wall collector, the ΔT (T_{outlet} - T_{inlet}) levels above 2 °C were between 28% to 74% of the monitoring time in four research sites (three schools and one house).

4.3.1.3 Volumetric flow rate of the outlet air

The volumetric flow rate of the outlet air was estimated using the air mass flow rate divided by the air density. Levels of the mean (SD) and median (minimum–maximum) volumetric flow rate of the SAH outlet air in different schools and different years are shown in Table 4-9.

Table 4-9 Solar air heater outlet air volumetric flow rate (m^3/h)

Year	**2013**		**2014**	
School (s)	**Mean (SD) [95% CI]**	**Median (minimum–maximum)**	**Mean (SD) [95% CI]**	**Median (minimum–maximum)**
S1	39.9 (9.5) [37.2–42.6]	42.2 (15.2–54.7)	25.0 (7.7) [23.4–26.6]	26.2 (4.3–43.6)
S2	40.7 (9.6) [38.0–43.4]	43.4 (10.3–51.1)	31.5 (9.8) [29.5–33.6]	32.7 (4.7–46.4)
S3	52.8 (13.1) [48.5–57.1]	58.6 (16.8–65.3)	30.0 (13.9) [26.7–33.2]	25.7 (8.0–61.1)
S4	42.3 (7.2) [39.4–45.2]	42.7 (18.2–51.5)	37.1 (8.6) [33.6–40.5]	39.3 (21.0–49.2)
S5	NA	NA	30.7 (11.7) [27.6–33.8]	29.9 (7.4–55.7)
S6	NA	NA	33.7 (13.1) [31.2–36.2]	33.3 (6.0–63.4)

In 2013, the mean volumetric flow rate of the outlet air in the four schools ranged from 39.9 m^3/h to 52.8 m^3/h, with the minimum and maximum values of 10.3 m^3/h and 65.3 m^3/h respectively. In 2014, the mean volumetric flow rate of the outlet air in the six schools ranged from 25.0 m^3/h to 37.1 m^3/h, with the minimum and the maximum values of 4.3 m^3/h and 63.4 m^3/h respectively. During the two-year fieldwork, it was found that the mean (SD) volumetric flow rate of the outlet air was 34.0 (12.9) m^3/h with a temperature of 28.9 (10.6) °C at the velocity of 0.8 (0.3) m/s. At this flow rate, it will take 6.5 hours for a complete air change of a 220 m^3 classroom. This ventilation rate was 25 times lower than the recommended ventilation rate by NZS 4303 “Ventilation for Acceptable Indoor Air Quality”, as 864 m^3/h fresh air is required for a classroom occupied by 30 pupils (Standards New Zealand, 1990)[1].

[1] NZS 4303:1990 – Ventilation for Acceptable Indoor Air Quality requires 8 litres per second per person (l/s/person) of fresh air. Assuming the classroom was occupied by 30 children, the required fresh air is 864 m^3/h (8 l/s/person * 30 person * 3600 * 0.001).

The SAH was designed for space heating and ventilation. However, it appears that the required ventilation rate was not achieved. Consequently, future research should focus on increasing the volumetric flow rate of the outlet air whenever the outlet air temperature is above 18 °C. This could be achieved by a modification of the algorithm in the fan controller, or by increasing the fan capacity.

4.3.1.4 Efficiency

The thermal efficiency of a SAH is defined as the ratio of the energy converted to the solar energy incident on the SAH collector panel. Levels of the mean (SD) and median (minimum–maximum) efficiency of the SAH in different schools and different years are shown in Table 4-10.

Table 4-10 Solar air heater efficiency (%)

Year	**2013**		**2014**	
School (S)	**Mean (SD) [95% CI]**	**Median (minimum–maximum)**	**Mean (SD) [95% CI]**	**Median (minimum–maximum)**
S1	20 (10) [17–24]	19 (4–39)	14 (10) [12–16]	11 (3–38)
S2	20 (10) [16–23]	18 (3–48)	15 (10) [12–17]	13 (1–51)
S3	21 (9) [17–25]	18 (9–36)	15 (13) [11–19]	10 (2–56)
S4	21 (9) [17–26]	20 (8–44)	16 (9) [12–20]	15 (5–36)
S5	NA	NA	12 (9) [9–15]	10 (1–46)
S6	NA	NA	17 (11) [14–19]	15 (2–53)

In 2013, the mean efficiency of the SAH in the four schools ranged from 20% to 21%, with minimum and maximum values of 3% and 48% respectively. In 2014, the mean efficiency of the SAH in the six schools was from 12% to 17%, with minimum and maximum values of 1% and 56% respectively. Across all schools and both years, the mean (SD) efficiency of the SAH was 16% (11)%. The median level was 14%, with the 1st quartile (Q_1) and 3rd quartile (Q_3) of 8% and 21% respectively.

To achieve a volumetric flow rate of 850 m^3/h, the required area (A_c) of the SAH under different levels of solar radiation on the SAH panel (I_T) and different efficiencies (η) was calculated. The efficiencies of the SAH were set between 10% and 40%. The solar radiation on the SAH panel was between 300 W/m^2 and 1000 W/m^2. The ΔT (T_{outlet} - T_{inlet}) was 6 °C. The required outlet air volumetric flow rate was 850 m^3/h. Assuming the air density is 1.225 kg/m^3, the required area (A_c) of the SAH could be calculated using Equation 4-2.

$$A_c = \frac{\rho \vartheta A_d C_P (T_o - T_i)}{\eta I_T} = \frac{1.225 * \frac{850}{3600} * 1007 * 6}{\eta I_T} = 1747.565 \;/\; \eta I_T \qquad \text{Equation 4-2}$$

Table 4-11 shows the required size of the SAH, calculated by Equation 4-2, to achieve the volumetric flow rate of 850 m^3/h, under different solar radiation and efficiency conditions.

Table 4-11 Required sizes of the solar air heater (m^2) to achieve 850 m^3/h outlet air at the temperature difference of 6 °C under different solar radiation and efficiency conditions

Efficiency (%) / Solar radiation (I_T) W/m^2	10%	15%	20%	30%	40%
300	58.3	38.8	29.1	19.4	14.6
400	43.7	29.1	21.8	14.6	10.9
500	35.0	23.3	17.5	11.6	8.8
600	29.1	19.4	14.6	9.7	7.3
700	25.0	16.6	12.5	8.3	6.2
800	21.8	14.6	10.9	7.3	5.5
900	19.4	13.0	9.7	6.5	4.9
1000	17.5	11.6	8.8	5.8	4.4

[1] The ΔT (T_{outlet} - T_{inlet}) threshold of a 6 °C increase in temperature was selected, this is because the outlet air temperature of 18 °C (WHO recommended minimum temperature) should be achieved when the temperature increase was at 6 °C, as the mean level of SAH inlet air temperature (ambient temperature) during the fieldwork was between 12 °C and 13 °C.

When the solar radiation on the SAH panel was 300 W/m^2, and the efficiency of the SAH was 20%, if the SAH is to become the primary source of ventilation in the classroom, to achieve an outlet air volumetric flow rate of 850 m^3/h, a SAH of at least 29.1 m^2 is required. This is close to 60% of the full sun-facing roof of the classroom building, assuming classrooms have a roof length of 10 m and the sun-facing (north) width of 5 m. A diagram is attached to Appendix C2 to illustrate it.

4.3.2 Impacts of weather conditions on the solar air heater outlet air temperature

A multiple linear model was built to investigate the impact of weather conditions and time on the SAH outlet air temperature. In this model, the input variables included the solar radiation, wind speed, ambient temperature, rainfall, hours and months. The output variable was the SAH outlet air temperature. The variables of the solar radiation, wind speed, ambient temperature and rainfall are numeric, while the time (hours and months) is categorical. The model was built using 75% of the available data and validated using the remaining 25% of data. Table 4-12 shows the effect of these variables on the SAH outlet air temperature.

Table 4-12 Effects of variables on solar air heater outlet air temperature

Variables	Coefficients	Standard error	p	Significant [1]
Hour 10	2.284	1.406	0.105	
Hour 11	1.961	1.51	0.195	
Hour 12	-0.630	1.566	0.688	
Hour 13	-2.421	1.574	0.125	
Hour 14	-4.869	1.504	0.001	**
Solar radiation (W/m^2)	0.047	0.003	< 0.001	***
Wind speed (m/s)	-0.218	0.038	< 0.001	***
Ambient temperature (°C)	0.243	0.174	0.165	
Rainfall (mm)	-1.669	0.622	0.008	**
Month July	-2.735	1.247	0.029	*
Month August	-4.441	1.184	< 0.001	***
Month September	-7.832	1.209	< 0.001	***

[1] Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

As shown in Table 4-12, the solar radiation and the ambient temperature positively impacted the SAH outlet air temperature. The wind speed and rainfall negatively impacted the SAH outlet air temperature. For every 1 m/s increase in the wind speed, the SAH outlet air temperature dropped 0.2 °C, while for every 10 W/m^2 solar radiation increase, the SAH outlet air temperature increased 0.5 °C. The SAH outlet air temperature at 2 pm (Hour 14) was significantly different from at 9 am. Similarly, the SAH outlet air temperatures in July, August, and September were significantly different from in June. The regression equation is shown in Equation 4-3.

$$\begin{aligned} &Outlet\ air\ temperature \\ &= 21.46 + 2.284 * Hour\ 10 + 1.961 * Hour\ 11 - 0.630 * Hour\ 12 \\ &- 2.421 * Hour\ 13 - 4.869 * Hour\ 14 + 0.047 * Solar\ radiation \\ &- 0.218 * Wind\ speed + 0.243 * Ambient\ air\ temperature \\ &- 1.669 * Rainfall - 2.735 * July - 4.441 * August - 7.832 \\ &* September \end{aligned} \quad \text{Equation 4-3}$$

This model accounted for 57.5% (multiple R^2) of the variance. To validate this model, the statistical errors based on the validation dataset were calculated. They were mean absolute error (6.21), mean square error (55.79), root mean square error (7.47) and mean absolute percentage error (23.43%). Figure 4-5 shows the hourly mean measured and predicted SAH outlet air temperature in different months. This plot is based on the validation dataset.

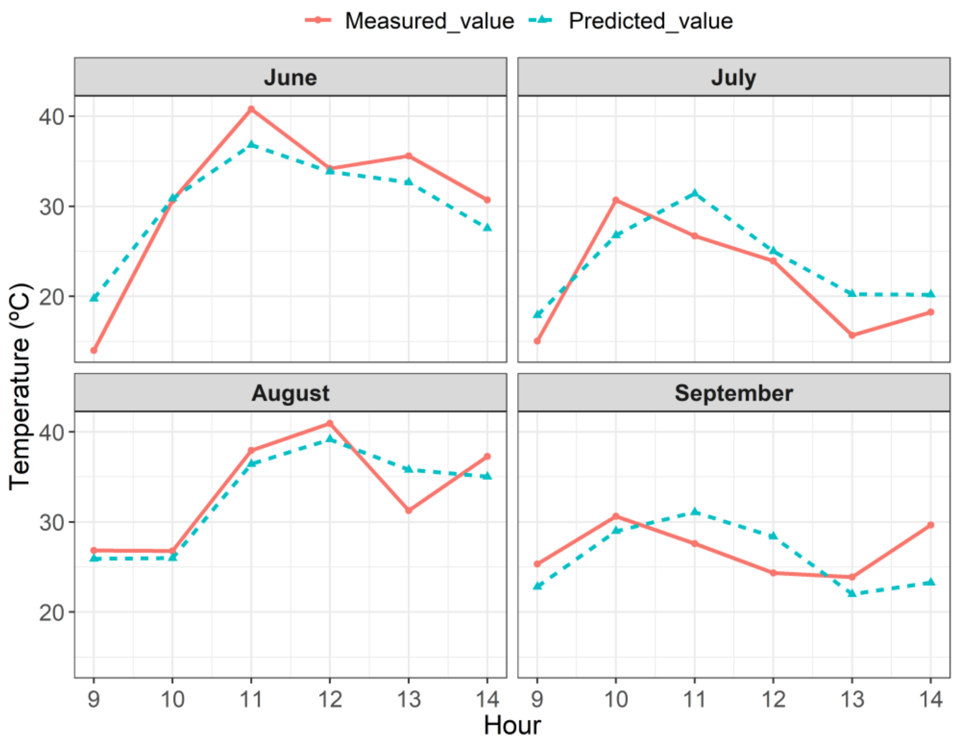

Figure 4-5 Measured and predicted solar air heater outlet air temperatures (°C) (This plot is based on the validation dataset.)

In all months, the measured values were well aligned with the predicted values. The mean and median residuals were 0.22 °C and -1.17 °C with Q_1 and Q_3 values of -5.10 °C and 5.38 °C. The mean and median errors (residuals/measured value) were - 5.4% and - 4.7%, with Q_1 and Q_3 values of -27.4% and 14.6%. This model was also used to predict the SAH outlet air temperature in other NZ cities, namely Auckland, Hamilton, New Plymouth, Gisborne, Wellington, Blenheim, Christchurch, Dunedin and Invercargill. These cities locate in NZ different regions, with different climate conditions. They represent all the possible climate conditions in NZ.

Figure 4-6 shows the predicted SAH outlet air temperature in different NZ cities.

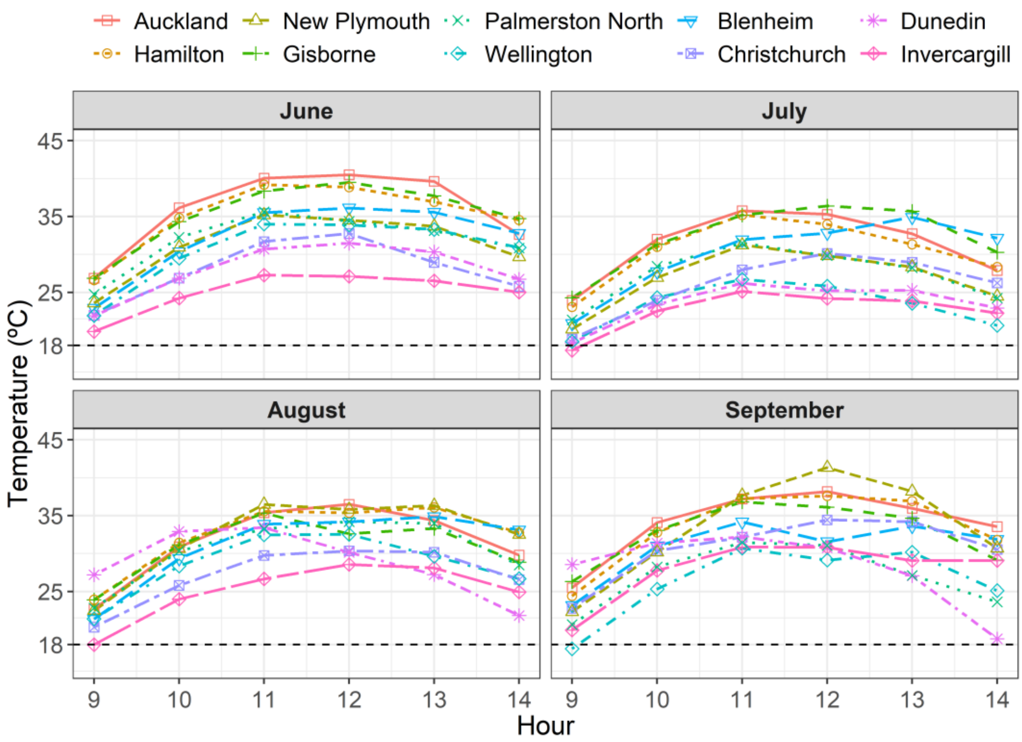

Figure 4-6 Predicted solar air heater outlet air temperature (°C) in different New Zealand cities

The model predicted the hourly mean temperature in main NZ cities from June to September. The predicted result was correlated to the local weather conditions. Figure 4-6 shows the predicted SAH outlet air temperature in the northern cities, like Auckland, Hamilton and Gisborne, is higher than in the South Island cities. The predicted SAH outlet air temperature in the southern cities, like Invercargill and Dunedin, is lower than in the North Island cities. During school hours, the mean (SD) value of the SAH outlet air temperature difference from it was operated in Auckland and in Invercargill is predicted to be 11.0 (2.9) °C in June, 8.7 (2.2) °C in July, 6.6 (1.6) °C in August and 6.2 (1.0) °C in September. The SAH outlet air temperature rose before noon and decreased after noon. Expect for at 9 am, the mean hourly SAH outlet air temperature was above 18 °C in all these cities. It is estimated that the results of this study can be generated in other locations where the climate conditions are similar to NZ. This means the operation of a SAH can also be a supplementary way of providing ventilation in most other countries.

4.3.3 Comparisons of the solar air heater performance

This section compares the SAH outlet air temperature drop between the outlet air temperature was measured in the duct 0.5 m (Chapter 3) and 5.0 m (Chapter 4) from the SAH panel. Figure 4-7 shows the outlet air temperature versus levels of solar radiation on the absorber panel, when the temperature was measured at 0.5 and 5.0 m from the SAH panel respectively. The regression model for the outlet air temperature of the SAH under different solar radiation levels was added.

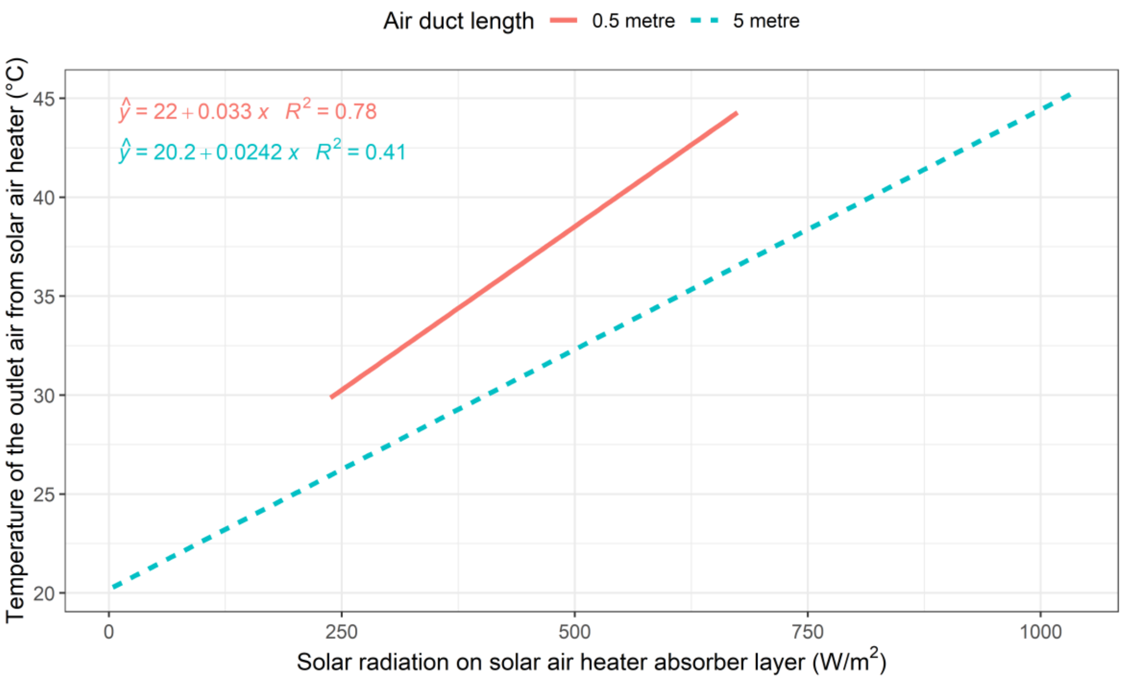

Figure 4-7 Solar air heater outlet air temperature (°C) at 0.5 m and 5 m from the back plate versus levels of solar radiation on the absorber panel

From the regression equation, it was calculated that for every 100 W/m^2 increase in the solar radiation falling on the SAH, the temperature of the outlet air had a 2.8 °C decrease between the outlet air measured at 0.5 m and 5.0 m from the SAH back plate. When the solar radiation was 500 W/m^2, the temperature decrease between these two spots was 6.0 °C. As the duct was within the classroom and surface mounted on the wall, any heat loss through the duct was transferred into the classroom. However, this heat was not captured by the monitoring device located at the 5.0 m distance.

Table 4-13 shows the comparison of SAH efficiencies in the fieldwork study (the present study) and in the experimental study (Chapter 3), and an NZ solar wall study (Jaques *et al.*, 2010).

Table 4-13 Comparison of efficiencies (%) of the solar air heater in the present study and a New Zealand solar wall study

Study	Types of solar air heaters	Size of the absorber layer (m^2)	Duct length (m)	Location	Maximum hourly efficiency (%)	Mean hourly efficiency (%)
Jaques *et al.* (2010)	Solar wall	14	1.5	Auckland	36%	NA
		18	0.6	Hamilton	24%	NA
		7.3	0.5	Hamilton	49%	NA
		18.5	2.2	Invercargill	63%	NA
Present study – (Chapter 3)	Custom-made support frame mounted solar air heater	3	0.5	Auckland (Albany)[1]	56%	46%
Present study – (Chapter 4)	Roof-mounted solar air heater	3	5.0	Palmerston North	56%	16%

[1] The experiment was undertaken with a fan at 75% the maximum speed. This setting was as the same as it was in the fieldwork.

In the study carried out by Jaques *et al.* (2010), the size of the solar wall absorber layer ranged from 7.3 m^2 to 18.5 m^2; the duct length ranged between 0.5 m and 2.2 m; and the maximum hourly efficiency ranged from 24% to 63%. In the present study, the size of the absorber layer was 3.0 m^2; and the duct length was approximately 5.0 m. This roof-mounted SAH had a mean and maximum hourly efficiency of 16% and 56% respectively. When the length of the outlet air duct was 0.5 m, mean and maximum hourly efficiencies of 46% and 56% were obtained. The negative relationship between the efficiency of the SAH and the air duct length was reported by (Heinrich, 2007), as the efficiency of the solar wall dropped from 54% to 15% when the duct length increased from 0.5 m to 2.2 m.

Due to the fieldwork and the experiment being conducted at different locations and under different weather conditions, the efficiency cannot be compared. Additionally, the fan speed and the fan used in the present study was not as the same as in Jaques *et al.* (2010) study. This means the thermal efficiency of the solar wall and the SAH was unable to be compared either.

4.3.4 Discussion

The results showed that the SAH average outlet air temperature in 2014 was lower than in 2013. This was consistent with 2014 having lower levels of solar radiation. The mean solar radiation was 315 W/m^2 in 2013 and 280 W/m^2 in 2014. The performance of the SAH in different schools in the same year varied. Because results of this study focused on the unoccupied school days (weekends and school term break). The number of unoccupied school days in each school was determined by the levels of CO_2 were less than 450 ppm and no heater was in use during the entire day. In different schools and years, the number of unoccupied school days ranged from 4 to 18. This means the weather conditions of the unoccupied days in different schools were not the same. Consequently, the performance of the SAH in different schools could not be compared.

A multiple linear regression model was built to estimate the SAH outlet air temperature. Results of this model showed that solar radiation, ambient air temperature, wind speed and rainfall were influential on the SAH outlet air temperature. Alta *et al.* (2010) found a similar result, which the levels of solar radiation positively influenced the SAH outlet air temperature. Alta *et al.* (2010) also found that the air mass flow rate of the outlet air negatively impacted the SAH outlet air temperature. The outlet air mass flow rate was close to consistent in this study. Therefore, the impact of the air mass flow rate on the SAH outlet air temperature was not obtained. Paya-Marin *et al.* (2015) found that the temperature rise of the SAH was not affected by the wind speed in the 0.3–4 m/s range. In this study, the wind ranged from 1.9 m/s to 50.0 m/s, and for every 10 m/s increase in wind speed, the SAH outlet air temperature decreased by 2.2 °C. By using this multiple linear model, the SAH outlet air temperature above 18 °C was predicted, when it was operated in different NZ cities. This means this SAH can be used in other NZ cities for school buildings space heating and ventilation purpose.

This study has potential limitations. First, the drop in temperature between measured at 0.5 m and 5.0 m from the SAH back plate was estimated using the model built with a different dataset. This estimated temperature would be more accurate if the data was recorded in the fieldwork. Second, the outlet air temperature of this SAH in different NZ cities was estimated using a multiple linear regression model. This model was built using the fieldwork data collected in PN and using the global solar radiation as one of the input variables. In fieldwork, the solar radiation inclined on the SAH absorber layer is different from the global radiation. It is determined by the panel orientation angle, inclination angle, the latitude and longitude of the location. However, it is not possible to calculate the solar radiation inclined on the absorber layer without knowing the above-mentioned parameters.

In this study, it is estimated that if the SAH is to become the primary source of the ventilation in classrooms, to achieve an outlet air volumetric flow rate of 850 m^3/h, a SAH of at least 29.1 m^2 is required. This is close to 60% of the full sun-facing roof of the classroom building, assuming classrooms have a roof length of 10 m and the sun-facing (north) width of 5 m. In future, it would be interesting to investigate if operating a SAH to provide the space heating and ventilation is better than investing in a solar photovoltaic panel which generates the electricity to power the heating and ventilation systems.

4.4 Conclusion

This chapter investigated the space heating and ventilation performance of a SAH when it was roof-mounted on school buildings. It is the first NZ study to investigate the SAH space heating and ventilation performance for the school environment. The fieldwork was conducted from July to September in four schools in 2013, and from June to September in six schools in 2014. Levels of the outlet air temperature, the temperature difference between the outlet and inlet air (ΔT, $T_{outlet} - T_{inlet}$), the volumetric flow rate of the outlet air, and the efficiency of the SAH were analysed. To limit the impact of the classroom temperature, which would include heat gain from the occupants and heater use, on the measurement of the outlet air temperature, the data analysis focused on the unoccupied school hours.

Results of this study showed that operating the SAH was a useful supplement to natural ventilation, but on its own was insufficient to achieve NZMoE required ventilation rate. Future improvements should focus on increasing the volumetric flow rate of the outlet air by changing the setting of the fan controller or enlarging the fan capacity, and also optimising the length of the outlet air duct to minimise the temperature drop within the duct.

Acknowledgements

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5 Change of School Environment

Effects on the classroom indoor air quality in winter from the use of a solar air heater – a case study in 6 Palmerston North primary schools

Chapter reference:

Y. Wang, R. Phipps, M. Boulic, M. Plagmann, C. Cunningham. Effects on the classroom indoor air quality in winter from the use of a solar air heater – a case study in 6 Palmerston North primary schools, paper to be submitted.

Abstract

A crossover intervention study was performed to investigate the effect of operating a roof-mounted solar air heater (SAH) on classroom temperature and ventilation. This study was carried out in four primary schools from July to September in Palmerston North (PN), New Zealand (NZ) in 2013, and in six primary schools (four previous ones plus two new ones) from June to September in PN, NZ in 2014. In each school, two adjacent classrooms were randomly either assigned to a treatment group (SAH installed and operated) or to a control group (SAH installed but not operated).

Levels of temperature and velocity of the outlet air from the SAH were monitored at the 10-min intervals, 24/7. Classroom temperature, relative humidity (RH) and carbon dioxide (CO_2) levels were measured at 2-min intervals, 24/7. Heater use in all classrooms was monitored. Classroom hourly ventilation rate was estimated using the tracer gas technique with CO_2 as the tracer gas. Data analysis focused on both unoccupied NZ school hours (weekend and school term break, from 9 am to 3 pm) and occupied school hours (Monday to Friday, from 9 am to 3 pm).

Results showed with the operation of the roof-mounted SAH, levels of the temperature in treatment classrooms were on average 0.5 °C higher than in control classrooms when both control and treatment classrooms had the same level of heater use. When the control and treatment classrooms had the same temperature, the heater use in treatment classrooms was 73% of the heater use in control classrooms. Across all schools, CO_2 levels in treatment classrooms were 96 ppm lower than in control classrooms. Only one treatment classroom had a ventilation rate above 4 air changes per hour. Overall, operating a roof-mounted SAH played a positive role in increasing classroom temperature and ventilation, but it was not sufficient. Future research should focus on designing a custom SAH which is used to provide with a satisfying learning environment for NZ schools.

5.1 Introduction

The inadequate ventilation in schools is of public concern. The required ventilation rate in classrooms specified by ASHRAE 62, REHVA handbook, EN 15251, EN13779, BB101, AS 1668, NZS 4303 and NZMoE document DQLS 2017 has been described in Section 2.4.3. The level of carbon dioxide (CO_2) can be used as a surrogate to estimate the ventilation rate of a zone (or a building) (ASTM, 2012; Bearg, 1993). The estimation is conducted using tracer gas techniques, under a well mixed[1], single zone[2] and homogeneity[3] assumption (Persily, 1997; Sherman, 1990). An indoor CO_2 concentration below 1000 ppm, namely 0.1% of the air composition, is required to achieve the minimum ventilation rate (ASHRAE, 2016; CEN, 2007). Based on ASHRAE (1989), the NZS 4303:1990 "Ventilation for Acceptable Indoor Air Quality" recommends a minimum ventilation rate of 8 l/s/person, with an assumed maximum occupant density of 0.5 users/m^2 (50 people per 100 m^2 floor area), and it results in a CO_2 concentration below 1000 ppm (Standards New Zealand, 1990). At this ventilation rate, a classroom will have an average ACH of 4 h^{-1} (BRANZ, 2007b).

Another ventilation requirement for New Zealand (NZ) school buildings built and renovated after January 2018 recommends an average daily CO_2 level below 1200 ppm, and the maximum CO_2 level should not exceed 3000 ppm (Ministry of Education, 2017a). It is noticed that the requirement for CO_2 concentrations from NZMoE (averaged level 1200 ppm) was higher than NZS 4303:1990 (averaged level 1000 ppm). A query was sent to NZ Ministry of Education (NZMoE) to clarify the alignment of these two requirements. NZMoE responded that regarding CO_2 concentration, the NZ Building Code (NZBC) links with NZS 4303 requirement and will be the governing document, as all buildings must comply with NZBC requirements.

[1] In a well mixed zone, any outside air or inject tracer gas becomes instantaneously and homogeneously dispersed within the zone.

[2] The zone only communicates with the outside, an area whose concentration of the tracer gas is unaffected by the zone.

[3] The fluid properties (i.e. density and tracer gas concentration) are assumed to be the same at every point within the zone.

In NZ, three studies have reported inadequate ventilation rates (based on CO_2 levels above 1000 ppm) in schools in winter (Bassett *et al.*, 1999; Cutler-Welsh, 2006; McIntosh, 2011). The results of these three studies were summarised in Section 2.4.3 of this thesis. Inadequate ventilation rates have also been found in European schools. From 2010 to 2012, a European project called Schools Indoor Pollution and Health: Observatory Network in Europe (SINPHONIE) was undertaken in 114 primary schools (340 classrooms in total) from 54 cities in 23 European countries. Eighty-six percent of the participating classrooms were naturally ventilated. Levels of CO_2 were measured during a full school week. Results showed that CO_2 levels were between 269 ppm and 4957 ppm among all schools, with the mean and median values of 1433 ppm and 1257 ppm respectively. In 50% of these participating schools, the occupants' exposure to CO_2 levels exceeded 1000 ppm for more than 50% of the school hours. Fisk (2017) reviewed levels of ventilation rate during occupied school hours in 3494 classrooms from 1242 schools in 13 countries[1], and confirmed that inadequate ventilation rates in schools were a worldwide issue, as the average and median of peak CO_2 levels exceeded 1000 ppm in all schools.

The insufficient ventilation rate in schools negatively affects occupant respiratory health. Smedje *et al.* (2000) studied the influence of the ventilation rate on student respiratory symptoms. The fieldwork was undertaken in approximately 100 classrooms from 39 randomly selected schools in 1993 and 1995. After the monitoring in 1993 and before the monitoring in 1995, 12% of the classrooms had a mechanical ventilation system installed. This new system increased the ventilation rate from 0.5 to 4.0 ACH, while the other classrooms had 3.1 ACH for both years. In classrooms with the new ventilation system, the pupils reported fewer asthmatic symptoms, and there was a reduce in reporting the asthmatic symptoms from 1993 to 1995. This study showed a negative relationship between asthmatic symptoms (cough, wheeze, shortness of breath) and the increase in ventilation rates in classrooms, with the mean OR of 0.3 (95% CI: 0.1–0.8).

[1] These 13 countries included France, Portugal, Germany, Scotland, Netherlands, United States of America, South Korea, Denmark, China, Sweden, Italy, Singapore and Greece.

The acceptable ventilation rate in classrooms is associated with a high school attendance (Mendell *et al.*, 2013). An American study involved 162 classrooms (3rd to 5th grade) in three school districts, over two school years showed that when the ventilation rate increased from 4 to 7 l/s/person, for every 1 l/s/person increase in the ventilation rate, the absenteeism rate due to medical reasons was reduced by 1.6% ($p < 0.05$) (Mendell *et al.*, 2013).

These studies have identified that many schools have high CO_2 levels and insufficient ventilation rates in winter. The insufficient ventilation rate in schools adversely affects occupant respiratory health and school attendance. Therefore, solutions to increase ventilation rates in schools are needed. Taking the ambient air directly into classrooms is not always applicable in the NZ winter, as NZ has very humid and often cold ambient air in winter. Many schools install heat pumps to heat or cool classrooms, however no fresh air is brought into classrooms by using the heat pumps. Research shows that well designed, well maintained and well operated mechanically ventilated classrooms have an acceptable ventilation rate (Canha *et al.*, 2013; Gao *et al.*, 2014). However, mechanical ventilation systems are capital and energy expensive, and need maintenance (Angelon-Gaetz *et al.*, 2015; Cutler-Welsh, 2006). Mechanical ventilation systems are not affordable for most NZ schools, especially following the introduction in 2010 by NZMoE of the capped budget for purchased energy[1] (Ministry of Education, 2010). Consequently, an alternative and affordable method to improve the ventilation rate in NZ primary schools in winter is needed.

School hours in NZ (from 9 am to 3 pm) are well aligned with the optimum solar radiation (Jaquiery, 2018). Jaques *et al.* (2010) investigated the heating performance of a solar wall in three NZ secondary schools and one NZ house. With the operation of the solar wall, the heated ambient air was pushed into the classrooms. However, shading issues from the building wing walls were found, which reduced the performance of the solar wall. Stasinopoulos (2002) reported that a roof-mounted solar air heater (SAH) performs better than a vertically mounted solar wall, as it is free from shading and is not affected by the building

[1] The operational funding for New Zealand schools was fixed in 2010 at a level based on an average of each school's last three year's use. This funding covers electricity, gas, coal and wood, and water supply.

wall thermal resistance. Given the building wall is the back plate of the solar wall, the building wall with a higher thermal resistance would reduce the heat loss, and vice versa (Stazi *et al.*, 2012). Besides, roof-mounted SAHs have no negative impacts on the building daylighting availability. Most importantly, no studies have investigated the ventilation and space heating performance of a roof-mounted SAH in school buildings in NZ.

The present study aimed to investigate the effects of operating a roof-mounted SAH on levels of temperature, relative humidity (RH) and CO_2 in classrooms. The ventilation rates in classrooms were estimated using tracer gas (CO_2) technique.

The SAH was composed of a cover plate, a black felt absorber layer, a perforated aluminium back plate and an aluminium frame. The cover plate is a transparent double layer polycarbonate sheet with the solar transmission of 0.77 and visible transmission of 0.85 (McGowan, 2016). The diameter of air inlet holes on the perforated back plate is 1.5 mm. These holes are evenly distributed in a grid, spaced at 15 mm apart (approximately 4300 holes/m^2). The diameter of the outlet air duct is 125 mm. The length, width, and air channel depth of this SAH were 3000 mm, 1020 mm and 75 mm respectively. The ambient air was heated as it passed through the perforated back plate and through the felt absorber layer. This heated air was then pushed into the outlet air duct by a fan. The outlet air velocity was controlled by a fan speed controller (regulator).

The experimental performance of this SAH was investigated under Auckland (36.7° S, 174.7° E), NZ climate, and this was reported in thesis Chapter 3. During the test, the air flow was set at 50%, 75% and 100% the maximum fan speed. The outlet air duct was 0.5 m in length. Results showed when the SAH was operated at a mass flow rate between 0.054 kg/s and 0.058 kg/s, the wind speed (between 0 m/s and 6 m/s) did not impact the temperature rise between the outlet air and the inlet air. The mean (SD) thermal efficiency of the SAH increased from 34 (5) % at the airflow between 0.021 kg/s and 0.023 kg/s, to 47 (6) % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, to 71 (4) % at the airflow between 0.054 kg/s and 0.058 kg/s. The maximum thermal efficiency of 75% was obtained at the airflow of 0.057 kg/s. The mean (SD) effective efficiency of the SAH was 32 (5) % at the airflow between 0.021 kg/s and 0.023 kg/s, 42 (6) % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, and 46 (11) % at the airflow between 0.054 kg/s and 0.058 kg/s.

The fieldwork performance of the SAH was also investigated in Palmerston North (PN, 40.4° S, 175.6° E), NZ and this was reported in thesis Chapter 4. This SAH was roof-mounted on four PN school buildings in winter 2013 and on six PN school buildings in winter 2014. During the Auckland experiment, the SAH panel was 52° off the horizontal surface (local latitude 37° plus 15°). The panel faced due north (at the azimuth angle of 0°). However, in the PN fieldwork, the SAH inclined angles ranged from 58.2° to 67.3°. The panel azimuth angles were between -30° and 19°. Other differences between the settings of the Auckland experiment and PN fieldwork were the length of the outlet air duct and the setting of the outlet air speed controller. The outlet air duct was estimated to have a length of 0.5 m in Auckland experimental study and 5.0 m in the PN fieldwork study. The air flow was set at 50%, 75% and 100% the maximum fan speed in Auckland experimental study, while it was only 75% the maximum fan speed in PN fieldwork.

Results of the PN fieldwork showed that the outlet air temperature was up to 50.2 °C, with the mean (SD) value of 28.9 (10.6) °C. The mean (SD) temperature difference between the outlet air and the inlet air was 16.6 (10.4) °C. The mean (SD) thermal efficiency of the SAH was 16 (11) %. The mean (SD) volumetric flow rate of the outlet air was around 34.0 (12.9) m^3/h with a temperature of 28.9 (10.6) °C at a mean velocity of 0.8 (0.3) m/s.

This chapter (Chapter 5) is the second part of the PN fieldwork analysis, which aimed to investigate the changes of temperature, RH, CO_2 and ventilation rate in classrooms from when the roof-mounted SAH was operating and not operating. Results reported in this chapter are focused on the change of these indoor air quality (IAQ) parameters during both unoccupied (weekends, school term breaks) and occupied (Monday to Friday) school hours (from 9 am to 3 pm).

This chapter is organised as follows: Section 1 introduced the study. Section 2 presents materials and methods that were used to investigate the effects of operating a roof-mounted SAH on temperature, RH, CO_2 and ventilation rate in schools, including the study design, data collection and data analysis. Section 3 presents and discusses the results. Section 4 concludes the chapter along with future research.

5.2 Materials and Methods

This was a two-year crossover intervention study. The intervention was the operation of a roof-mounted SAH. The structure of the SAH was shown in Chapter 3, Section 3.2.1. The location of this study was described in Chapter 4, Section 4.2.2. The school recruitment and description, including the construction characteristics and the population characteristics for each classroom, were presented in Chapter 4, Section 4.2.3. The setup of the SAH in fieldwork was outlined in Chapter 4, Section 4.2.4. This section describes the study design, the data collection and the data analysis.

5.2.1 Study design

Prior to the fieldwork commencing, the SAH was installed on the sun-facing (north in the southern hemisphere) roof of all participating classrooms. In each school, the two adjacent participating classrooms were randomly assigned either to a treatment group (SAH installed and operated) or to a control group (SAH installed but not operated). Table 5-1 shows the control and treatment status of all classrooms in 2013 and 2014 fieldwork.

Table 5-1 Control and treatment status of all classrooms in 2013 and 2014

School (S)	Room (R)	2013	2014	
		Term 3	**Term 2**	**Term 3**
S1	R1	Control (C)	Control (C)	Treatment (T)
	R2	Treatment (T)	Treatment (T)	Control (C)
S2	R1	T	T	C
	R2	C	C	T
S3	R1	C	C	T
	R2	T	T	C
S4	R1	T	T	C
	R2	C	C	T
S5	R1	N/A	T	C
	R2	N/A	C	T
S6	R1	N/A	C	T
	R2	N/A	T	C

The classrooms kept the same control or treatment status for the entire school Term 2[1]. During the term break between Term 2 and Term 3, the treatment classrooms became control classrooms and vice versa for the entire school Term 3. In the control classrooms, the outlet air duct was sealed to avoid air coming into or getting out of the classroom via the duct.

The fieldwork was expected to start at the beginning of Term 2 and end by the end of Term 3. However, in 2013, due to technical constraints, installing the SAH in primary schools took longer than anticipated. This delayed the commencement of the fieldwork to the beginning of Term 3.

5.2.2 Data collection

Temperature, RH and CO_2 levels in classrooms were monitored at 2-min intervals, 24 hours per day and 7 days per week (24/7), including school days, weekends and public holidays. The monitoring devices were either a Gas Probe IAQ monitor (BW Technologies Ltd, Canada) or a Model 8552 Q-Trak IAQ monitor (Trust Science Innovation, (TSI) Incorporated, Shoreview, USA) or a Model 7545 IAQ-Calc Meter (TSI Incorporated, Shoreview, USA).

To prevent tampering by occupants of classrooms and keep stable monitoring, these devices were placed inside a custom-made support structure. The probe was mounted at the height of 1.1 m above the floor level, which was the average height when students were seated at a desk. The devices were located in the best available location in classrooms. All devices were away from the doorway and direct sunlight. Figure 5-1 shows the custom-made support structure with the monitoring device.

[1] New Zealand schools have four terms per year. Each school term consists of 10 or 11 weeks. There are two-week term breaks between each term, except for the term break between Term 4 and Term 1 (in the following year). Among these four terms, Term 2 and Term 3 cover the winter month (June, July and August).

Figure 5-1 Custom-made support structure with the monitoring device

During the fieldwork, teachers were free to operate (turn on-off) the heaters as they would normally do. The heater use was recorded by a type K thermocouple connected to a microvolt logger, as shown in Figure 5-2.

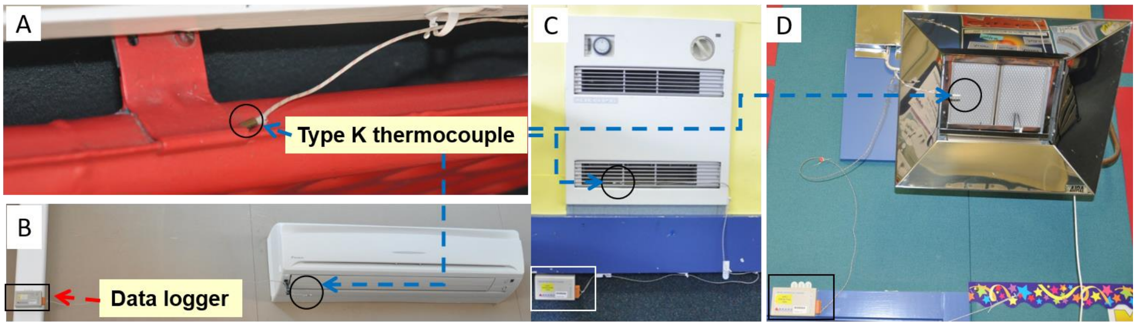

Figure 5-2 Thermocouple connected to a data logger to monitor the heater use
(A) Central radiator; (B) Inverter heat pump; (C) Electric heater; (D) Unflued gas heater

This thermocouple was located in front of each heater. The logger was developed by the BRANZ Ltd (French *et al.*, 2007). A hot wire anemometer (AM4214SD, Lutron electronic enterprise co. Ltd.) was placed at the centre of the outlet air duct to monitor the temperature and velocity of the air from the SAH at 10-min intervals, 24/7. The levels of global solar radiation, ambient temperature, wind speed and rainfall in PN were retrieved from a local climate monitoring station.

All monitoring devices involved in this study were calibrated and checked before and after the fieldwork. The characteristics of these monitoring devices are shown in Table 4-4. This study protocol was approved by the Massey University Human Ethics Committee (MUHEC 12/49). The approval letter is attached in Appendix B.

5.2.3 Data analysis

Data analysis focused on NZ school hours, which are from 9 am to 3 pm. The data was split into two categories, namely unoccupied school hours and occupied school hours. The unoccupied school hours included the data collected during weekends and school term breaks. The occupied school hours consisted of weekdays (Monday to Friday) data.

The analysis of unoccupied school hours aimed at investigating the effects of operating a SAH on classroom temperature, when there were no occupants activities or no heater use in the classroom. As CO_2 was released during the occupants' respiratory process, the CO_2 levels were used as a surrogate of the occupancy. During the unoccupied school hours, the level of CO_2 was below 450 ppm at all times, which confirmed the classroom was unoccupied. Heater use was also checked. It confirmed that, during these unoccupied periods, no heaters were in use both during and outside the school hours in any of the classrooms. This removed the influence of operating the heater on the classroom temperature.

During the occupied school hours, the hourly average values of the temperature, RH and CO_2 were calculated. Results were presented with mean (SD) and 95% CI. The difference in these parameters between treatment and control classrooms were calculated and compared by t test. The percentage of school hours when the temperature and RH levels were in the comfort zone was calculated for each classroom. The criteria for the comfort zone were temperature between 18 °C and 24 °C and RH between 40% and 60% simultaneously.

To report the distribution of CO_2 levels in all schools, the percentage of school hours with different CO_2 ranges was calculated. Based on the CO_2 threshold reported in ASHRAE 62 (ASHRAE, 2017), European Standard EN13779 (CEN, 2007), British guildline (BB101, 2018) and NZMoE document DQLS 2017

(Ministry of Education, 2017a), the CO_2 levels were categorised into six ranges: < 800, [800–1000], (1000–1500], (1500–2000], (2000–3000] and (3000–5000] ppm. Figure 5-3 gives the rationale for these thresholds.

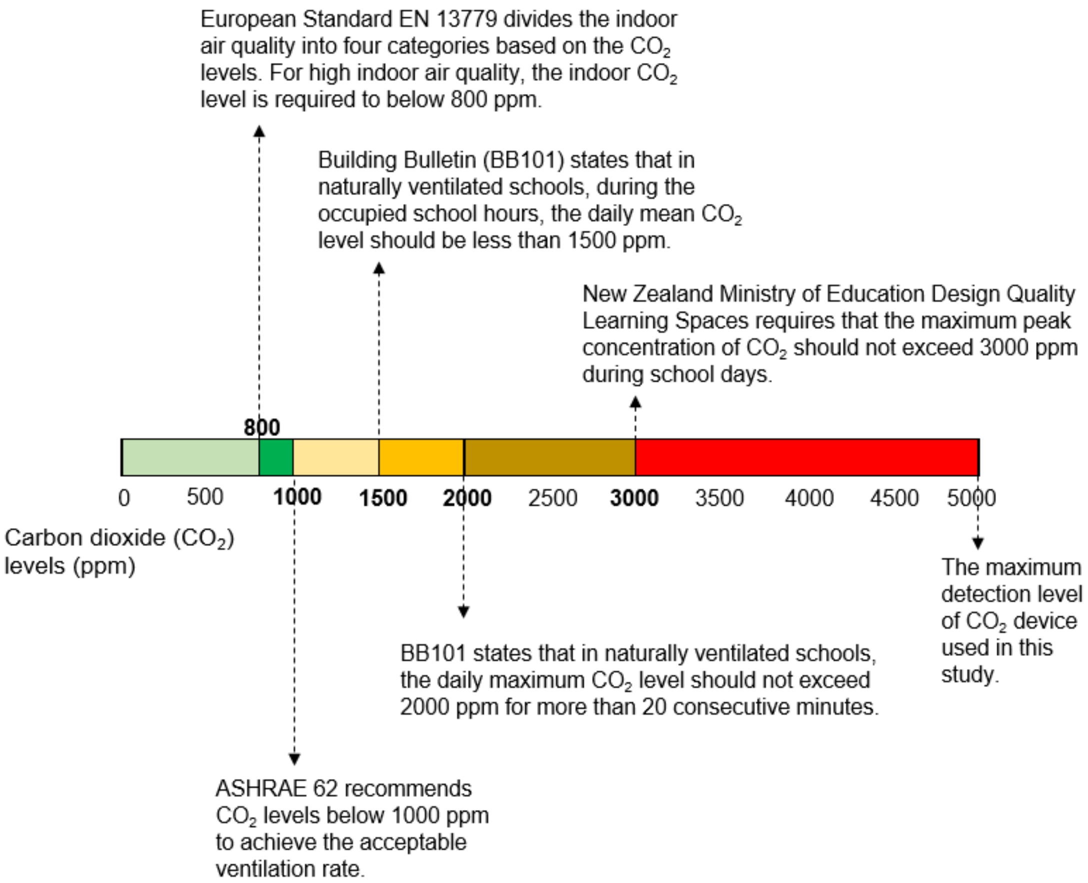

Figure 5-3 The rationale for the carbon dioxide thresholds

The ventilation rate (air changes per hour, ACH, h^{-1}) in all classrooms was estimated using the tracer gas technique (ASTM, 1998; Bearg, 1993). CO_2 has been used in different studies to estimate the ventilation rate (Gao *et al.*, 2014). In this study, the ventilation rate in classrooms was estimated with the levels of CO_2, according to Equation 5-1.

$$\boldsymbol{V\,dC(t)/dt = S + FVC_{out} - FVC(t)} \qquad \text{Equation 5-1}$$

Where,

V	Classroom volume (m^3)
$dC(t)/dt$	Net change in CO_2 concentration at time t ($mg/m^3/h$)
S	CO_2 generated in classrooms at time t (mg/h)
F	Number of air changes per hour (/h)
C_{out}	CO_2 concentration coming from outside (mg/m^3)
$C(t)$	CO_2 concentration in classrooms at time t (mg/m^3);

In the classroom environment, Equation 5-1 can be described as the CO_2 generated in classrooms plus the CO_2 coming into classrooms from the outside minus the CO_2 getting out from classrooms is equal to the net change in CO_2 in classrooms (ASTM, 1998; Bearg, 1993). The volume of each classroom was measured. The number of occupants in all classrooms was the enrollment number. The CO_2 generation rate used in this study was 0.0052 l/s/person for an adult and 0.0029 l/s/person for a pupil under office work activity (ASTM, 2012). The ambient CO_2 concentration of 400 ppm was confirmed by the PN ambient air pollutant measurements (M.S.A Development *et al.*, 2018). This level was also assumed in the European Standard EN13779 (CEN, 2007).

Heater use was categorised into four groups: (i) Early morning [0 am–6 am); (ii) Before school hours [6 am–9 am); (iii) School hours [9 am–3 pm]; and (vi) After school hours (3 pm–0 am). For each group, the heater use hours were totalled.

In the results section, the unoccupied results are shown first, following by the occupied results. Table 5-2 shows the number of unoccupied and occupied fieldwork days for each school in different years. For the same school, the control classroom and the treatment classroom had the same number of the monitored days.

Table 5-2 The number of unoccupied and occupied days in 2013 and 2014

School (S)	2013		2014	
	Unoccupied days	**Occupied days**	**Unoccupied days**	**Occupied days**
S1	16	44	28	70
S2	12	36	24	82
S3	16	44	32	82
S4	16	42	28	73
S5	NA	NA	30	72
S6	NA	NA	27	74

In 2013, the fieldwork started in late July. In 2014, the fieldwork was conducted from the beginning of June to the end of September.

All calculations were conducted using the statistical computing and graphics platform programming language R version 3.4.3 (R Core Team, 2016). The statistical significance was defined at a level of 0.05.

5.3 Results and Discussion

5.3.1 Classroom temperature during unoccupied school hours

During the unoccupied school hours, the median solar radiation was 270 W/m^2, with the 1st quartile (Q_1) and 3rd quartile (Q_3) levels of 147 W/m^2 and 406 W/m^2 respectively. The median ambient temperature was 12.3 °C (Q_1–Q_3: 10.8–14.0 °C). The median wind speed was 18.5 m/s (Q_1–Q_3: 11.1–24.1 m/s).

Figure 5-4 shows the hourly averaged (across all schools and both years) temperature difference between the treatment and the control classrooms. The grey area shows the 95% CI of the temperature difference.

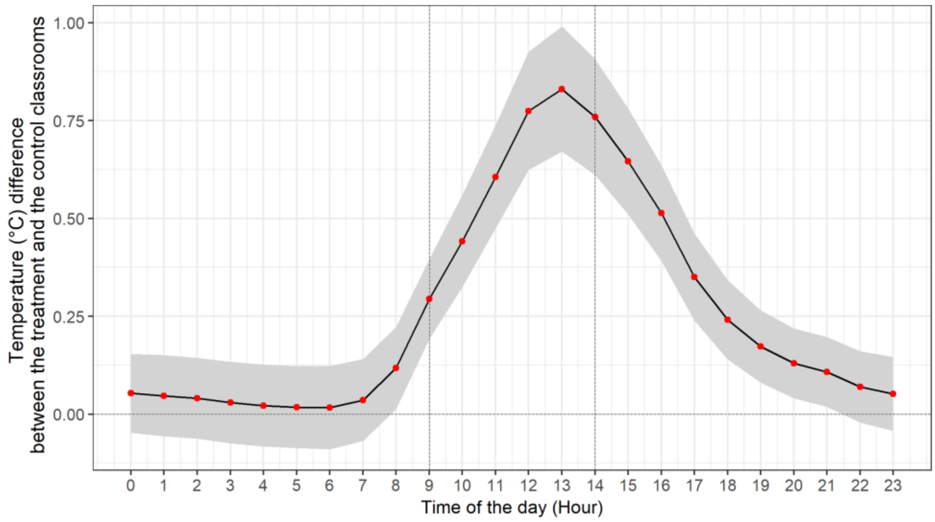

Figure 5-4 Hourly temperature (°C) difference between treatment and control classrooms (The grey area represents the 95% confidence interval.)

The temperature difference between the treatment and the control classrooms (during school hours), across all schools, ranged from -0.7 °C to 3.0 °C, with the mean value of 0.6 °C (95% CI: 0.5–0.7 °C). Figure 5-4 shows that hourly averaged temperature differences between treatment and control classrooms increased from 7 am (sunrise), and reached the peak at 1 pm (approximately maximum solar radiation level). The mean maximum temperature difference was 0.8 °C (95% CI: 0.7–1.0 °C). During nights, when there was no heating source in all classrooms, the temperature difference between the treatment and control classrooms was 0.1 °C.

Figure 5-5, Figure 5-6 and Figure 5-7 show the temperature difference between the treatment classrooms and the control classrooms, when the SAH was operated under different levels of solar radiation, ambient temperature, wind speed and rainfall. The unoccupied days (no heater use and CO_2 levels below 450 ppm) were different in each school. Consequently, the weather conditions of the unoccupied days in each school were different. During the unoccupied periods, School 1 was the only school that experienced various weather conditions. Therefore, the classrooms from School 1 were selected in all these scenarios. In these three figures (Figure 5-5 to Figure 5-7), the temperature levels above 18 °C are highlighted. The two vertical dash lines show the start and the end of the school hours.

Figure 5-5 shows the effect of operating the SAH on classroom temperature under different solar radiation levels. Under this scenario, the levels of ambient temperature were similar. The average wind speed range was from 8 m/s to 10 m/s. The rainfall was 0 mm.

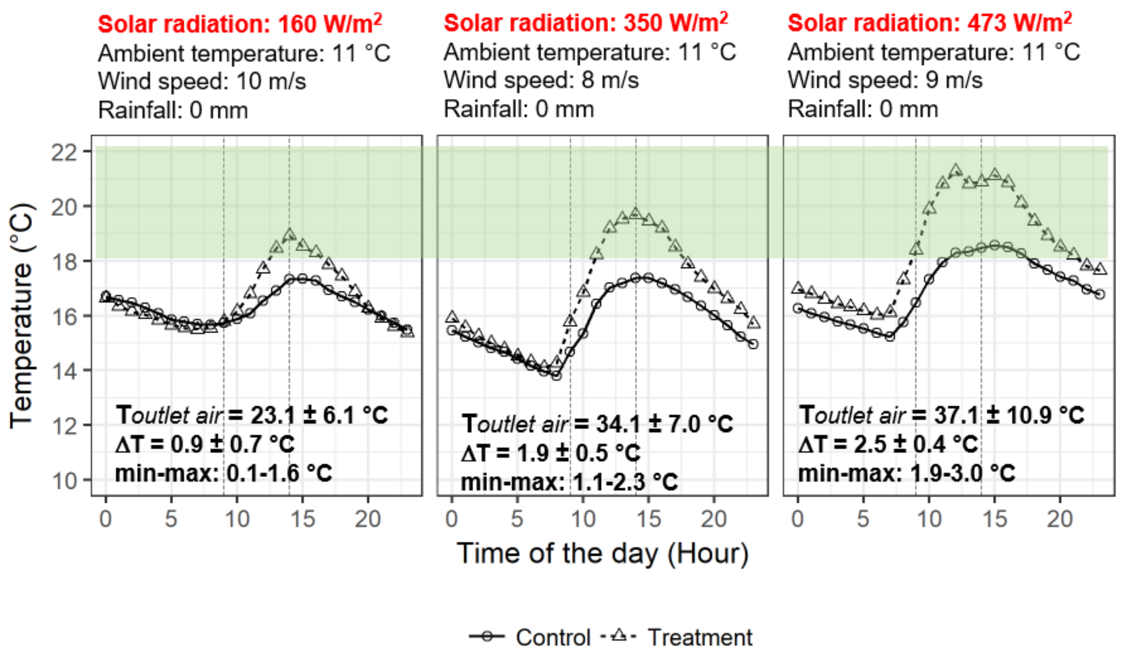

Figure 5-5 Effects of operating the solar air heater on classroom temperatures (°C) under different levels of solar radiation

T*outlet air* was the solar air heater outlet air temperature (°C). ΔT was the temperature difference (°C) between the treatment classroom and the control classroom.

Figure 5-5 shows under these three solar radiation levels, the hourly mean temperatures during the school hours were all higher in the treatment classrooms than in the control classrooms. The temperature difference between the treatment classrooms and the control classrooms increased with the increase in the solar radiation. Among these three days of the case study, the maximum temperature difference of 3.0 °C was obtained at 12 noon, when the hourly solar radiation was 611 W/m^2. On the day with the mean hourly solar radiation during school hours of 160 W/m^2, there was sufficient heat to achieve an acceptable temperature (18 °C) for 2 out of 6 school hours in the treatment classroom, while the temperature was below 18 °C in the control classroom during the full school day. The mean temperature difference between the treatment classroom and the control classroom was 0.9 °C, with a range of 0.1 °C to 1.6 °C.

On the day with the mean hourly solar radiation level during school hours of 350 W/m^2, there was sufficient heat to achieve an acceptable temperature level (18 °C) for 4 out of 6 school hours in the treatment classroom, while the temperature was below 18 °C in the control classroom for the full school day. The mean temperature difference between the treatment classroom and the control classroom was 1.9 °C, with a range of 1.1 °C to 2.3 °C. On the day with the mean hourly solar radiation during school hours of 473 W/m^2, there was sufficient heat to achieve an acceptable temperature for the full school day without the heater use. The mean temperature difference between the treatment classroom and the control classroom was 2.5 °C, with a range of 1.9 °C and 3.0 °C. Figure 5-5 (middle graph) shows that some heat in the treatment classroom was retained till midnight, as the temperature in the treatment classroom was still higher than in the control classroom at midnight.

Figure 5-6 shows the effect of operating the SAH on classroom temperature under different levels of wind speed.

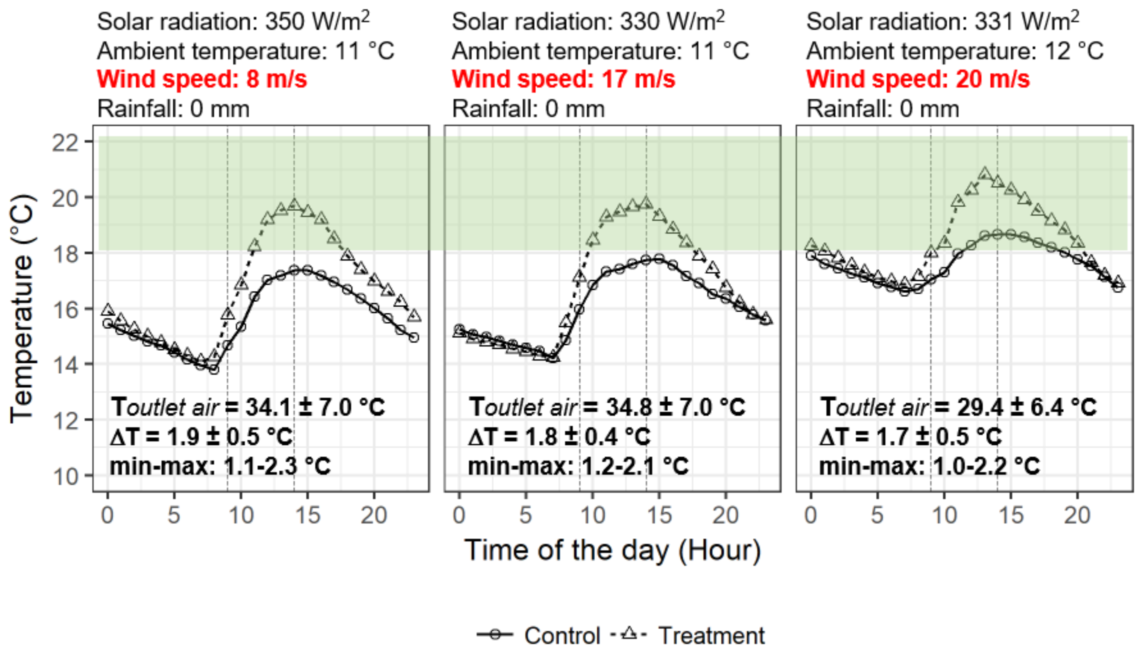

Figure 5-6 Effects of operating the solar air heater on classroom temperatures (°C) under different wind speeds

T*outlet air* **was the solar air heater outlet air temperature (°C). ΔT was the temperature difference (°C) between the treatment classroom and the control classroom.**

Figure 5-6 left and middle graphs show that under a similar solar radiation level (350 W/m^2 vs 330 W/m^2) and a similar ambient temperature, the mean temperature difference between the treatment and the control classrooms reduced from 1.9 °C to 1.8 °C when the wind speeds increased from 8 m/s to 17 m/s. Figure 5-6 middle and right graphs show that, under similar levels of solar radiation and ambient temperature, the mean temperature difference between the treatment classroom and the control classroom reduced from 1.8 °C to 1.7 °C, when the wind speed rose from 17 m/s to 20 m/s. This means that the wind speed reduced the SAH space heating performance. The influence of the wind speed on the heat loss from classrooms was assumed to be the same for the control classroom and the treatment classroom from the same school.

Figure 5-7 shows the effect of operating the SAH on classroom temperature on days with different rainfall.

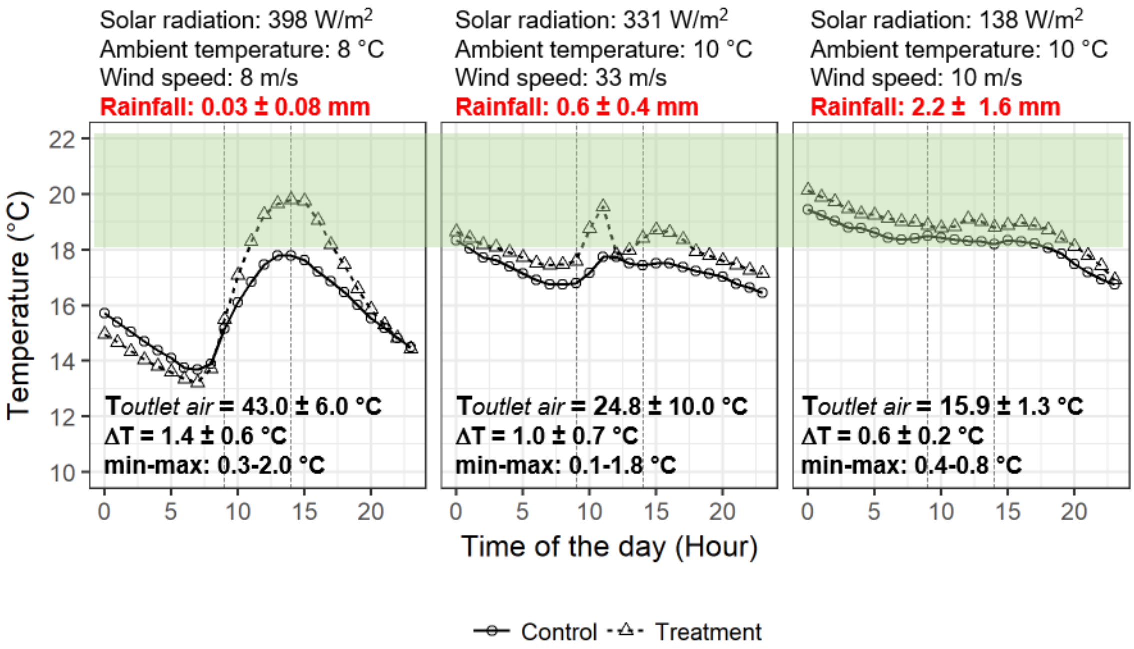

Figure 5-7 Effects of operating the solar air heater on classroom temperatures (°C) on rainy days

T*outlet air* was the solar air heater outlet air temperature (°C). ΔT was the temperature difference (°C) between the treatment classroom and the control classroom.

The left graph shows the SAH space heating performance on a day with a shower of rain at 9 am. The middle graph shows a full day of rain except for a dry period at 11 am. On this day, the rainfall was 0.6 mm and 1.0 mm at 9 am and 10 am respectively. It was 0 mm at 11 am and varied between 0.4 mm and 1.0 mm for the rest of the school hours. The right graph shows a day of continuous rain during school hours. During school hours, the hourly mean (SD) rainfall was 2.2 (1.6) mm.

On the day with only morning rainfall of 0.2 mm at 9 am (Figure 5-7, left), the SAH contributed to the classroom space heating for the rest of the school day. On a day with continuous rain and hourly mean solar radiation of 138 W/m^2 (Figure 5-7, right), the temperature in the treatment classroom was slightly higher than in the control classroom, with the mean temperature difference of 0.6 °C. Figure 5-7 (right) graph shows the classroom had a temperature above 18 °C on the previous night. There were two reasons to explain this overnight high temperature: first, this case study occurred in September, with an overnight ambient air temperature above 10 °C; second, the day before this case study, the classroom had high levels of temperature, with a maximum of 21.9 °C in the control classroom and 23.7 °C in the treatment classroom respectively. The temperature in both rooms was reduced to 20 °C by midnight.

Figure 5-7 (middle) graph shows a temperature drop in the treatment classroom from 11 am to 12 noon. This can be explained by the ambient weather conditions that occurred from 11 am to 12 noon, as the solar radiation reduced from 639 W/m^2 to 319 W/m^2, the rainfall increased from 0 mm to 0.8 mm, and the wind speed increased up to 44 m/s. After 2 pm, the rain ceased and the wind speed reduced to no more than 10 m/s. The temperature in the treatment classroom then began to rise.

To estimate the SAH space heating performance under different weather conditions, a regression model was built. In this model, the input variables included the ambient temperature, the rainfall, the solar radiation, the SAH outlet air volumetric flow rate, the wind speed and the time (hour). The output variable was the classroom temperature rise (the temperature difference between the treatment and control classrooms). Table 5-3 shows the effect of these variables on the classroom temperature rise.

Table 5-3 Effects of operating the solar air heater on the classroom temperature rise under different weather conditions

Variables	**Effect size (°C/unit)**	**Standard error**	**p**	**Significant[1]**
Ambient temperature (°C)	-0.041	0.013	0.002	**
Rainfall (mm)	-0.013	0.006	0.045	*
Solar radiation (W/m^2)	0.002	0.000	< 0.001	***
Wind speed (m/s)	-0.010	0.003	0.001	***
Solar air heater outlet air volumetric flow rate (m^3/h)	0.0003	0.001	0.760	
Time (hour)	0.051	0.019	0.006	**

[1] Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

As shown in Table 5-3, ambient temperature, solar radiation, wind speed, rainfall and time (hour) statistically significantly affected temperatures difference between the treatment and control classrooms, as the p less than 0.05 for these variables were obtained. The smaller the p, the stronger the evidence that the null hypothesis (no relationship between the independent variable and the dependent variable) should be rejected. Table 5-3 shows there are strongest evidence indicating a positive relationship between the solar radiation and the classroom temperature rise, and a negative relationship between the wind speed and the classroom temperature rise, as there is less than 0.1% probability the null hypothesis (no relationships between these two weather variables and the classroom temperature rise) fails to be rejected. A stronger negative relationship between the ambient temperature and the classroom temperature rise was obtained. The less strong negative relationship was obtained between the rainfall and the classroom temperature rise. Overall, the solar radiation played a positive role in SAH space heating performance. The wind speed, ambient temperature and rainfall negatively affected the SAH space heating performance.

5.3.2 Classroom temperature during occupied school hours

Table 5-4 shows the mean temperature during school hours in the control classrooms and in the treatment classrooms in winters of 2013 and 2014. It included the mean (SD) and 95% CI. The number of occupied school days in each school and different years were reported in Table 5-2.

Table 5-4 Mean (standard deviation) and 95% confidence interval of temperature (°C) in all classrooms in 2013 and 2014

Year	School (S)	Control classrooms	Treatment classrooms	Difference[1]	p
2013	S1	21.3 (1.3) [21.0–21.5]	22.6 (1.2) [22.5–22.8]	1.1 (1.3) [0.9–1.4]	< 0.01
	S2	22.5 (1.5) [22.3–22.7]	22.8 (2.1) [22.5–23.1]	0.3 (2.1) [0.0–0.6]	0.16
	S3	20.7 (1.8) [20.4–20.9]	21.6 (1.8) [21.3–21.8]	0.9 (1.6) [0.7–1.1]	< 0.01
	S4	21.5 (1.4) [21.3–21.7]	19.6 (1.7) [19.4–19.8]	-1.9 (1.9) [-2.2– -1.7]	< 0.01
2014	S1	22.0 (1.6) [21.8–22.2]	21.9 (1.6) [21.8–22.1]	0.0 (1.5) [-0.1–0.2]	0.81
	S2	22.0 (1.8) [21.8–22.2]	22.0 (1.9) [21.8–22.2]	0.0 (2.1) [-0.2–0.3]	0.82
	S3	21.6 (1.9) [21.4–21.7]	21.6 (1.9) [21.4–21.7]	0.0 (1.5) [-0.1–0.1]	0.99
	S4	19.3 (1.6) [19.1–19.4]	20.0 (2.0) [19.9–20.2]	0.8 (2.0) [0.6–1.0]	< 0.01
	S5	21.6 (1.9) [21.4–21.7]	22.5 (2.4) [22.3–22.7]	1.0 (3.0) [0.7–1.3]	< 0.01
	S6	20.5 (1.6) [20.3–20.7]	20.8 (1.7) [20.6–20.9]	0.3 (1.0) [0.2–0.4]	0.02

[1] The temperature difference between the treatment classroom and the control classroom.

The mean temperature in all classrooms (both control and treatment) ranged from 19.3 °C to 22.8 °C. This was within the WHO recommendation temperature range from 18 °C to 24 °C.

In 2013, the temperature levels in 2 out of 4 treatment classrooms were statistically significantly higher than in the control classrooms (S1 and S3). The opposite result was found in S4, where the temperature in the treatment classroom was statistically significantly lower than in the control classroom. This can be explained by the fact that heater use in the S4 treatment classroom was 64% less than in the S4 control classroom. To be specific, in S4, the daily school hours heater use was 0.9 hours in the treatment classroom and 2.5 hours in the control classroom.

The temperature difference between the treatment classroom and the control classroom in S2 was not statistically significant. In S1 and S3, the mean hourly temperature differences between the treatment and the control classrooms were

1.1 °C and 0.9 °C respectively. In S2, the mean temperature difference between the treatment and the control classroom ranged from 0.0 °C to 0.6 °C.

In 2014, the temperature levels in 3 out of 6 treatment classrooms were statistically significantly higher than in the control classrooms (S4, S5 and S6). Mean hourly temperature differences between the treatment and control classrooms ranged from 0.3 °C to 1.0 °C. In S1, S2 and S3, the levels of temperature between the control and treatment classrooms were not statistically significantly different.

Table 5-5 shows the percentage of school hours with different temperature levels. Temperature levels were categorised into five groups: < 16, [16–18), [18–24], (24–28], and > 28 °C.

Table 5-5 Percentage of school hours with different temperature levels (°C) in control and treatment classrooms

Year	School (S)	Classroom	< 16	[16–18)	[18–24]	(24–28]	> 28
2013	S1	Control (C)	0.00%	2.27%	96.21%	1.52%	0.00%
		Treatment (T)	0.00%	0.00%	88.26%	11.74%	0.00%
	S2	C	0.00%	1.39%	87.96%	10.65%	0.00%
		T	0.00%	0.93%	64.81%	33.80%	0.46%
	S3	C	1.52%	6.82%	90.15%	1.52%	0.00%
		T	0.38%	3.03%	89.77%	6.82%	0.00%
	S4	C	0.79%	2.38%	94.44%	2.38%	0.00%
		T	2.38%	13.89%	83.73%	0.00%	0.00%
2014	S1	C	1.43%	0.71%	85.71%	12.14%	0.00%
		T	0.48%	0.95%	87.38%	11.19%	0.00%
	S2	C	0.00%	2.34%	85.94%	11.72%	0.00%
		T	1.04%	2.60%	84.38%	11.98%	0.00%
	S3	C	0.20%	4.47%	87.60%	7.72%	0.00%
		T	0.41%	4.07%	88.01%	7.52%	0.00%
	S4	C	2.74%	20.09%	77.17%	0.00%	0.00%
		T	3.65%	12.79%	82.19%	1.37%	0.00%
	S5	C	0.93%	4.40%	85.42%	9.26%	0.00%
		T	2.55%	4.40%	67.36%	25.46%	0.23%
	S6	C	2.25%	6.76%	90.77%	0.23%	0.00%
		T	2.25%	4.73%	93.02%	0.00%	0.00%

Across all schools, in both the control classrooms and the treatment classrooms, the percentage of school hours where the temperature was between 18 °C and 24 °C ranged from 64.8% to 96.2%. In 15 out of 20 classrooms, there were less than 4.0% (between 0.2% and 3.7%) of school hours where the temperature was below 16 °C. In 2013, all classrooms had temperature levels between 16 °C and 18 °C except S1 treatment classroom. The amount of time spent in the temperature range between 16 °C and 18 °C was between 0.7% and 20.1% of the school day. Temperature levels in S4 were lower than in the other schools, as there were 13% to 20% of school hours with temperature levels between 16 °C and 18 °C in the treatment classroom in 2013 and in both control and treatment classrooms in 2014.

Temperature levels in the S2 treatment classroom in 2013 and in the S5 treatment classroom in 2014 were higher than in the other schools, as these two classrooms had temperatures between 24 °C and 28 °C for more than 25% of school hours, and even above 28 °C. This temperature is higher than the WHO recommendation. This could be rectified by either changing the thermostat point of the SAH controller, or preferably reducing the heater use in the classrooms. When compared to a previous NZ school study conducted by McIntosh (2011), the present study showed an increase in the mean temperature in most classrooms. McIntosh (2011) found that 14 out of 35 Wellington (NZ) primary classrooms had temperature levels below 18 °C for more than 50% of the school day. A low temperature level (mean = 13.4 °C, minimum–maximum: 10.3–15.2 °C) was found in a special language class which was only occupied sporadically by a small number of students (McIntosh, 2011).

5.3.3 Classroom heater use during occupied school days

Table 5-6 shows the heater use in all schools in 2013 and 2014. The heater use was separated into four groups according to the time of the day, including the heater use in the early morning [0 am–6 am), before school hours [6 am–9 am), during school hours [9 am–3 pm], and after school hours (3 pm–0 am). The boxplots of the hourly heater use in all schools in 2013 and 2014 are attached in Appendix D1. Daily heater use was totalled.

In all schools, the heater use before and during the school hours was higher than the other two groups (early morning and after school hours). This result was supported by school activities. Generally, the heater was turned on 2 or 3 hours prior to the start of the school days (9 am) to preheat the classroom. When the classroom had a comfortable temperature, the teachers turned off the heater. In most schools, the heaters were not being used in the afternoon. This means that in the afternoon the heat gain through the building envelope and the heat gain from the occupants were sufficient to warm the classroom. However, it was also seen that heaters were used during the middle of the night, in the early morning and after school hours.

Across two years, the total daily school hours heater use varied from 1.1 hours to 3.2 hours in the control classrooms, and from 0.4 hours to 3.5 hours in the treatment classrooms. The ratio of the heater use in the treatment classrooms to the heater use in the control classrooms (T/C ratio) ranged from 0.3 to 1.5. The maximum T/C ratio was 1.5 and this occurred in S4 and S5 in 2014. It was also noticed that S5 had the highest early morning heater use in 2014, in both the control and treatment classrooms. Across the two years and all schools, the T/C ratio was below 1.0 for 60% of school hours, with a range from 0.3 to 1.5.

In terms of the average daily heater use, this ranged from 1.4 hours to 6.0 hours in control classrooms, and from 0.9 hours to 6.4 hours in treatment classrooms. The maximum heater use per day (6.0 hours and 6.4 hours) occurred in the same classroom in S6, as the classroom control and treatment status were swapped during the term break between Term 2 and Term 3. Across two years and all schools, 50% of T/C ratios for the average daily heater use were below 1.0, with a range from 0.4 to 1.6.

The intention of this study was not to control the classroom activities. The teachers were not asked to change their behaviour. During the fieldwork, teachers were free to operate (turn on-off) heaters as they would normally do. There were different teachers in different classrooms, with a different perception of temperature. If the heater use in treatment classrooms was higher than in control classrooms, which might because the teacher in this classroom preferred the warmer temperature. Teachers also have different work routine. For example in S5, the teachers in the participating classrooms frequently worked in the late evening and early morning. Figure 5-8 shows the impacts of operating a SAH on classroom temperature, with considerations of heater uses.

Table 5-6 Mean (standard deviation) daily heater use (hours) in four groups according to the time of the day and the total daily heater use

Year	School (S)	Early morning [0 am–6 am]			Before school hours [6 am–9 pm)			During school hours [9 am–3 pm]			After school hours (3 pm–0 am)			Total daily heater use hours		
		Control (C)	Treatment (T)	Ratio[1]	C	T	Ratio[1]	C	T	Ratio[1]	C	T	Ratio[1]	C	T	Ratio[1]
2013	S1	0 (0)	0 (0)	NA	2.0 (1.2)	2.7 (0.3)	1.4	2.0 (1.2)	1.8 (0.2)	0.9	0 (0)	0 (0)	NA	4.0	4.5	1.1
	S2	0 (0)	0 (0)	NA	1.3 (0.4)	1.0 (0.6)	0.8	1.5 (1.6)	0.4 (0.6)	0.3	0 (0)	0 (0)	NA	2.8	1.4	0.5
	S3	0.1 (0.9)	0 (0)	0	0.6 (0.5)	0.5 (0.4)	0.8	1.6 (1.4)	1.0 (1.0)	0.6	0.1 (0.4)	0 (0.1)	0	2.4	1.5	0.6
	S4	0 (0)	0 (0)	NA	0.7 (0.2)	0.4 (0.3)	0.6	1.8 (1.1)	0.5 (0.6)	0.3	0 (0)	0 (0)	NA	2.5	0.9	0.4
2014	S1	0.5 (1.2)	0.2 (0.2)	0.4	2.1 (1.3)	2.3 (1.1)	1.1	1.5 (1.3)	1.8 (1.1)	1.2	0.4 (1.8)	0.1 (0.4)	0.2	4.5	4.4	1.0
	S2	0 (0.2)	0.1 (0.5)	Inf	1.2 (0.4)	1.1 (0.5)	0.9	1.7 (1.4)	1.3 (1.2)	0.8	0 (0.3)	0 (0.1)	NA	2.9	2.5	0.9
	S3	0.4 (1.4)	0.1 (0.5)	0.2	0.7 (0.7)	0.5 (0.4)	0.7	2.5 (1.9)	2.3 (1.7)	0.9	0.6 (1.8)	0.3 (1.1)	0.5	4.2	3.2	0.8
	S4	0 (0)	0.1 (0.7)	Inf	0.3 (0.3)	0.3 (0.3)	1.0	1.1 (1.2)	1.6 (1.7)	1.5	0 (0.2)	0.2 (0.9)	Inf	1.4	2.2	1.6
	S5	0.8 (0.5)	1.5 (1.9)	1.9	2.4 (0.7)	1.8 (1.2)	0.8	1.3 (1.5)	2.0 (2.0)	1.5	0.2 (0.4)	0.4 (1.7)	2.0	4.7	5.7	1.2
	S6	0 (0)	0 (0)	NA	2.7 (0.4)	2.7 (0.3)	1.0	3.2 (1.4)	3.5 (1.2)	1.1	0.1 (0.5)	0.2 (0.7)	2.0	6.0	6.4	1.1

[1] The ratio of the heater use in the treatment classroom to the heater use in the control classroom.

Figure 5-8 shows the relationship between the temperature difference (ΔT, temperature differences between the treatment classrooms and the control classrooms) and the ratio of the total heater use in the treatment classrooms to that in the control classrooms.

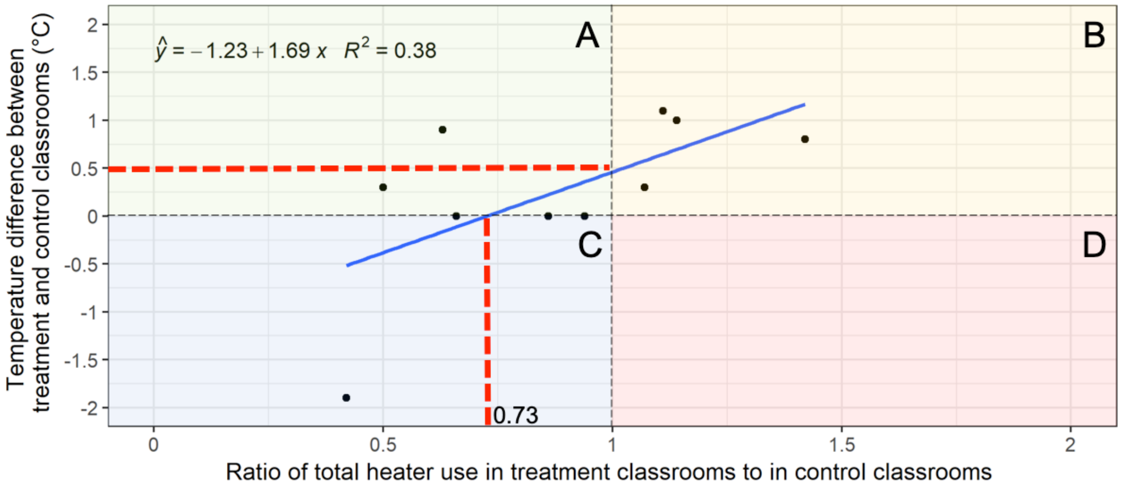

Figure 5-8 Relationship between the temperature difference (°C) and the ratio of total heater use in treatment classrooms to that in control classrooms

According to the temperature difference (ΔT > 0 or ΔT < 0) and the ratio of the heater use (> 1 or < 1), Figure 5-8 was divided into four parts. Part A (top left) was the area where the temperature in the treatment classrooms was higher than in the control classrooms, and the heater use in the treatment classrooms was less than in the control classrooms. This part showed the positive impact of operating the SAH on classroom temperature. Part B (top right) was the area where the temperature in the treatment classrooms was higher than in the control classrooms, however the heater use in the treatment classrooms was higher than in the control classrooms. This means the temperature gains were at least partly from the heater use. Part C (bottom left) was the area where the temperature in the treatment classrooms was lower than in the control classrooms, and the heater use in the treatment classrooms was less than in the control classrooms. Part D (bottom right) was the area where the temperature in the treatments classroom was lower than in the control classrooms, however the heater use in the treatment classrooms was higher than in the control classrooms. Not surprisingly, there were no data in Part D.

A linear model was built to estimate the effects of operating the SAH on the classroom temperature, taking the heater use ratio into considerations. Results showed that when the heater use hours were the same for the control and treatment classrooms, the temperature levels were 0.5 °C higher in the treatment classrooms than in the control classrooms. When temperatures in the control and treatment classrooms were the same, the heater use in the treatment classrooms was 27% less than in the control classrooms.

As shown in Figure 5-8, the lowest ratio of the total heater use in treatment classrooms to that in control classrooms was 0.4. This point corresponds to a temperature difference (between the treatment and control classroom) of -1.9 °C. This result was obtained in S4 (2013), where the heater use in the treatment classroom was 64% less than in the control classroom. To be specific, the daily heater use was 0.9 hours in the treatment classroom and 2.5 hours in the control classroom.

5.3.4 Classroom humidity during occupied school hours

Table 5-7 shows the mean levels of RH in all control and treatment classrooms.

Table 5-7 Mean (standard deviation) and 95% confidence interval of relative humidity (%) in all classrooms in 2013 and 2014

Year	School (S)	Control classrooms	Treatment classrooms	Difference[1]	p
2013	S1	48.3 (6.3) [47.2–49.3]	47.9 (5.7) [47.2–48.6]	-0.3 (2.9) [-0.8–0.1]	0.65
	S2	51.7 (6.7) [50.7–52.6]	48.6 (9.8) [47.2–50.0]	-2.6 (5.4) [-3.4– -1.8]	< 0.01
	S3	56.2 (6.0) [55.5–57.0]	54.3 (7.7) [53.4–55.2]	-1.9 (3.4) [-2.3– -1.5]	< 0.01
	S4	56.8 (6.4) [56.0–57.6]	56.7 (6.9) [55.8–57.6]	0.0 (4.7) [-0.6–0.6]	0.97
2014	S1	49.2 (5.4) [48.7–49.8]	48.2 (6.4) [47.5–48.8]	-1.1 (3.1) [-1.4– -0.8]	0.02
	S2	49.9 (7.0) [49.2–50.7]	48.8 (7.6) [48.0–49.6]	-0.9 (4.7) [-1.4– -0.4]	0.10
	S3	56.5 (6.6) [55.9–57.1]	55.7 (6.4) [55.2–56.3]	-0.8 (3.4) [-1.1– -0.4]	0.08
	S4	61 (10.2) [60.1–62.0]	57.7 (6.8) [57.1–58.4]	-3.3 (8.3) [-4.1– -2.5]	< 0.01
	S5	58.4 (5.1) [57.9–58.9]	55.0 (7.3) [54.3–55.7]	-3.4 (7.6) [-4.1– -2.7]	< 0.01
	S6	52.6 (5.2) [52.0–53.1]	53.8 (4.4) [53.4–54.3]	1.4 (3.1) [1.0–1.7]	< 0.01

[1] The relative humidity difference between the treatment classroom and the control classroom.

Table 5-7 shows that the mean RH levels in all schools were within a range between 40% and 60%, except in the S4 control classroom (2014). In five out of 10 schools (all participating schools in both years), the mean RH levels in the treatment classrooms were statistically significantly lower than in the control classrooms. The control classroom in S4 (2014) was the only classroom that experienced an hourly mean RH above 60%. This high level of RH happened in mid-June (in one week). During this week with the high RH level, the classroom temperature was below 18 °C for 85% of the time.

Table 5-8 shows the percentage of school hours within bands of RH levels.

Table 5-8 Percentage of school hours with different relative humidity (%) levels in control and treatment classrooms

Year	School (S)	Classroom	< 40	[40–60]	(60–70]	> 70
2013	S1	Control (C)	6.06%	84.09%	9.85%	0.00%
		Treatment (T)	7.95%	90.53%	1.52%	0.00%
	S2	C	5.09%	84.26%	10.19%	0.46%
		T	24.07%	60.65%	14.81%	0.46%
	S3	C	0.00%	79.17%	19.32%	1.52%
		T	1.52%	77.27%	15.91%	5.30%
	S4	C	0.00%	63.10%	35.32%	1.59%
		T	0.00%	67.86%	30.56%	1.59%
2014	S1	C	5.48%	92.14%	2.38%	0.00%
		T	12.14%	83.81%	4.05%	0.00%
	S2	C	8.33%	84.38%	6.25%	1.04%
		T	11.98%	78.13%	9.38%	0.52%
	S3	C	0.00%	70.53%	27.44%	2.03%
		T	0.20%	75.61%	23.37%	0.81%
	S4	C	0.00%	54.79%	29.68%	15.53%
		T	0.00%	63.24%	34.25%	2.51%
	S5	C	0.00%	50.23%	49.77%	0.00%
		T	1.39%	76.39%	18.29%	3.94%
	S6	C	0.00%	90.77%	9.23%	0.00%
		T	0.00%	92.79%	7.21%	0.00%

Table 5-7 shows that the treatment classrooms had more school hours with the RH levels below 40% than the control classrooms. Although in S6 (2014), the RH level in the treatment classroom was significantly higher than in the control classroom, 91% and 93% of school hours in the control and treatment classrooms respectively had the RH levels between 40% and 60%. 11 out of 20 classrooms had RH levels above 70% for less than 5% of school hours. Two out of 20 classrooms had RH levels above 70% for more than 5% of school hours. These were the treatment classroom in S3 (2013) and the control classroom in S4 (2014). High levels of RH in NZ classrooms are related to high levels of ambient RH during the winter months in NZ. Since all the participating schools were naturally ventilated buildings and connected directly to the ambient environment, open windows and doors can cause an increase in RH levels. High levels of RH were also related to the classroom layout. Although NZ classrooms typically have carpeted floors, an area of less than 5 m^2 of vinyl flooring was found in the classrooms located adjacent to the sink area. This area was observed to be frequently wet and this would release vapour into the air.

Levels of humidity ratio (HR, g/kg) in all classrooms were calculated and shown in Figure 5-9.

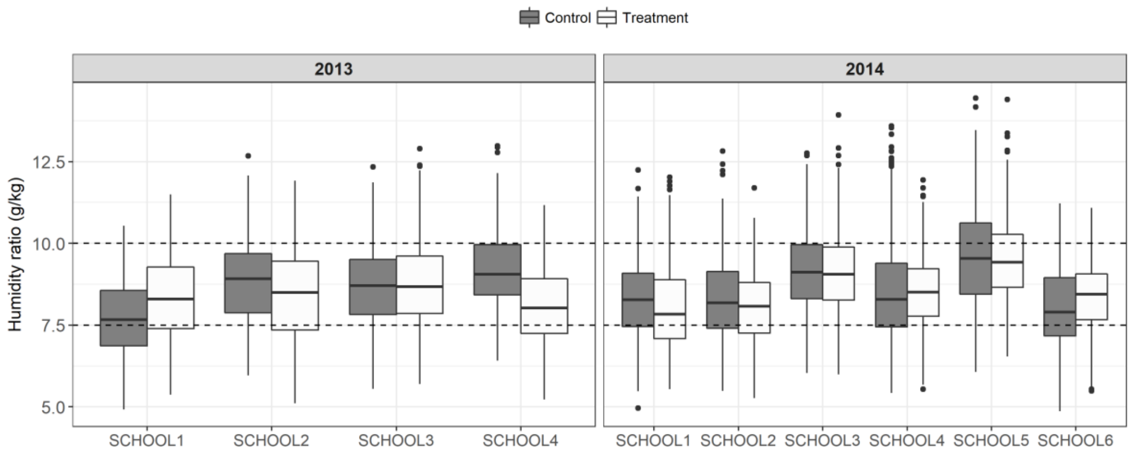

Figure 5-9 Humidity ratio (g/kg) levels in all schools in 2013 and in 2014

Hourly HR levels in control classrooms ranged from 4.9 g/kg to 14.4 g/kg, with a mean (SD) value of 8.7 (1.4) g/kg. In treatment classrooms, hourly HR levels were between 5.1 g/kg and 14.4 g/kg, with a mean (SD) value of 8.6 (1.3) g/kg. Both the mean and the median levels of HR in all classrooms were between 7.5 g/kg and 10.0 g/kg.

The mean levels of HR in all classrooms are shown in Table 5-9.

Table 5-9 Mean (standard deviation) and 95% confidence interval of humidity ratio (g/kg) in all classrooms in 2013 and 2014

Year	School (S)	Control classrooms	Treatment classrooms	Difference[1]	p
2013	S1	7.7 (1.2) [7.5–7.9]	8.3 (1.3) [8.2–8.5]	0.5 (0.7) [0.4–0.7]	< 0.01
	S2	8.9 (1.4) [8.7–9.1]	8.5 (1.5) [8.3–8.7]	-0.4 (0.7) [-0.5– -0.3]	0.01
	S3	8.7 (1.3) [8.5–8.8]	8.8 (1.3) [8.7–9.0]	0.2 (0.7) [0.1–0.3]	0.13
	S4	9.2 (1.3) [9.1–9.4]	8.1 (1.2) [8.0–8.3]	-1.1 (0.8) [-1.2– -1.0]	< 0.01
2014	S1	8.3 (1.3) [8.1–8.4]	8.0 (1.3) [7.9–8.2]	-0.2 (0.8) [-0.3– -0.1]	0.06
	S2	8.3 (1.3) [8.2–8.5]	8.1 (1.1) [8.0–8.2]	-0.2 (0.8) [-0.3– -0.1]	0.04
	S3	9.2 (1.3) [9.1–9.3]	9.1 (1.2) [9.0–9.2]	-0.1 (0.8) [-0.2– -0.1]	0.12
	S4	8.6 (1.6) [8.4–8.8]	8.5 (1.1) [8.4–8.6]	-0.1 (1.4) [-0.2–0.1]	0.42
	S5	9.6 (1.5) [9.4–9.7]	9.5 (1.2) [9.4–9.6]	-0.1 (1.3) [-0.2–0.0]	0.42
	S6	8.0 (1.2) [7.9–8.1]	8.4 (1.1) [8.2–8.5]	0.4 (0.8) [0.3–0.4]	< 0.01

[1] The humidity ratio difference between the treatment classroom and the control classroom.

Table 5-9 shows that, in 2013, the HR levels in the S1 treatment classroom were statistically significantly higher than in the S1 control classroom. However, the opposite results were obtained in S2 and S4, where the HR levels in the treatment classrooms were statistically significantly lower than in the control classrooms. In S3, there were no statistically significant differences in the HR levels between the control classroom and the treatment classroom.

In 2014, only in two (S2 and S6) out of six schools were the HR levels statistically significantly different between the control classrooms and the treatment classrooms. No statistically significant differences in HR levels between the control and treatment classrooms were found in the other schools. Levels of HR in classrooms are affected by students number (the main moisture source), classroom temperature, furniture and carpets. When the dew point temperature is reached, the indoor HR levels drop because of the condensation on different surfaces. However, when the classroom temperature increases and becomes higher than the dew point temperature, the HR levels rise as there are condensed moisture releasing back into the air (Rupp and Askew, 2017).

5.3.5 Exposure to comfort zone during school hours

The occupants were considered to be exposed to comfortable conditions when both the classroom temperature was in the range of 18°C to 24°C and the RH levels were in the range of 40% to 60%. This comfort zone threshold was used in an NZ home study (Boulic, 2012). Table 5-10 shows the percentage of school hours per day where the occupants were in the comfort zone in all the control and treatment classrooms in 2013 and in 2014.

Table 5-10 Percentage of school days where occupants were in the comfort zone in control and treatment classrooms in 2013 and 2014

Year	School (S)	Control classrooms	Treatment classrooms	Difference[1]
2013	S1	80.68%	78.79%	-1.89%
	S2	73.15%	37.04%	-36.11%
	S3	71.59%	69.70%	-1.89%
	S4	61.11%	59.52%	-1.59%
2014	S1	78.57%	74.29%	-4.29%
	S2	72.14%	67.19%	-4.95%
	S3	61.79%	67.28%	5.49%
	S4	43.84%	54.34%	10.50%
	S5	43.98%	52.31%	8.33%
	S6	81.76%	86.04%	4.28%

[1] The difference in percentage of school days where occupants were in the comfort zone between the treatment classroom and the control classroom.

Table 5-10 shows that the treatment classrooms experienced more than 50% of school hours exposed to conditions in the comfort zone, except for S2 during the winter in 2013. In 2013, the occupants had more school hours in the comfort zone in all control classrooms than in all treatment classrooms. This was most pronounced in S2, where the control classroom had 36% more time in the comfort zone. The distribution of the hourly averaged temperature, RH and calculated HR in the treatment classroom in S2 in 2013 is presented in a psychrometric chart in Figure 5-10. The comfort zone is highlighted. The psychrometric charts of all control classrooms and all treatment classrooms in both 2013 and 2014 are in Appendix D2.

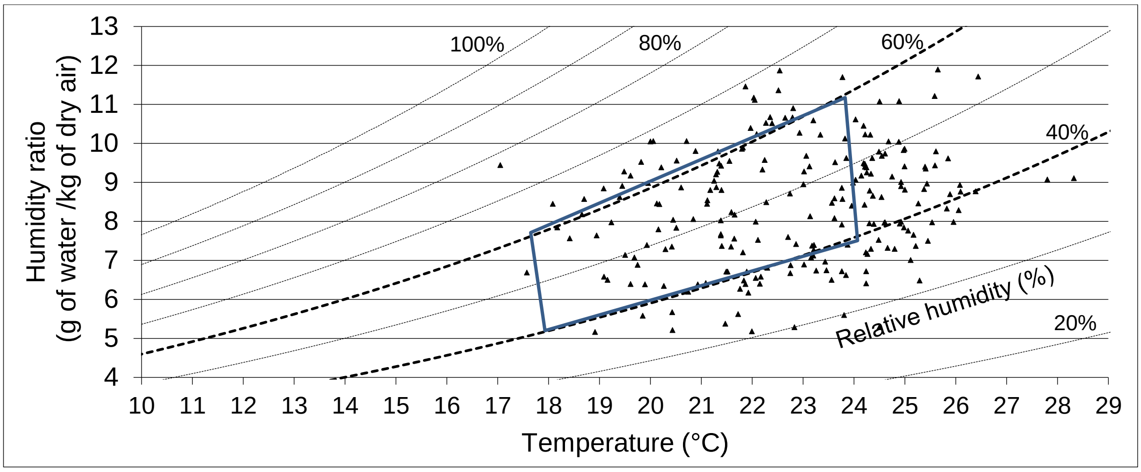

Figure 5-10 Hourly mean temperature (°C), relative humidity (%) and humidity ratio (g/kg) in the treatment classroom in School 2 in 2013

Figure 5-10 shows that, during the winter in 2013, overheating was the reason that the occupants in the S2 treatment classroom were outside the comfort zone. There were 34% of school hours with a temperature above 24 °C in S2 treatment classrooms in 2013. Overheating was also found in S1 and S3 treatment classrooms during the winter in 2013, where the occupants were exposed to a classroom temperature above 24 °C for 12% and 7% of school hours respectively. In 2013, occupants in treatment classrooms from S1, S2 and S3 experienced longer school hours with the temperature above 24 °C than occupants in the control classrooms. However, the ratio of the heater use in the treatment classrooms to the heater use in the control classrooms was all less than 1.0. Therefore, this temperature difference showed the space heating effects of the operation of the roof-mounted SAH.

In 2014, 4 out of the 6 treatment classrooms (S3 to S6) experienced more school hours (between 4% and 11%) in the comfort zone than the control classrooms. In S1, the occupants were exposed to RH levels below 40% for longer hours in the treatment classroom than in the control classroom (12% vs 6%), which caused the school hours in the comfort zone in the treatment classroom to be lower than in the control classroom (74% vs 79%). A similar dry classroom environment was also found in the treatment classroom in S2.

In S3, S4 and S5 (2014), the school hours when RH levels were above 60% in both the control classrooms and the treatment classrooms, were higher than the school hours with RH level below 40%. This result was consistent with the results presented in Table 5-8 (the percentage of school hours with different RH levels). In contrast to humidity problems in S1 to S5, S6 had problems with the temperature, so occupants were not in comfort conditions. In S6, the temperature was below 18 °C in both the control classroom and the treatment classroom for 9% and 7% of school hours per day. Overall, overheating and high RH levels prevented the classrooms from experiencing longer hours in the comfort zone during school hours.

Figure 5-11 shows the percentage of time in comfort zones in different schools in 2013.

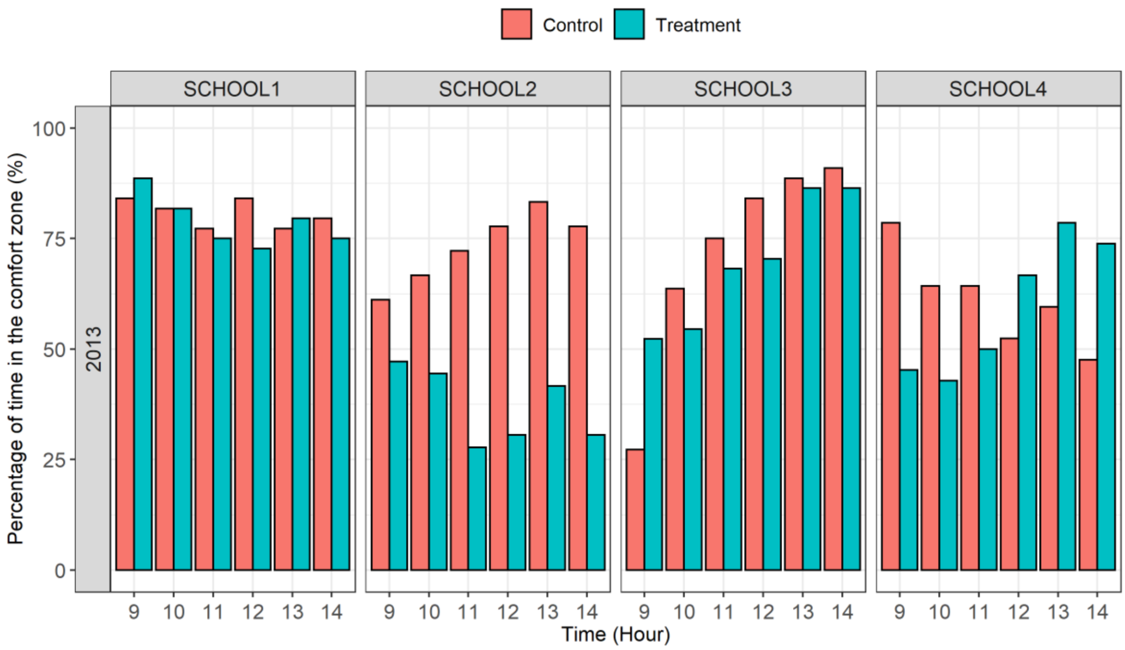

Figure 5-11 Percentage of time (%) in the comfort zone in different schools in 2013

In S1, the percentage of time in comfort conditions is close to being evenly distributed over the school hours, which is around 80%. In S2, the control classroom was with the lowest and the highest hourly comfort conditions at 9 am and 1 pm. However, in the treatment classroom, the lowest hourly comfort condition was obtained around noon. In S3, the hourly comfort zone exposure at 9 am was 50% higher in the treatment classroom than in the control classroom. However, a different result was found for S4.

Figure 5-12 shows the percentage of time in comfort zones in different schools in 2014.

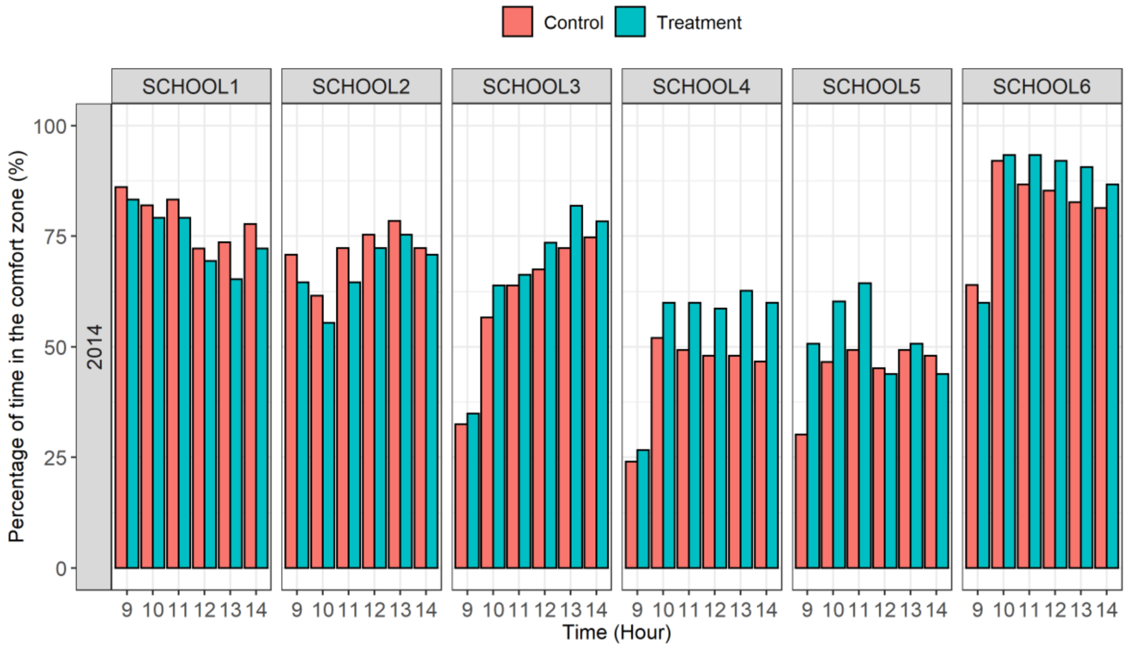

Figure 5-12 Percentage of time (%) in the comfort zone in different schools in 2014

In 2014, in 4 out of 6 schools (S3 to S6), in both the control and treatment classrooms, the hourly comfort zone exposure at 9 am was at least 20% lower than for the other school hours. In S3 and S4, during the full school day, the hourly comfort zone exposure in the treatment classrooms was higher than in the control classrooms. A similar result was obtained in S6, except for in the morning at 9 am. Overall, improving the comfort zone exposure at 9 am is needed.

5.3.6 Classroom carbon dioxide and ventilation rates during occupied school hours

Amongst all schools, the hourly CO_2 levels in the treatment classrooms ranged from 551 ppm to 4992 ppm, with a mean (SD) value of 1309 (619) ppm. In the control classrooms, the hourly CO_2 levels ranged from 550 ppm to 4830 ppm, with a mean (SD) value of 1405 (702) ppm. Results of the t test showed that CO_2 levels in the treatment classrooms were statistically significantly lower than in the control classrooms ($p < 0.01$), with a mean difference of 96 ppm.

Table 5-11 shows the mean levels of CO_2 in all classrooms.

Table 5-11 Mean (standard deviation) and 95% confidence interval of carbon dioxide (ppm) in control and treatment classrooms in 2013 and 2014

Year	School (S)	Control classrooms	Treatment classrooms	Difference[1]	p
2013	S1	741 (183) [710–772]	815 (259) [783–847]	119 (326) [64–175]	< 0.01
	S2	1016 (381) [963–1070]	954 (313) [909–998]	-68 (344) [-118– -17]	0.07
	S3	1317 (497) [1256–1377]	1376 (478) [1318–1434]	65 (357) [22–109]	0.13
	S4	1393 (463) [1335–1452]	1091 (356) [1045–1136]	-317 (471) [-377– -257]	< 0.01
2014	S1	1095 (447) [1051–1140]	1011 (404) [970–1053]	-101 (466) [-151– -51]	< 0.01
	S2	1083 (362) [1044–1121]	1007 (337) [972–1042]	-68 (362) [-107– -30]	0.01
	S3	1933 (892) [1853–2012]	1729 (701) [1667–1791]	-204 (648) [-262– -146]	< 0.01
	S4	1521 (592) [1465–1577]	1411 (473) [1366–1455]	-111 (700) [-178– -45]	< 0.01
	S5	1877 (845) [1796–1958]	1854 (783) [1779–1929]	-26 (860) [-108–56]	0.64
	S6	1175 (488) [1125–1225]	1208 (492) [1158–1257]	39 (477) [-11–89]	0.29

[1] The carbon dioxide difference between the treatment classroom and the control classroom.

In 5 out of 10 schools (50%), CO_2 levels in the treatment classrooms were statistically significantly lower than in the control classrooms. In both years, a positive result (CO_2 levels in treatment classrooms lower than in control classrooms) was found in S4. According to ASHRAE 62, an acceptable CO_2 level is under 1000 ppm. This was obtained in S1 (both the control and the treatment classrooms) and S2 (the treatment classroom) in 2013. In the other schools (S3 in 2013, S4 in 2013 and S1 to S6 in 2014), the mean school hours CO_2 levels were all above ASHRAE 62 recommended level. It was found that CO_2 levels in S3 and S5 were higher than in other schools.

The device used in this study had a maximum CO_2 detection limit of 5000 ppm. This maximum CO_2 level of 5000 ppm was found in S3 and S5. This data was checked and it confirmed that the high level of CO_2 reading was not caused by someone who had exhaled onto the CO_2 sensor, as CO_2 levels above 4800 ppm lasted from 0.8 hours to 1.7 hours in S3 and S5 in both the control and the treatment classrooms.

There are two reasons for the higher levels of CO_2 in S3. Firstly, S3 was built to the Dominion Basic Plan that consisted of a row of four classrooms, with a corridor built along the long axis of the classroom block. There was a cloakroom between the classroom main entrance door and outside. This meant the classroom only had two external walls. This design would limit the cross ventilation and the possible infiltration. Second, it was observed that there were thick curtains on the north side windows in the two classrooms from S3, which were always pulled across the windows during the winter to reduce the heat loss from the classroom. In combination, these factors reduced the fresh air coming into the classroom.

In terms of the CO_2 levels in S5, the small volume of the classroom and the high density of the occupants caused a high level of CO_2. The volume of the classroom in S5 was 175.8 m^3, which was smaller than the other classrooms where the volume was from 182.8 m^3 to 313.6 m^3. More importantly, the number of students in S5 in both the control classroom and the treatment classroom (mean 29 students per room) was higher than the other classrooms (mean 25 students per room). Additionally, the students in S5 classrooms were typically from 10 to 13 years old and older than in the other classrooms, who were 5 to 10 years old. The children aged from 10 to 13 years old generate higher levels of CO_2 than students aged between 5 and 10 years old, assuming students were at the same level of physical activities (Persily and de Jonge, 2017).

Based on the CO_2 threshold reported in ASHRAE 62 (ASHRAE, 2017), European Standard EN13779 (CEN, 2007), British guideline (BB101, 2018) and NZMoE document DQLS 2017 (Ministry of Education, 2017a), CO_2 levels were categorised into six ranges: < 800, [800–1000], (1000–1500], (1500–2000], (2000–3000] and (3000–5000] ppm. Figure 5-13 shows the distribution of CO_2 levels in all schools in 2013.

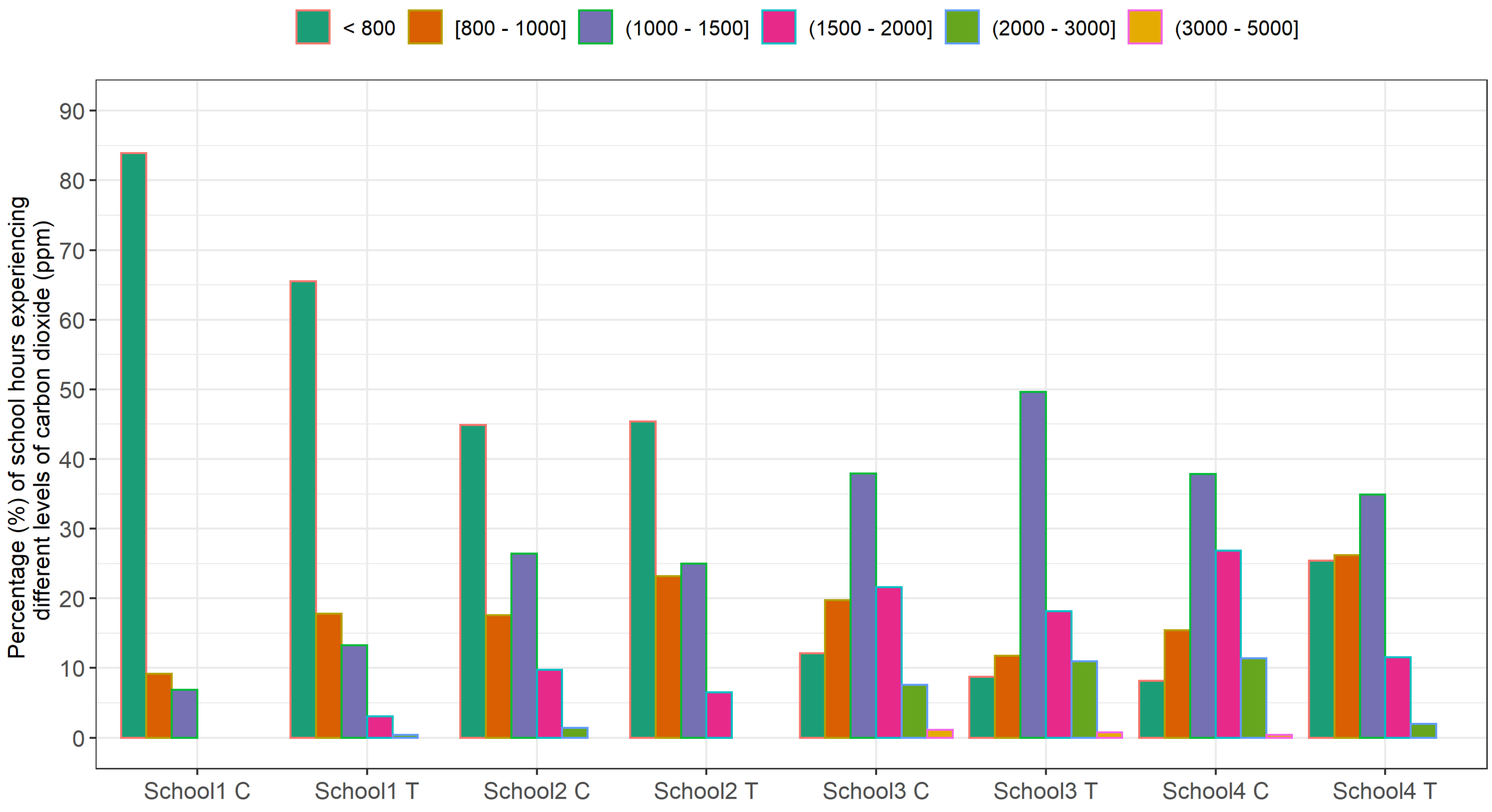

Figure 5-13 Percentage of school hours (%) in different levels of carbon dioxide in 2013

(C stands for the control classroom. T stands for the treatment classroom.)

Figure 5-13 shows that in S1 and S2, for more than 45% of school hours, the occupants in both the treatment classrooms and the control classrooms were exposed to levels of CO_2 below 800 ppm. There were 9% to 23% of school hours in the CO_2 range of 800 ppm to 1000 ppm. In S3 and S4, the percentage of school hours with a CO_2 level in the band between 1000 ppm and 1500 ppm was higher than for the other CO_2 ranges. In S4, the treatment classroom had a CO_2 level in the 1500 ppm–3000 ppm range for 25% fewer hours than in the control classroom (13% vs 38%). CO_2 levels between 3000 ppm and 5000 ppm were found in S3 and S4 in both the control and treatment classrooms. In S3, 80% of these high CO_2 values occurred in the morning at 10 am. In S4, the peak occurred at 11 am.

Figure 5-14 shows the distribution of CO_2 levels in all schools in 2014.

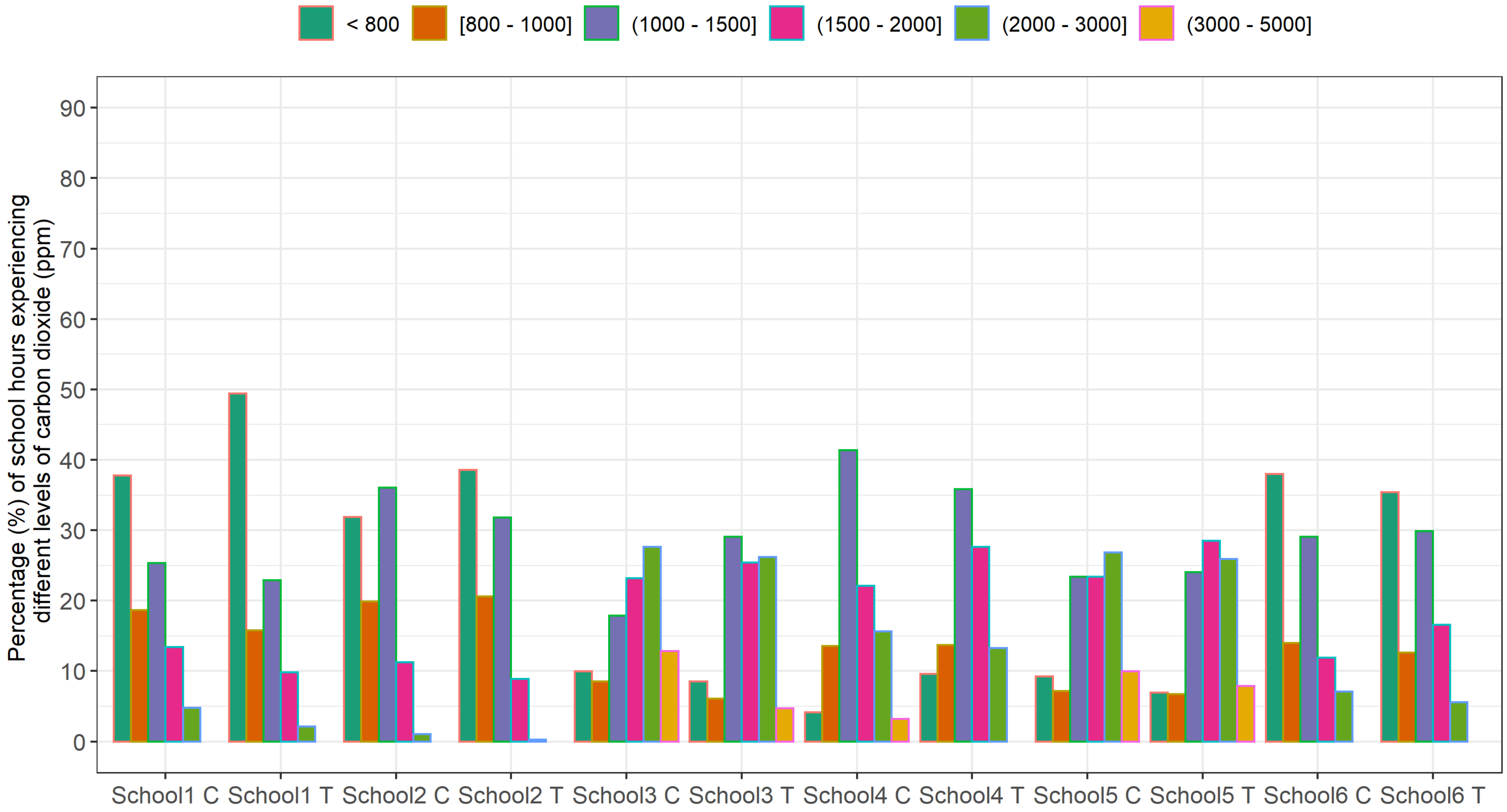

Figure 5-14 Percentage of school hours (%) in different levels of carbon dioxide in 2014

(C stands for the control classroom. T stands for the treatment classroom.)

Figure 5-14 showed the occupants in S1, S2 and S6 were exposed to CO_2 levels less than 800 ppm for 30% to 50% of school days, while the other three schools (S3, S4 and S5) had less than 10% of school hours where the CO_2 level was below 800 ppm. CO_2 levels between 3000 ppm and 5000 ppm were found in S3, S4 and S5, for a range of 3% to 13% of the school day. Importantly, for all these three schools, the percentage of school hours where the occupants were exposed to levels of CO_2 between 3000 ppm and 5000 ppm in treatment classrooms were lower than in control classrooms: 5% vs 13% in S3, 0% vs 3% in S4, and 8% vs 10% in S5. In S3 and S5, the CO_2 levels were between 2000 ppm and 3000 ppm in both control classrooms and treatment classrooms for about 25% of the school day. This figure was 16% and 13% in the S4 control and treatment classrooms. Comparing Figure 5-13 with Figure 5-14, the common results were that CO_2 levels in S1 and S2 were lower than in the other schools in both years. The CO_2 levels in S3 were higher than the other schools.

Table 5-12 shows the air changes per hour (ACH, h^{-1}) in both control and treatment classrooms in all schools in 2013 and 2014. The results include mean (SD) and 95% CI. The ACH was estimated using the tracer gas (CO_2) technique.

Table 5-12 Mean (standard deviation) and 95% confidence interval of air changes per hour (ACH, h^{-1}) in all classrooms in 2013 and 2014

Year	School (S)	Control classrooms	Treatment classrooms	Difference[1]	p
2013	S1	3.8 (1.6) [3.5–4.1]	3.5 (1.6) [3.3–3.7]	-0.6 (2.1) [-0.9– -0.2]	< 0.01
	S2	3.8 (2.3) [3.5–4.1]	4.4 (2.6) [4.0–4.8]	0.6 (2.5) [0.3–1.0]	0.02
	S3	1.7 (1.0) [1.6–1.9]	1.5 (0.9) [1.4–1.6]	-0.3 (0.7) [-0.3– -0.2]	< 0.01
	S4	1.3 (0.8) [1.2–1.4]	1.8 (1.0) [1.7–1.9]	0.6 (1.0) [0.5–0.7]	< 0.01
2014	S1	2.5 (1.6) [2.4–2.7]	2.8 (1.6) [2.6–2.9]	0.3 (2.1) [0.1–0.5]	0.03
	S2	3.2 (2.2) [3.0–3.5]	3.4 (2.1) [3.2–3.6]	0.1 (2.6) [-0.2–0.3]	0.74
	S3	1.3 (1.2) [1.2–1.4]	1.4 (1.2) [1.3–1.5]	0.1 (1.0) [0.0–0.2]	0.13
	S4	1.1 (0.7) [1.1–1.2]	1.3 (0.9) [1.2–1.4]	0.1 (1.0) [0.0–0.2]	0.01
	S5	2.1 (2.0) [1.9–2.3]	1.8 (1.4) [1.7–1.9]	-0.2 (2.1) [-0.4–0.0]	0.04
	S6	2.9 (2.1) [2.7–3.1]	2.7 (1.9) [2.5–2.9]	-0.2 (1.9) [-0.4–0.0]	0.13

[1] The air changes per hour (ACH, h^{-1}) difference between the treatment classroom and the control classroom.

In 2013, the mean ACH ranged from 1.5 h^{-1} to 4.4 h^{-1} in treatment classrooms and from 1.3 h^{-1} to 3.8 h^{-1} in control classrooms. Similar to the finding of CO_2 levels in each school, the ACH in the treatment classrooms in S2 and S4 were statistically significantly higher than in the control classrooms. The opposite results were obtained in S1 and S3.

In 2014, the mean ACH in treatment classrooms ranged from 1.3 h^{-1} to 3.4 h^{-1}, and it was from 1.1 h^{-1} to 3.2 h^{-1} in control classrooms. In 2 out of 6 schools (S1 and S4), the ACH levels in treatment classrooms were statistically significantly higher than in control classrooms. However, the contrasting result was obtained in S5, where the ACH level in the treatment classroom was statistically significantly lower than in the control classroom. The reason for this unexpected result was explained earlier in the CO_2 concentration section. It was the combination of the small volume of the classrooms and the high density of the occupants.

Across schools and years, in 4 out of 10 schools, the mean ACH levels were statistically significantly higher in the treatment classrooms than in the control classrooms. The difference of 0.6 (h^{-1}) was found in S1 and S4 in 2013. ACH levels in S3, S4 and S5 were lower than in S1, S2 and S6. The mean ACH levels in S3 and S4 were less than 2 h^{-1} in both control and treatment classrooms.

5.3.7 Discussion

The mean temperature in all classrooms (both control and treatment) ranged from 19.3 °C to 22.8 °C. This was within the WHO recommended temperature range (18–24 °C). The temperature result in this study was different from a previous NZ school study, which showed that for 9 out of 35 Wellington (NZ) primary classrooms, the mean temperature was below 18 °C, with a range of 13.4 °C to 17.7 °C during school hours (McIntosh, 2011). In contrast to the previous NZ school study, overheating was found in this study, as the indoor temperature levels in the S2 treatment classroom in 2013 and in the S5 treatment classroom in 2014 had temperatures between 24 °C and 28 °C for more than 25% of school hours, and even above 28 °C. To prevent overheating, adjustments to the SAH controller algorithm are required when the indoor temperature exceeds 24 °C.

All classrooms were within the acceptable RH range (between 40% and 60%) for more than half of the school day, with a range of 50% to 93%. McIntosh (2011) found an RH level above 60% for more than 50% of the school days in NZ classrooms during the winter. Differences in RH levels between the present study and the previous one might be explained by the difference in the classroom temperature. In the present study, the mean classroom temperature was between 18 °C and 24 °C (WHO recommendation) in all classrooms, while McIntosh (2011) found that 14 out of 35 Wellington (NZ) primary classrooms had temperature levels below 18 °C for more than 50% of the school day.

High levels of CO_2 in classrooms indicate the inadequate ventilation. Inadequate ventilation was also reported in overseas naturally ventilated classrooms. Canha *et al.* (2016) reported that the median weekly CO_2 concentration was 1250 ppm (Q_1–Q_3: 970–1670 ppm) from 51 French classrooms (17 schools). Batterman *et al.* (2017) found that, in 147 classrooms of 37 schools, 90% of the median level of the CO_2 during the school days was above 2000 ppm. Fisk (2017) summarised the ventilation rate during occupied school hours in 3494 classrooms from 1242 schools in 14 countries. These samples consisted of 550 naturally ventilated classrooms, 1182 mechanically ventilated classrooms, 866 mixed ventilated classrooms and 731 classrooms where the types of ventilation were not specified. The remaining 165 classrooms were from 62 naturally ventilated and two mechanically ventilated schools. This review showed maximum CO_2 concentrations in these classrooms ranged from 3000 ppm to 6000 ppm during school hours. The average CO_2 concentration during the school hours exceeded 1000 ppm in the majority of schools, with the maximum levels between 1400 ppm and 5200 ppm. Overall, Fisk (2017) reported that inadequate ventilation rates in school buildings are a worldwide issue.

NZMoE requires a minimum ACH of 4 h^{-1} during the winter (Ministry of Education, 2017a). The treatment classroom in S2 in 2013 was the only classroom which met this ventilation requirement, with a mean ACH of 4.4 h^{-1} (95% CI: 4.0–4.8). In other classrooms, the mean ACH ranged from 1.1 h^{-1} to 3.8 h^{-1}. Across all these classrooms and both years, the occupants were exposed to ACH above 4 h^{-1} for 15% of school hours. Of this, 46% and 54% occurred in the control classroom and in the treatment classroom respectively. This means operating the SAH played a positive role in increasing the ventilation rate in the classrooms, although there was not sufficient airflow to satisfy the ventilation requirements.

The study has potential limitations. First, windows and doors in control and treatment classrooms from the same school were assumed to have the same open-closed conditions. However, according to the observational data during the fieldwork, this assumption may not be true for some schools. Second, the ventilation rate was estimated using CO_2 as a tracer gas. In the calculation, the source strength number (the student number) was the enrolment number in each classroom, rather than in the attendance report or the class curriculum. This might potentially overestimate the ventilation rate. Therefore, in future, monitoring open and close conditions of windows and doors would be needed, though there are technical difficulties with monitoring the airflow through a window opening. It would also be interesting to investigate the classroom ventilation rate using different tracer gases, such as sulphur hexafluoride to remove the effects of occupants number on the ventilation rate calculation.

5.4 Conclusion

This study investigated the effects of operating a roof-mounted SAH on temperature and ventilation rate in NZ primary schools, based on the measurement of temperature and CO_2. Improvements to classroom temperature and ventilation have been made with the intervention, but this improvement is not sufficient to make the ventilation rate in all treatment classrooms meet the requirement. Future research needs to investigate the impact of operating a SAH on school ventilation and temperature with consideration of occupant behaviour and optimising the SAH to supply a higher air flow rate at lower outlet air temperature. Further fieldwork should be undertaken in a larger number of schools which were built with different construction characteristics and located in different NZ cities, to investigate effects of operating a SAH on the IAQ in schools.

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6 General discussion

An acceptable IAQ in the school environment is important to student decision-making, respiratory symptoms, absenteeism rate and academic performance (Annesi-Maesano *et al.*, 2012; Apte *et al.*, 2000; Bakó-Biró *et al.*, 2007; Gaihre *et al.*, 2014; Haverinen-Shaughnessy *et al.*, 2011; Satish *et al.*, 2012). However, the NZ school environment in winter fails to meet the levels recommended by different organisations. What is more, the capped budget policy in NZ schools makes it impossible to use the traditional approach to improve the school environment in NZ in winter. To provide children with a healthy learning environment, this research investigated the effect of operating a roof-mounted SAH on IAQ in NZ schools in winter.

This thesis investigated the performance of a SAH (both the experimental and fieldwork performance) and the change of classroom environment (temperature, humidity, CO_2 and ventilation rate) with the intervention of operating the SAH. In chapters 3, 4 and 5, results of the SAH performance and the impacts of operating the SAH on the classroom environment were presented. The purpose of this discussion is to place the research outcomes in the international context.

The first section of this chapter discusses the experimental and fieldwork performance of this SAH. The second section discusses the classroom environment (temperature, humidity, CO_2 and ventilation rate) from two aspects: the levels of these environment parameters in classrooms, and the changes in these parameters with the operation of the SAH. The third section discusses the ventilation performance of the SAH compared with the method proposed by other researchers, as reviewed in Section 2.5.3. The last section presents the summary.

6.1 Solar air heater performance

Studies have shown the contribution of operating solar thermal systems to the energy supply (Mauthner *et al.*, 2016). This results in an increase in research investigating solar thermal collectors and their applications (Kalogirou, 2004). In

2010, NZMoE introduced the capped budget[1] for purchased energy (Ministry of Education, 2010). This means an alternative and affordable approach is needed to produce the energy for NZ primary schools. The free solar energy could be the alternative solution, as school hours in NZ, from 9 am to 3 pm, are well aligned with the optimum solar radiation. In this context, this study is conducted with the aim to investigate the change in classroom temperature, humidity, CO_2 and ventilation rate when a roof-mounted SAH is operated. The subsequent sections discuss the research findings of the SAH experimental performance and fieldwork performance.

6.1.1 Solar air heater experimental performance

The performance of a SAH was associated with the design components (i.e. the cover, flow types and the absorber layer) and the operational conditions (i.e. the air mass flow rate and the weather conditions). The thermal performance of SAHs with different design components and operating conditions was discussed in Chapter 3. Among these reported SAHs, a maximum thermal efficiency of 86% was found. From the literature, no study has been found to investigate the performance of a SAH with the design configuration similar to the SAH in this study.

In Chapter 3, the result of the SAH experimental performance was presented and discussed. In summary, the SAH was operated under the mean (SD) air mass flow rate between 0.022 (0.001) kg/s and 0.056 (0.005) kg/s. Thermal efficiency and effective efficiency were calculated. The mean (SD) thermal efficiency of the SAH increased from 34 (5) % at the airflow between 0.021 kg/s and 0.023 kg/s, to 47 (6) % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, to 71 (4) % at the airflow between 0.054 kg/s and 0.058 kg/s. The maximum thermal efficiency of 75% was obtained at the airflow of 0.057 kg/s. The mean (SD) effective efficiency of the SAH was 32 (5) % at the airflow between 0.021 kg/s and 0.023 kg/s, 42 (6) % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, and 46 (11) % at the airflow between 0.054 kg/s and 0.058 kg/s.

[1] New Zealand Ministry of Education changed the heat, light and water funding to a fixed amount for each school, based on the school's energy costs over the previous three years.

The comparison of the SAH efficiency with SAHs reported in the literature was presented in Chapter 3. In short, the efficiency of this SAH was higher than the efficiency of other SAHs reported in the literature, when it was operated at an air mass flow rate of 0.057 kg/s. However, when this SAH was operated at 50% and 75% of the maximum fan capacity, its efficiency was lower than the efficiency of SAHs reported in the literature that were operated in a similar manner.

6.1.2 Solar air heater fieldwork performance

In NZ, school hours are generally from 9 am to 3 pm, and are closely aligned with the optimum solar radiation (Jaquiery, 2018). Jaques *et al.* (2010) conducted one study to investigate the solar wall performance in schools in NZ. The solar wall system was reported to be installed in Canadian schools for the purpose of ventilation and space heating (Chen, 2013). These studies agreed that operating a solar wall brought the heated air into the indoor environment. The disadvantage of the solar wall (shading, influenced by the wall thermal resistance) can be overcome by the roof-mounted SAHs. However, there are limited studies to investigate SAHs performance when it was roof-mounted and operated in schools. Therefore, a two-year fieldwork was conducted to investigate the space heating and ventilation performance of a roof-mounted SAH. This study was carried out with the aim of increasing the temperature and ventilation rate while reducing energy use in schools. The result of the SAH fieldwork performance was presented in Chapter 4.

Results of this fieldwork study are similar to (Chen, 2013) and (Jaques *et al.*, 2010), where the temperature rise (temperature difference between the outlet air and the inlet air) correspond with the solar radiation. The wind speed negatively impacts the temperature rise; the stronger the wind, the more wind chill was experienced by the SAH. The indoor temperature influences the measurements of the SAH outlet air temperature. A regression model was built to estimate the SAH performance in other NZ cities. It is estimated that the results of this study can be generated in other locations where the climate conditions are similar to NZ. This means the operation of a SAH can also be a supplement to the space heating in most other countries. Regarding the SAH ventilation performance, the results of this study clearly showed the inefficiencies of operating a SAH in achieving an acceptable ventilation rate. The volumetric flow rate of the SAH ranged from 25.0 m^3/h to 52.8 m^3/h, with a mean (SD) value of 34 (12.9) m^3/h, in the two-year fieldwork. This was 25 times lower than NZMoE required ventilation rate. Therefore, operating the SAH was a supplemental way to increase the ventilation rate in schools. It was not enough to provide adequate ventilation to the classroom by using only the SAH.

The reviewed studies did not report the ventilation performance of the solar collectors. None of those above-mentioned studies reported the SAH outlet air volumetric flow rate, which means the SAH ventilation result of this study was unable to be proved or disapproved by the literature. This study brings out that optimising the SAH ventilation performance for the school environment is needed. The ventilation performance can be improved via customising the fan, such as enlarging the fan capacity; or by customised design of a SAH for the school environment.

6.2 Classroom environment

The classroom environment played a vital role in students respiratory health, their attendance and their learning outcomes (Annesi-Maesano *et al.*, 2012; Apte *et al.*, 2000; Bakó-Biró *et al.*, 2007; Gaihre *et al.*, 2014; Haverinen-Shaughnessy *et al.*, 2011; Satish *et al.*, 2012). The requirement for the temperature, humidity and CO_2 in classrooms has been reviewed in Section 2.4. The levels of these three parameters in both local and international schools in winter have also been reviewed in Section 2.4. Literatures showed the IAQ in NZ schools in winter failed to meet the requirement (Bassett *et al.*, 1999; Cutler-Welsh, 2006; McIntosh, 2011). Additionally, NZMoE introduced the capped budget for purchased energy in NZ schools in 2010. Therefore, a study to improve the classroom IAQ with the use of SAHs in winter was conducted.

Results of this study showed that the IAQ in NZ schools in winter still unable to met the requirement. Low levels of ventilation rate were found in almost all monitored classrooms. In all control classrooms, the ventilation rate failed to meet the ASHRAE recommendation. Only in one treatment classroom, a mean ACH of 4 h^{-1} was achieved. The results are similar to other international research where the substandard IAQ has been found in primary schools in winter (Csobod *et al.*, 2014). However, compared with the existing NZ school studies, this study found the overheating problems in NZ classrooms. For 25% and 34% of school hours, the temperature above 24 °C was obtained in two treatment classrooms. Heater use in all classrooms was monitored, which enabled the discovery of reasons for the overheating (heater use or contribution from the operation of the SAH). The subsequent sections discuss the research findings of the classroom environment (temperature, humidity, CO_2 and ventilation rate).

6.2.1 Classroom temperature and humidity levels

There are a large number of studies reporting levels of temperature and humidity in primary schools in winter (see Table 2-5). Temperature and RH levels found in this study were shown in Chapter 5. In this study, a mean temperature from 19.3 °C to 22.8 °C was found in all classrooms (including all control and treatment classrooms), which was within the WHO recommendation (between 18 °C and 24 °C). As shown in Table 2-5, the temperature levels below 18 °C were found in 30 naturally ventilated Chinese (Shanghai) classrooms (Mi *et al.*, 2006). However, different results were reported by Madureira, Paciencia, Rufo*, et al.* (2015), Shendell, Winer*, et al.* (2004) and Marks *et al.* (2010), where a mean temperature between 20.1 °C and 20.9 °C was reported in 20 Porto, 12 Los Angeles and 22 New South Wales schools. However, the heater use in these studies was not presented regardless of its impact on the classroom temperature.

In all participating classrooms, between 50% and 93% of school hours had the recommended RH levels (between 40% and 60%). This is in line with the classroom temperature levels. As pointed out earlier, compared to the previous NZ school studies, classrooms were found to be warmer. RH levels were within the recommended levels, meaning the environment is unlikely to result in the growth of mould and other bio-pollutants. Consequently, the students' health and the school attendance would be positively beneficial (Borras-Santos *et al.*, 2013).

In this study, it was calculated that for 37% to 86% of school hours the students were in the comfort zone (temperature from 18 °C to 24 °C and RH from 40% to 60%). The time of the comfort zone exposure is associated with the heater use, as in some schools the low comfort exposure is caused by the overheating. Studies reported in the literature summarized the temperature and RH levels in schools only. None of them reported the percentage of time that students were exposed to the recommended temperature and RH levels. None of them reported the time that students were exposed to the comfort zone, either.

6.2.2 Carbon dioxide and ventilation rates

Table 2-6 shows the guideline for CO_2 and ventilation rate in schools teaching and learning spaces. This study found 85% investigating classrooms where the mean CO_2 level exceeded 1000 ppm during school hours. In 3 out of 6 schools, CO_2 levels between 3000 ppm and 5000 ppm were obtained, ranging from 3% to 13% of school hours. This result is similar to previous NZ studies. McIntosh (2011) found a mean CO_2 level above 1000 ppm in 13 out of 35 NZ classrooms for more than 50% (between 51% and 85%) of school hours. The mean CO_2 level above 1000 ppm during school hours was also found in 4 out of 5 Christchurch (NZ) classrooms (Cutler-Welsh, 2006).

High levels of CO_2 are in line with results reported in international studies. In a study involving 30 naturally ventilated classrooms from 10 schools located in Shanghai, China, 55% of the classrooms had a mean CO_2 concentration above 1000 ppm (Mi *et al.*, 2006). Madureira, Paciencia, Pereira*, et al.* (2015) reported a mean CO_2 level of 1669 ppm in 73 classrooms from 20 naturally ventilated schools in Porto Portugal, where 85% of the classrooms had a median CO_2 level above 1000 ppm. Stabile *et al.* (2017) reported median CO_2 levels in the 1400–3000 ppm range for five naturally ventilated schools in Italy. Canha *et al.* (2016) reported mean CO_2 levels of 1290 ppm for 50 classrooms in France (median = 1250 ppm, maximum = 2220 ppm). Similar to the findings of these above-mentioned studies, the result of SINPHONE (Schools Indoor Pollution & Health Observatory Network in Europe) study confirmed the inadequate ventilation rate in European schools (Csobod *et al.*, 2014), where the mean and median CO_2 levels of 1433 ppm and 1257 ppm were found in 114 primary schools (340 classrooms in total) from 54 cities in 23 European countries. In addition, results of review studies conducted by Chatzidiakou *et al.* (2012) and Fisk (2017) are consistent with the high levels of CO_2 reported in these studies in the school environment.

However, compared with high levels of CO_2 found from these studies, the different results were obtained in mechanically ventilated schools. In a study involving two mechanically ventilated schools in the UK, the mean CO_2 levels of 672 ppm and 907 ppm were reported (Mahyuddin *et al.*, 2013). Kim *et al.* (2007) reported a mean CO_2 level of 815 ppm in 22 mechanically ventilated schools in Uppsala City, Sweden. An acceptable ventilation rate (NZMoE recommendation, 4 h^{-1}) was achieved in one treatment classroom in this study, with a mean ACH of 4.4 h^{-1} (95% CI: 4.0–4.8 h^{-1}). This means operating the SAH contributed to the classroom ventilation, though there was not sufficient air flow to achieve the required ventilation rate in all participating classrooms.

6.3 Performance of the intervention

Most previous studies on increasing classroom ventilation rates reported the ventilation rate change only. There have been limited studies reporting the temperature change. However, this study suggests that operating a SAH in schools can lead to positive changes in the temperature. During the unoccupied school hours, when there was no heater used in all classrooms, a mean temperature difference of 0.6 °C (95% CI: 0.5–0.7 °C) between the treatment and the control classrooms was found. During the occupied school hours, when the heater use was the same for the control and treatment classrooms, the temperature levels were 0.5 °C higher in the treatment classrooms than in the control classrooms; When temperatures in the control classrooms and in the treatment classrooms were the same, the heater use in treatment classrooms was 27% less than in control classrooms.

In contrast to previous studies (Mysen *et al.*, 2005) and (Bakó-Biró *et al.*, 2012), which brought the ambient air into the classrooms directly without the preheating, in the present study at least 62.5% of the air being brought into the classroom with the temperature above 18 °C, which avoided the deterioration of the classroom temperature due to the supply of the ambient cold air (Mysen *et al.*, 2005). Only in one treatment classroom, a mean ACH above 4 h^{-1} (NZMoE recommendation) was achieved. This result is in line with the findings from some ventilation intervention studies (Geelen *et al.*, 2008), where the ventilation rate in classrooms was increased; however, CO_2 levels were not below 1000 ppm (NZ Standard recommendation) for all the school hours.

This result is in contrast to the intervention study, which was driven by the CO_2 concentrations. Rosbach *et al.* (2013) reported a mean CO_2 level of 841 ppm (minimum–maximum: 743–925 ppm) and 975 ppm (minimum–maximum: 887–1077 ppm) in classrooms with the operation of a custom-designed CO_2 controlled mechanical ventilation system, when the indoor CO_2 targeted levels were set at 800 ppm and 1200 ppm respectively. Gao *et al.* (2014) reported a mean CO_2 level of 942 ppm (SD = 185 ppm) in classrooms with automatically openable windows and an exhaust fan, and 757 ppm (SD = 147 ppm) in classrooms with a balanced mechanical ventilation system respectively. These results indicate that ventilation approaches controlled by the CO_2 concentration work better. However, the high capital cost and operation cost are beyond the school's budget in most instances.

Low cost approaches to increase the ventilation rate in schools are reported. These include providing advice on the occupant's behaviours (Geelen *et al.*, 2008), providing a strategy for manually using windows (Stabile *et al.*, 2017) and using the roof-mounted split-duct windcatcher (Jones *et al.*, 2012). All these studies showed the insufficient ventilation rate in classrooms if the air was supplied only by the operation of these means. In future, a temperature compensated CO_2 set-point fan is recommended to remove the overheating and overcome the inadequate ventilation in the classrooms. Increasing the fan capacity is also another way to increase the volumetric flow rate of the SAH outlet air.

6.4 Summary

This chapter discussed the results of this study, in the aspects of the SAH experimental and fieldwork performance, the classroom environment, and the intervention performance (operating a SAH in the school environment). The discussion reveals the positive change in temperatures in NZ classrooms in winter. As compared with previous NZ school studies, all participating classrooms had their mean temperature within the WHO recommendation. However, high levels of CO_2 and low levels of ventilation rate were still a problem in NZ and international schools.

The operation of a SAH played positive roles in increasing the ventilation rate in schools. However, it was not sufficient to achieve the acceptable ventilation rate if this was the only means to ventilate the classroom. Other low cost ventilation approaches have the similar weakness. In contrast, ventilation approaches controlled by the CO_2 concentration worked better. The next chapter presents the conclusions and recommendations, including the contribution, the limitations and the suggestion for future research.

7 Conclusions and Recommendation

An acceptable IAQ in the school environment is essential for the student health and academic performance. A number of studies suggest temperature, humidity and ventilation in NZ primary schools are unable to meet WHO and ASHRAE recommendations. This study investigated the change in the classroom temperature, humidity, CO_2 and ventilation rate from when a SAH was operating (the treatment classroom) and not operating (the control classroom). Three journal papers have been written (drafted) to report the results. The experimental performance (Objective 1, Chapter 3) and fieldwork performance (Objective 2, Chapter 4) of the SAH were investigated. Changes in the classroom temperature, humidity, CO_2 and ventilation rate were reported (Objective 3, Chapter 5). The results showed positive changes from operating the roof-mounted SAH on the temperature and ventilation in NZ schools in winter.

7.1 Original contribution

Previous studies on IAQ in NZ primary schools focused on monitoring the level of temperature and CO_2 and found classrooms were cold and underventilated during the winter months. Although NZBC Clause G4 Ventilation requires the area of openable windows in classrooms is in excess of 5% of the floor area to achieve sufficient ventilation, only less than 40% of teachers open windows during their teaching in winter. Previous NZ studies have not trialled a solution to improve the unacceptable IAQ and this is a significant research gap.

This study identified that the school hours in NZ are closely aligned with the optimum solar radiation and classrooms lend themselves to heat from solar energy. Thus, a project was undertaken to investigate if operating a roof-mounted SAH could improve the classroom temperature and ventilation during the winter.

The performance of SAHs has been investigated in other studies. The majority of these studies on SAHs have concentrated on modifying the configuration of SAHs to increase the energy conversion. Field testing of SAHs in the real world conditions is underresearched, and this is the second research gap identified.

This study addressed these two research gaps, as applied a roof-mounted SAH to NZ school buildings. This is the first study that integrated them, to investigate the change in the classroom temperature, humidity, CO_2 and ventilation rate from when the SAH was operating (the treatment classroom) and not operating (the control classroom), over two winters.

This study was carried out in NZ. However, the results of this SAH fieldwork performance are applicable to other locations where the climate conditions are similar to NZ. This means the operation of a SAH can also be a supplementary way of providing ventilation in many other countries.

7.2 Findings derived from the study objectives

This study aimed to investigate if operating a roof-mounted SAH could improve the classroom temperature and ventilation during the winter. Three research objectives were developed to achieve this overarching aim. This section describes the findings derived from each of the research objectives.

First Objective: The first objective was to investigate the SAH experimental performance, when it was operated under different air mass flow rates. Nine days experiment were carried out to operate the SAH at 50%, 75% and 100% of the maximum fan capacity respectively. During the experiment, all parameters needed to calculate the SAH efficiency were monitored. The SAH efficiency in the experimental study was calculated according to the equation.

Findings: The efficiency of this SAH was higher than the efficiency of other SAHs reported in the literature, when it was operated at an air mass flow rate of 0.057 kg/s (100% of the maximum fan capacity). However, when this SAH was operated at 50% and 75% the maximum fan capacity, its efficiency was lower than the efficiency of SAHs reported in the literature that were operated in a similar manner.

Second Objective: The second objective was to investigate the SAH fieldwork performance, when it was roof-mounted and operated in PN schools. The data collected from the two years fieldwork and the SAH experimental study together achieved this research objective.

Findings: The mean (SD) temperature and volumetric flow rate of the SAH outlet air was 28.9 (10.6) °C and 34.0 (12.9) m^3/h respectively. The mean (SD) efficiency of the SAH was 16 (11) %. For every 100 W/m^2 increase in the solar radiation, the outlet air temperature dropped 2.8 °C between it was measured in the duct 0.5 m and 5.0 m from the SAH panel. Operating a SAH was a useful supplement to the heating and ventilation of the classroom, but on its own was insufficient to meet NZMoE required ventilation rate. Future research should focus on increasing the volumetric flow rate and keeping the outlet air temperature around 18 °C. This could be achieved by either changing the setting of the fan controller or enlarging the fan capacity. Optimising the length of the outlet air duct to minimise the temperature drop within the duct is also needed.

Third Objective: The third objective was to investigate the change in the classroom temperature, humidity, CO_2 and ventilation rate from when the SAH was operating and not operating. The changes were the differences in levels of these IAQ parameters between treatment classrooms (SAH installed and operated) and control classrooms (SAH installed but not operated). A two-year fieldwork investigation was conducted to achieve this research objective with the monitoring of real-time levels of temperature, RH, CO_2 and heater use in all participating classrooms.

Findings: With operating the roof-mounted SAH, during the unoccupied school hours, mean temperature differences between treatment and control classrooms ranged from -0.7 °C to 3.0 °C, with the mean value of 0.6 °C (95% CI: 0.5–0.7) During the occupied school hours, temperatures in treatment classrooms were on average 0.5 °C higher than in control classrooms when both control and treatment classrooms had the same heater use. When the control and treatment classrooms had the same temperature, the heater use in treatment classrooms was 73% of the heater use in control classrooms.

Across all schools, CO_2 levels in the treatment classrooms were 96 ppm lower than in the control classrooms. Only in one treatment classroom was the ACH above 4 h^{-1}. Overall, operating a roof-mounted SAH played a positive role in increasing classroom temperature and ventilation rate. However, there was not sufficient airflow to satisfy the ventilation requirements.

7.3 Limitations of the study

1) In the first year fieldwork (2013), due to technical constraints, installing SAHs in primary schools took longer than anticipated. This delayed the commencement of the fieldwork to late July rather than May.

2) Windows and doors in control and treatment classrooms from the same school were assumed to have the same open-closed conditions. However, according to the observational data during the fieldwork, this assumption may not be true for some schools. The analysis of the ventilation result would be beneficial if the windows and doors open-closed conditions and the airflow through these windows and doors were monitored.

3) The ventilation rate was estimated using CO_2 as a tracer gas. In the calculation, the source strength number (the student number) was the enrolment number in each classroom, rather than in the attendance report or the class curriculum. This might potentially overestimate the ventilation rate if there were children absent or the classroom was not occupied sporadically, such as during the physical education lesson. This effect was assumed to be randomised.

4) This study would benefit from adding a survey to include qualitative aspects such as the teachers and students satisfaction of the classroom environment with operating the SAH, and if operating the SAH has any positive or adverse impacts on their learning environment, i.e. if operating the SAH improved the odours in the classrooms or caused any noise to the learning environment.

5) Life cycle assessment of the SAH which evaluates the environmental impacts of SAH components over a long-term was not covered. By conducting the life cycle assessment of this SAH, a comprehensive view of the SAH environmental impacts will be presented.

6) Operating a SAH to heat and ventilate the classroom will reduce the consumption of traditional energy, which reduces the emission of the greenhouse gas (GHG). Consequently, this contributes to the achievement of net zero carbon goals that have been announced by the government. However, the decrease in the GHG resulted from operating the SAH was not calculated in this study.

7) The cost benefit analysis is not included in the scope of this study, because the SAH was installed in two classrooms in each participating school, rather than the entire school. The energy use was monitored for the entire school rather than at the classroom level. Besides, the energy end use in schools was not monitored. It is therefore difficult to calculate the benefit of operating the SAH from the energy bill. Additionally, the classroom environment has been improved with the operation of the SAH. However, the benefits of the improved classroom environment on the student health and the academic performance were not monitored. So, it is not possible to carry out a full cost benefit analysis based on the data monitored in this study.

7.4 Suggestions for future research

1) This study shows the positive influence of using a SAH on the classroom temperature. In both years, among all schools, the mean (SD) outlet air temperature was 28.9 (10.6) °C. For at least 78.4% of school hours the outlet air temperature was above 18 °C. However, the volumetric flow rate of the outlet air was less than the required levels of classroom ventilation to be acceptable. It would be interesting to customise performances of the SAH for schools, such as keeping the outlet air temperature around 18 °C and maximising the outlet air volumetric flow rate.

2) This study reveals that if the SAH is to become the primary source of ventilation in classrooms, to achieve the acceptable ventilation rate (4 h^{-1} ACH), a SAH of at least 29.1 m^2 is required, given the solar radiation was 300 W/m^2 and the efficiency of the SAH was 20%. This is close to 60% of

the full sun-facing roof of the classroom building, assuming classrooms have a roof length of 10 m and the sun-facing (north) width of 5 m. It would be interesting to investigate if operating the SAH to heat and ventilate classrooms is better than investing in a solar photovoltaic panel which generates the electricity to power the heating and ventilation systems.

3) This study shows the impacts of operating a roof-mounted SAH on the classroom temperature and ventilation. School buildings participated in this study were all constructed before NZ insulation requirements came into action. Since the insulation conditions and the construction materials influence building heat loss, it would be interesting to investigate the impacts of operating a SAH in a recently built school.

4) This study investigated the ventilation rate in classrooms, with CO_2 as the tracer gas. The more expensive the tracer gas, the more accurate the result is. It would be interesting to investigate the difference in the ventilation rate that is estimated using different tracer gases.

5) This study promotes a sustainable approach to improve the temperature and ventilation rate in classrooms. It assumes the performance of the SAH in PN could be at the medium level compared to NZ as a whole. However, given the difference in school construction characteristics, the changes in the classroom temperature and ventilation rate with the operation of a SAH would not be the same. Therefore, it would be interesting to carry out a nationwide study to investigate the effect of operating a SAH on the temperature and ventilation in classrooms in winter.

6) This study investigated the changes in temperature, humidity, CO_2 and ventilation rate in classrooms from when a roof-mounted SAH was operating and not operating. Other pollutants, such as formaldehyde, VOCs, PM and mould, were not monitored. The occupant satisfaction with the classroom environment after operating the SAH was not included. It would be interesting to conduct a study monitoring the changes in different pollutant levels and occupant satisfaction with the operation of the SAH.

7) It would be interesting to carry out a study to calculate the reduction in GHG emission, to conduct the cost benefit analysis, and to evaluate the life cycle assessment of operating the SAH. Besides, a study to compare the ventilation performance of different ventilation means would be interesting.

7.5 Significance of the findings and implications

1) At least 78.4% of school hours had an outlet air temperature above 18 °C. With the same levels heater use, temperature in the treatment classrooms was on average 0.5 °C higher than in the control classrooms. As heating accounts for two-thirds of the energy use in schools, replacing purchased energy with solar collectors would reduce the need for purchased energy. This would reduce GHG emissions and increase classroom ventilation rates as well. As a direct result of this study, SAHs have been registered as a new technology that attracts a 50% subsidy from the Energy Efficiency and Conservation Authority for the use in schools.

   - **Schools need to be encouraged and supported to operate solar ventilation units for the space heating and ventilation purpose.**

2) This study found heater use outside school hours, namely after school hours and in the early morning. There was also heater use during the weekend. This could be because teachers worked in their classrooms when they needed to work outside school hours. This makes an inefficient use of energy.

   - **Teachers need to have a heated space where they can share if working outside school hours is needed to make the school energy efficient.**

3) Only in one treatment classroom did the ventilation rate meet the NZMoE recommended level (ACH of 4 h^{-1}). Exposure to low levels of ventilation

rate (high levels of CO_2) can adversely affect the student respiratory health, academic performance and school attendance.

- **Schools need to install the CO_2 monitoring device to make sure the real-time CO_2 concentration is accessible.**
- **Teachers and students need to be able to access the real-time CO_2 levels in classrooms, to ensure it is possible to maintain an acceptable CO_2 level in classrooms.**
- **Teachers need to be informed of the risk of exposure to low levels of ventilation rate (high levels of CO_2) and be educated about approaches to increase the ventilation rate (reduce CO_2 levels).**

8 Reference

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9 Appendices

Appendix A: Solar air heater experimental performance

Appendix A1

Solar energy analysis equations

Spencer model for estimating the declination angle.

$$\delta = (180/\pi)(0.006918 - 0.366612\cos B + 0.070257\sin B - 0.006758\cos 2B + 0.000907\sin 2B - 0.002697\cos 3B + 0.00148\sin 3B)$$

$$B = (n-1)\frac{360}{365}$$

Where

δ	the declination angle
n	the nth day of the year

Spencer model for calculating the extra-terrestrial radiation incident on a plane.

$$G_{on} = G_{SC}(1.000110 + 0.034221\cos B + 0.001280\sin B + 0.000719\cos 2B + 0.000077\sin 2B)$$

$$G_{SC} = 1366.1\ W/m^2$$

Where

G_{on}	the extra-terrestrial radiation incident on a plane
G_{SC}	the solar constant

Boland-Ridley-Lauret (BRL) model for estimating the horizontal diffuse solar radiation from the global horizontal solar radiation.

$$d = \frac{I_{diffuse}}{I_{global}} = \frac{1}{1 + e^{-5.38+6.63k_t+0.006AST+0.007\alpha+1.75K_t+1.31\psi}}$$

$$k_t = \frac{I_{global}}{H_0}$$

$$K_t = \frac{\sum_{j=1}^{24} I_{global_j}}{\sum_{j=1}^{24} H_{0_j}}$$

$$\psi = \begin{cases} \frac{k_{t-1} + k_{t+1}}{2}, sunrise < t < sunset \\ k_{t+1}, t = sunrise \\ k_{t-1}, t = sunset \end{cases}$$

Where

d	Diffuse fraction
$I_{diffuse}$	Hourly horizontal diffuse solar radiation
I_{global}	Hourly horizontal global solar radiation
k_t	Hourly clearness index
AST	Apparent solar time
α	Solar angle in degrees
K_t	Daily clearness index
ψ	Error or residual values
H_0	Hourly extraterrestrial radiation

Hay and McKay model for estimating the solar irradiance on a tilted panel.

$$D_s = D[{}^{I}/_{I_o} * {}^{\cos i}/_{\cos z} + 0.5(1 - {}^{I}/_{I_o})(1 + \cos\rho)]$$

Where

D_s	Diffuse solar irradiance for an inclined surface
D	Diffuse sky irradiance
I	Radiant intensity at normal incidence
I_o	Solar constant
i	Angle of incidence between Sun and normal to the surface
z	Solar zenith angle
β	Panel tilt angle (slope angle)

Appendix A2

Fan mechanical power calculation equations

The required mechanical power (P_m) can be estimated according to Equation 9-1.

$$P_m = Q\Delta P = \vartheta A_d \Delta P \qquad \text{Equation 9-1}$$

Where,

P_m	Mechanical power required to force the air through the solar air collector (W)
Q	Volume flow rate (m^3/s)
ΔP	Pressure drop inside the air channel (N/m^2)

In this study, the pressure drops due to others have been discarded, while the pressure drops due to the air moves through the absorber layer and inside the air channel are estimated according to Equation 9-2.

$$\Delta P = \frac{2\rho f \vartheta^2 L}{D_h} \qquad \text{Equation 9-2}$$

Where,

ΔP	Pressure drop inside the air channel (N/m^2)
ρ	Density of air (kg/m^3)
f	Friction factor
ϑ	Air velocity (m/s)
L	Length of the solar air heater (m)
D_h	Hydraulic diameter (m)

The fraction factor can be estimated according to Equation 9-3 and Equation 9-4.

$$f = 0.059{R_e}^{-0.2}\ (for\ turbulent\ flow) \qquad \text{Equation 9-3}$$

$$f = \frac{16}{R_e}\ (for\ lamina\ flow) \qquad \text{Equation 9-4}$$

Hydraulic diameter of the air channel can be estimated according to Equation 9-5.

$$D_h = \frac{2ab}{(a+b)} \qquad \text{Equation 9-5}$$

Where,

D_h	Hydraulic diameter (m)
a	Width of the air channel (m)
b	Depth of the air channel (m)

The hydraulic diameter of the absorber layer needs to multiply the porosity of the absorber layer. The porosity can be estimated according to Equation 9-6.

$$\varphi = \frac{\pi {d_H}^2}{4{d_S}^2} \qquad \text{Equation 9-6}$$

Where,

φ	Porosity
d_H	Diameter of the holes (1.5 mm)
d_S	Spaces between the evenly distributed holes (15 mm)

Reynolds number can be estimated according to Equation 9-7.

$$R_e = \frac{\rho \vartheta D_h}{\mu} \qquad \text{Equation 9-7}$$

Where,

R_e	Reynolds number
μ	Dynamic viscosity (kg/(m*s))

The air dynamic viscosity was set according to the air temperature, as shown in the table below.

Air temperature (K)	**Air dynamic viscosity ×10^{-5} (kg/(m*s))**
(273.15, 283.15]	1.748
(283.15, 293.15]	1.797
(293.15, 303.15]	1.844
(303.15, 313.15]	1.892
(313.15, 323.15]	1.938
(323.15, 333.15]	1.984
(333.15, 343.15]	2.029

Appendix B: Ethics application approval letter

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

8 November 2012

Dr Mikael Boulic
School of Engineering & Advanced Technology
PN456

Dear Mikael

Re: HEC: Southern A Application – 12/49
Improving health and well-being in low decile classrooms with a low cost solar ventilation system

Thank you for your letter dated 30 October 2012.

On behalf of the Massey University Human Ethics Committee: Southern A I am pleased to advise you that the ethics of your application are now approved. Approval is for three years. If this project has not been completed within three years from the date of this letter, reapproval must be requested.

If the nature, content, location, procedures or personnel of your approved application change, please advise the Secretary of the Committee.

Yours sincerely

Mr Jeremy Hubbard, Acting Chair
Massey University Human Ethics Committee: Southern A

cc Prof Don Cleland, HoS
School of Engineering & Advanced Technology
PN456

Massey University Human Ethics Committee
Accredited by the Health Research Council

Research Ethics Office

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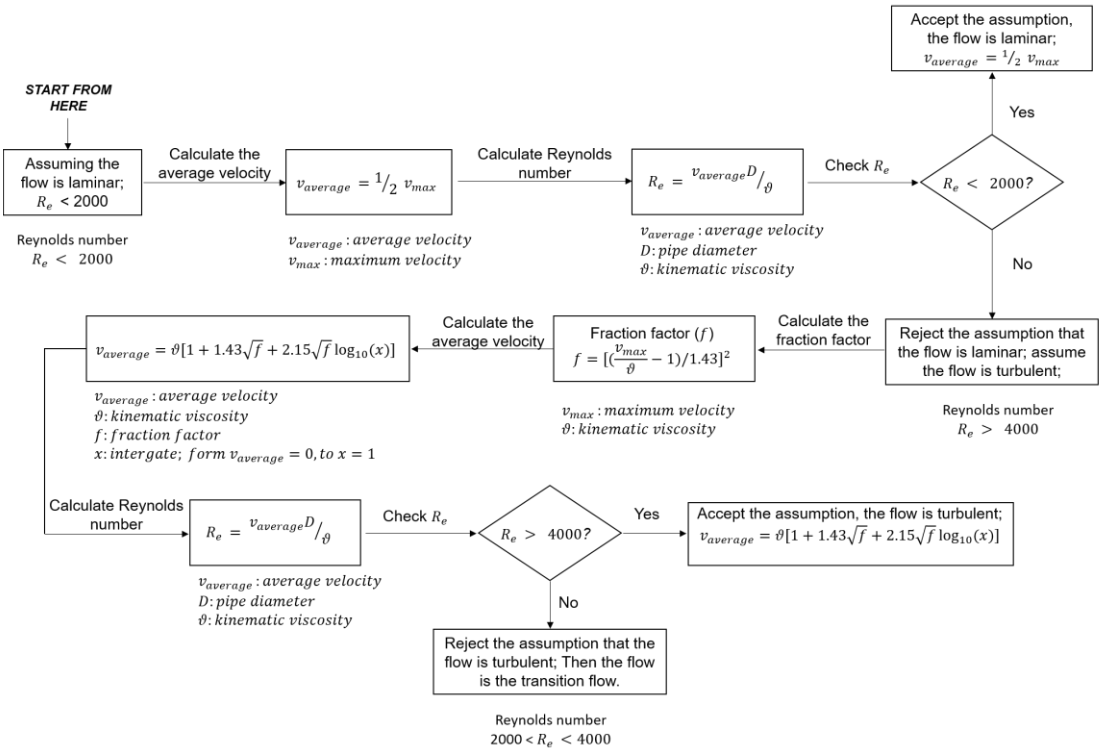
Appendix C: Solar air heater fieldwork performance

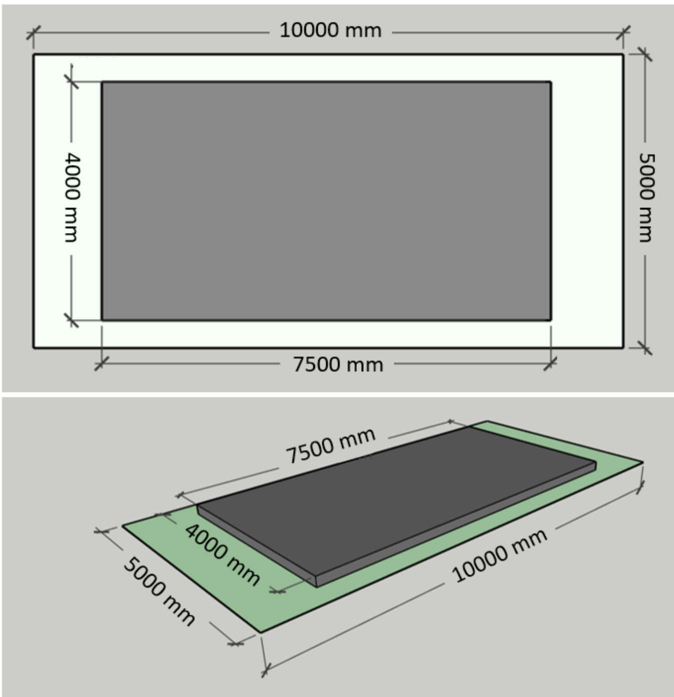
Appendix C1

Process of calculating Reynolds number and average velocity



Appendix C2

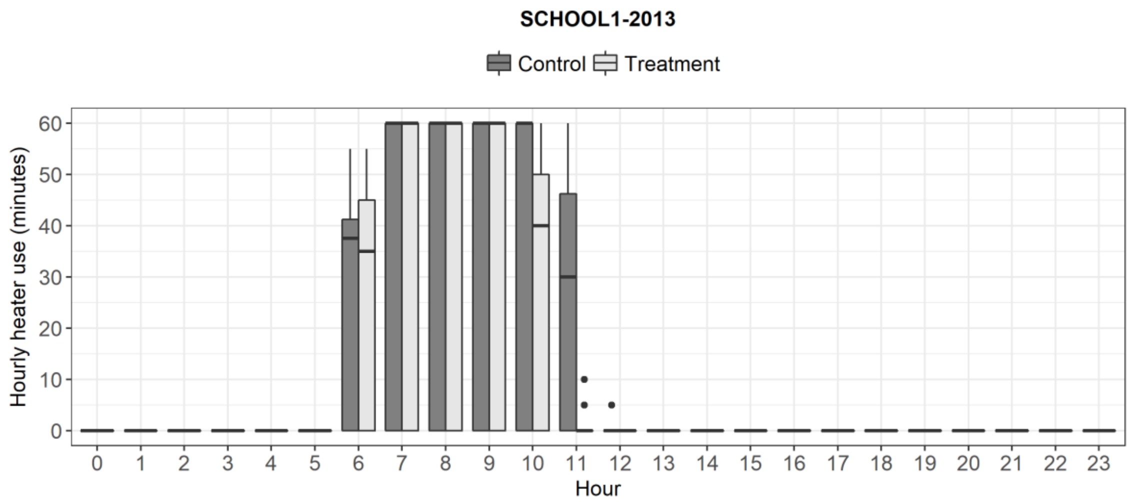
Diagram illustrating the proportion of the SAH size to the sun-facing roof area



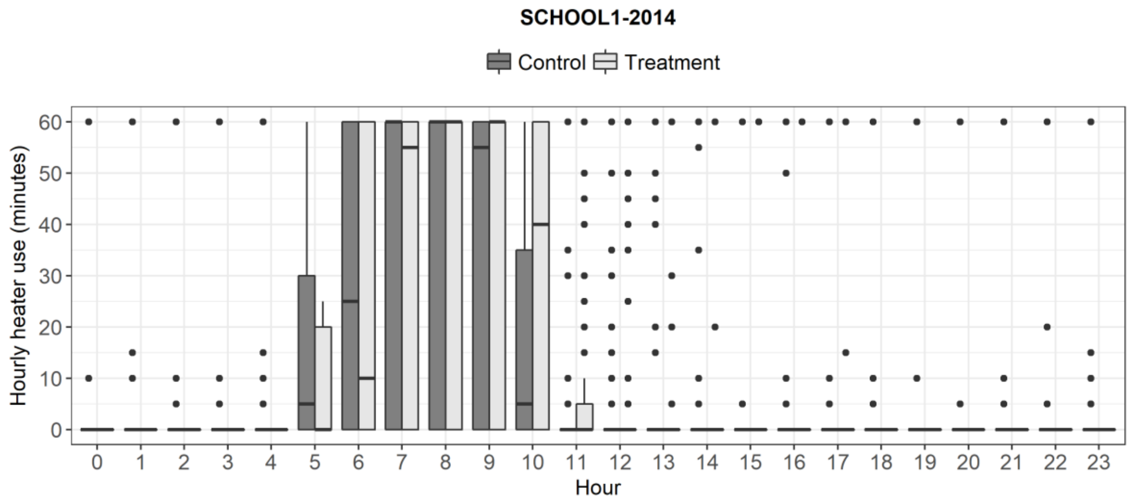
Appendix D: Change of the school environment

Appendix D1

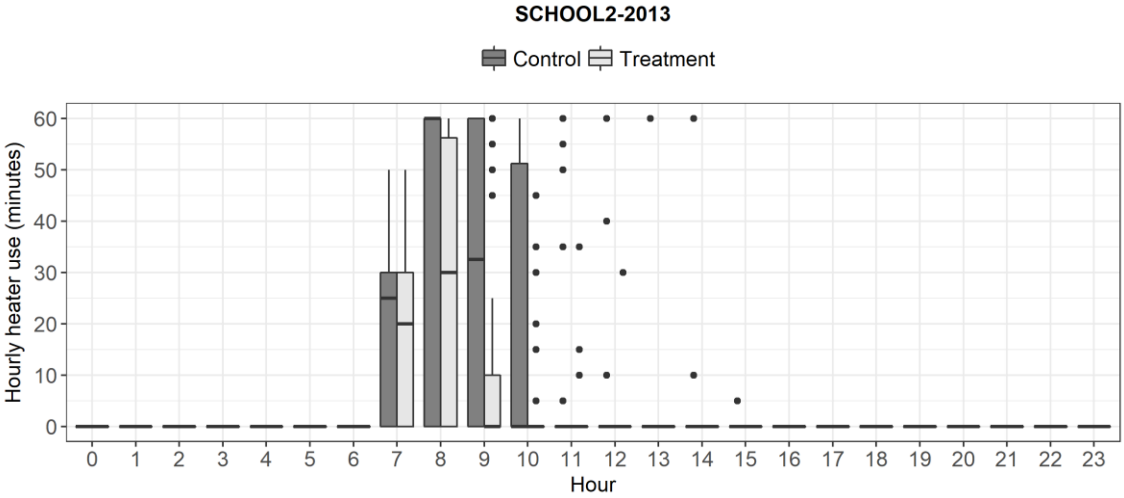
Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 1 in the winter of 2013



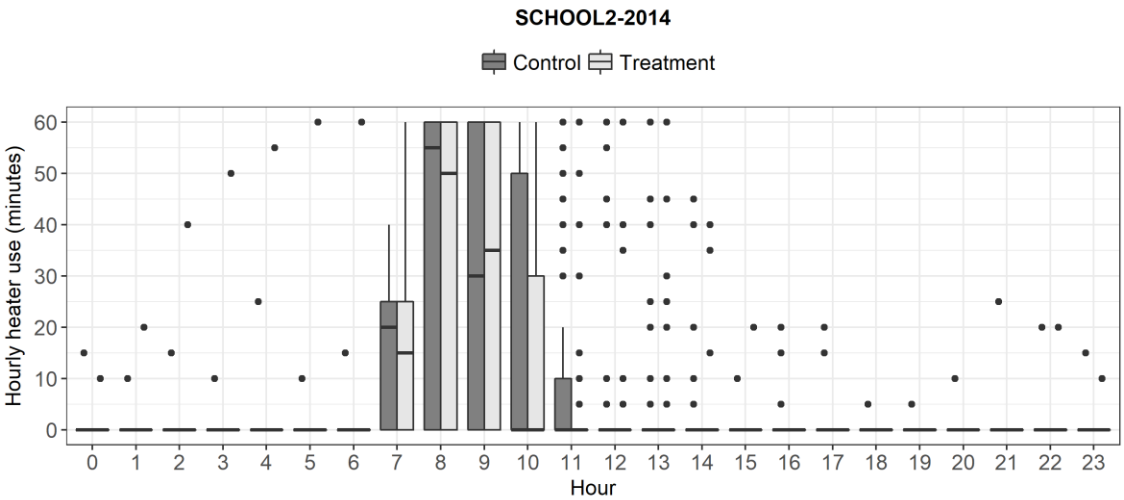
Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 1 in the winter of 2014



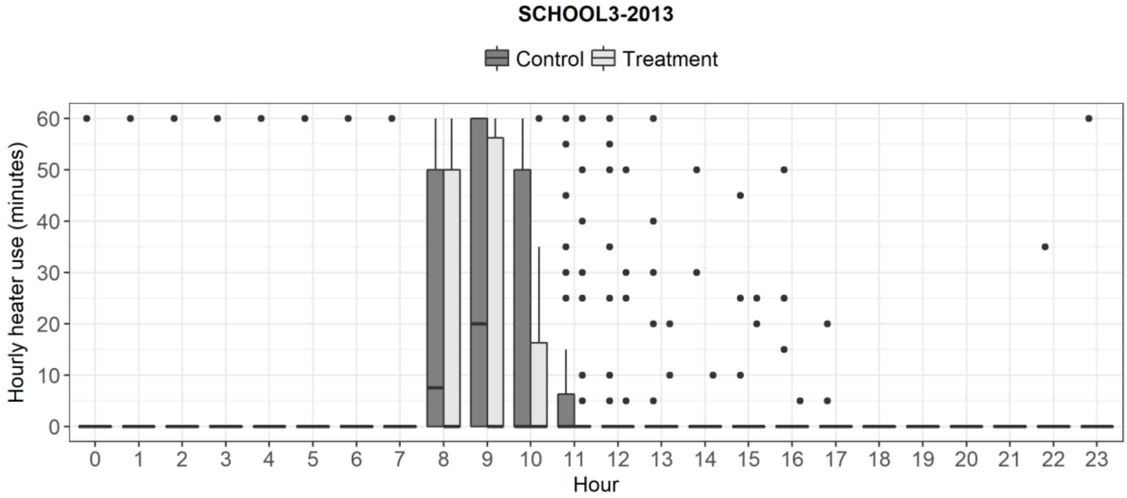
Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 2 in the winter of 2013



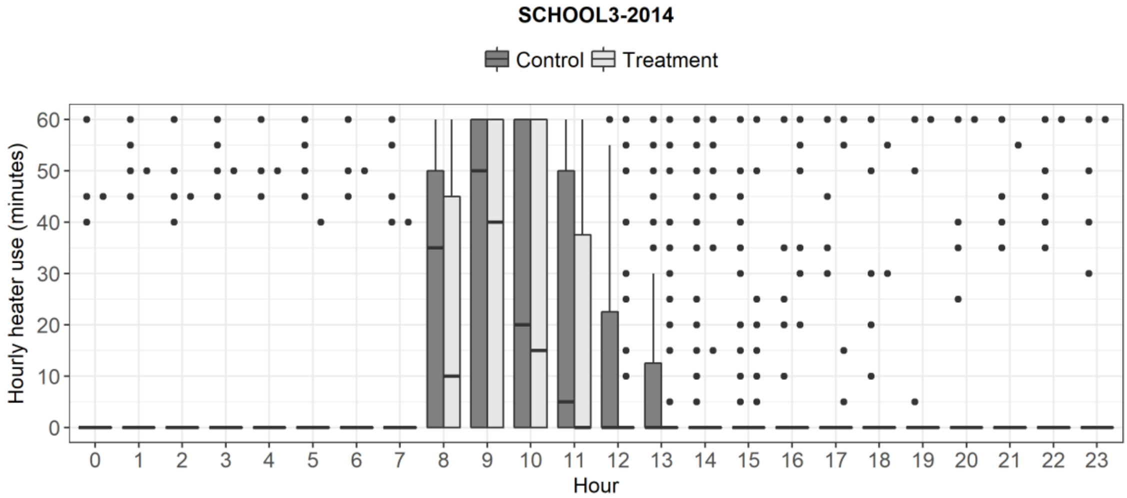
Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 2 in the winter of 2014



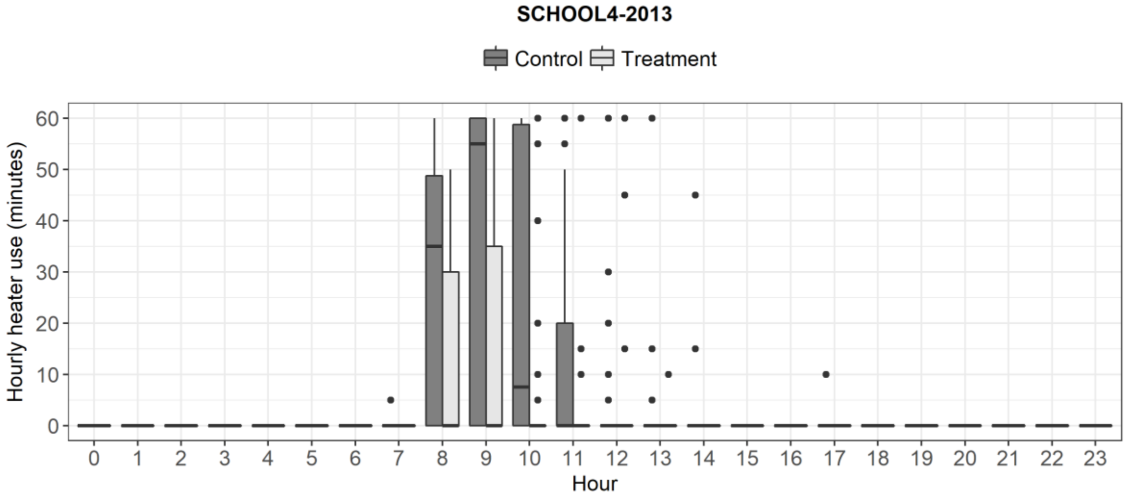
Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 3 in the winter of 2013



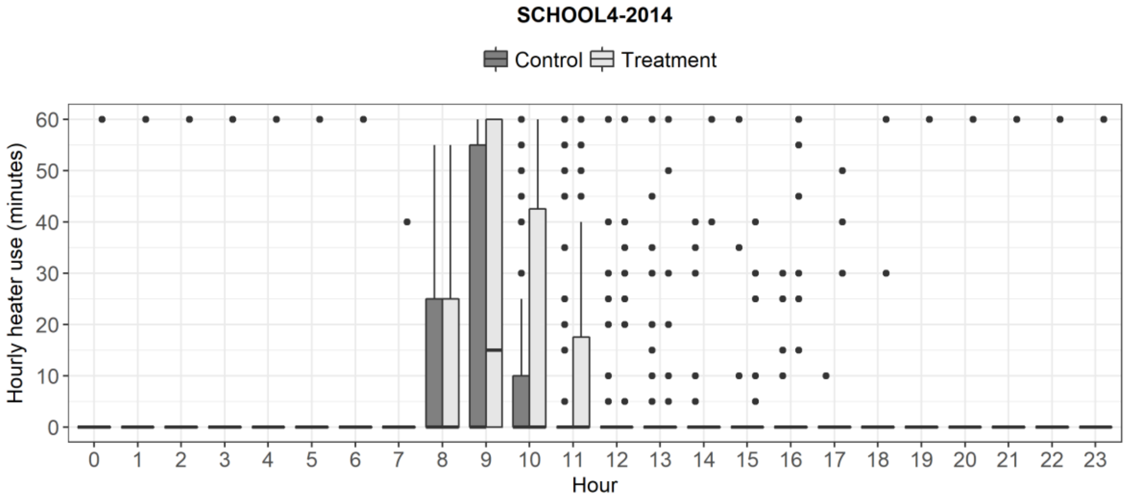
Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 3 in the winter of 2014



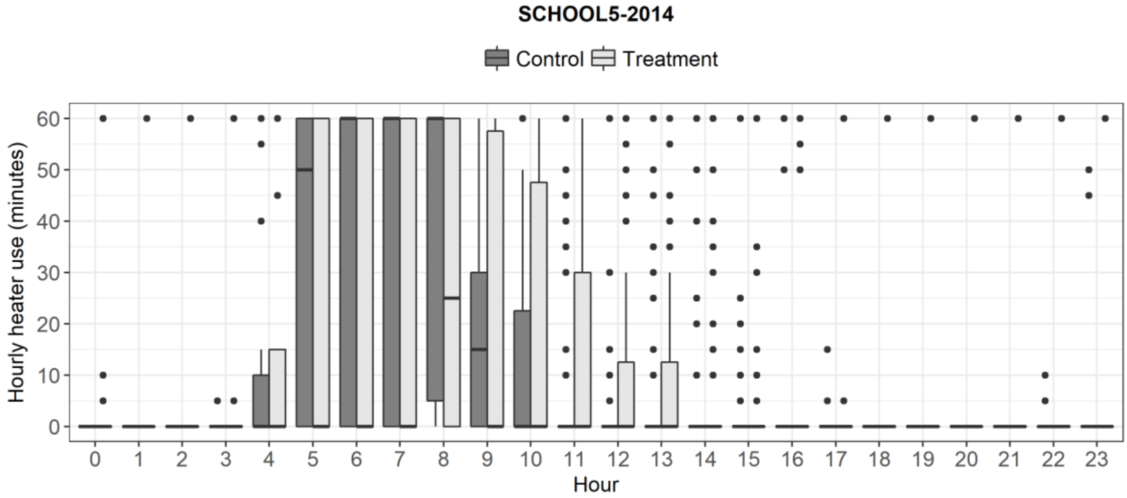
Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 4 in the winter of 2013



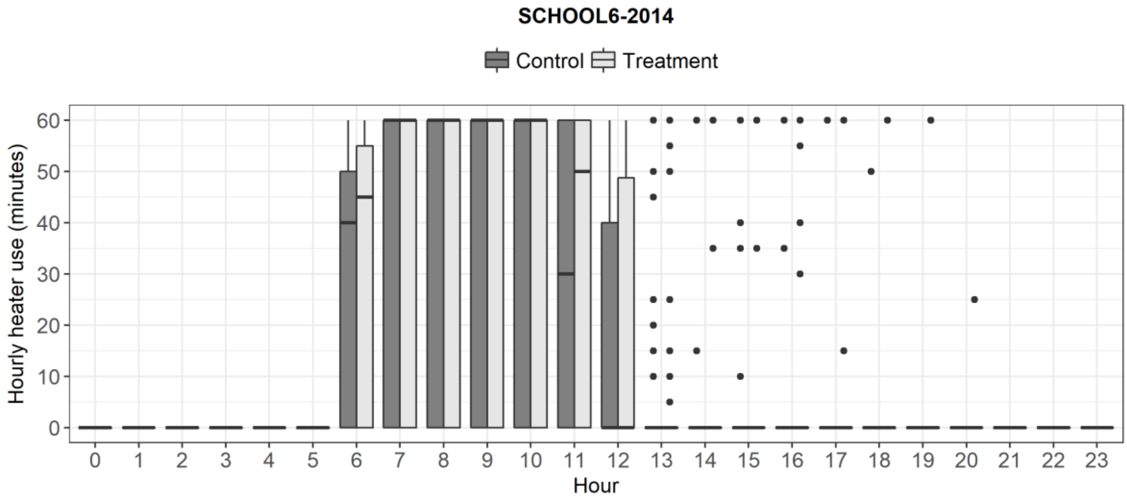
Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 4 in the winter of 2014



Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 5 in the winter of 2014

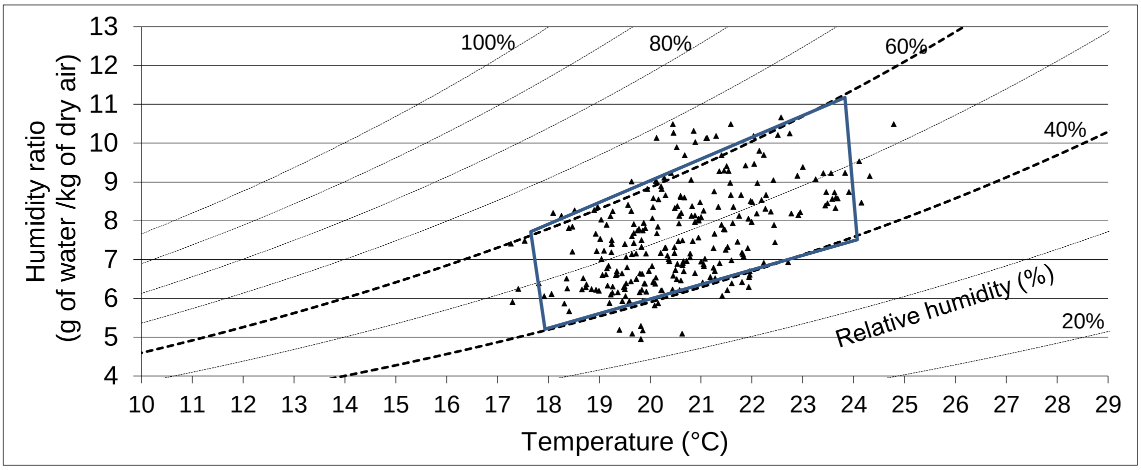


Hourly heater use (minutes) in both the control classroom and the treatment classroom in School 6 in the winter of 2014

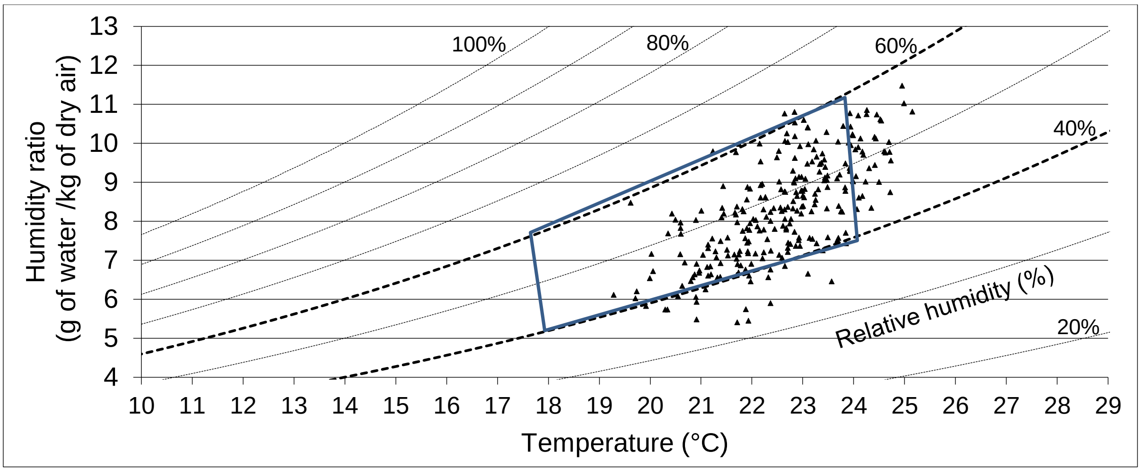


Appendix D2

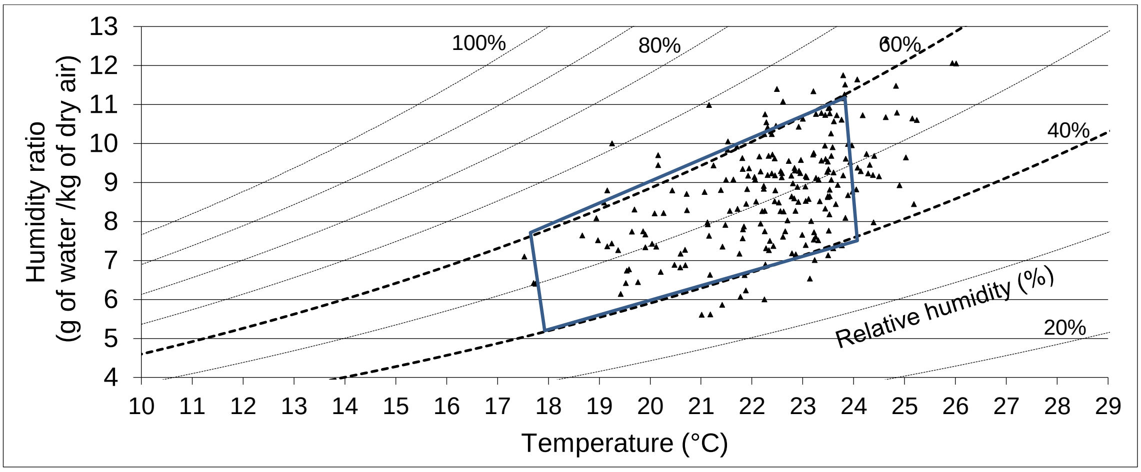
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 1 control classrooms in 2013



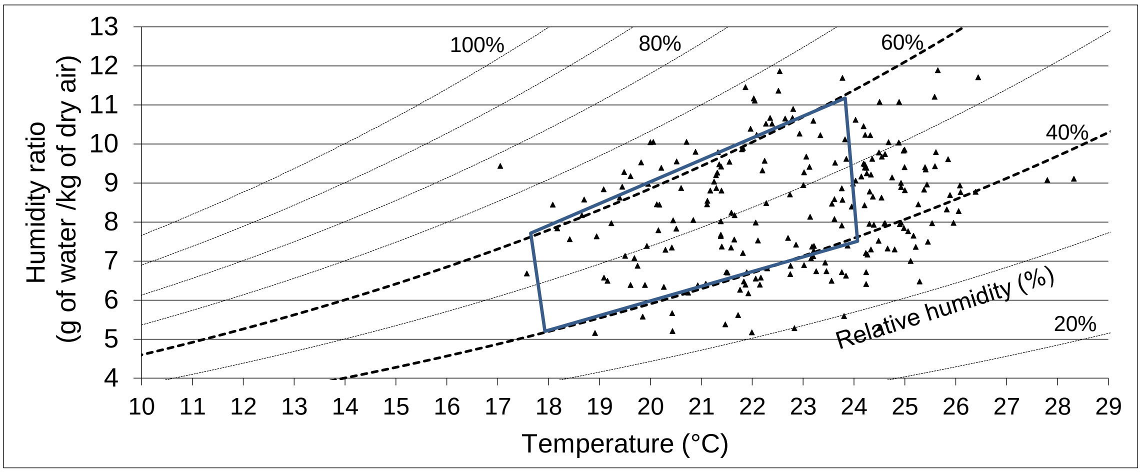
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 1 treatment classrooms in 2013



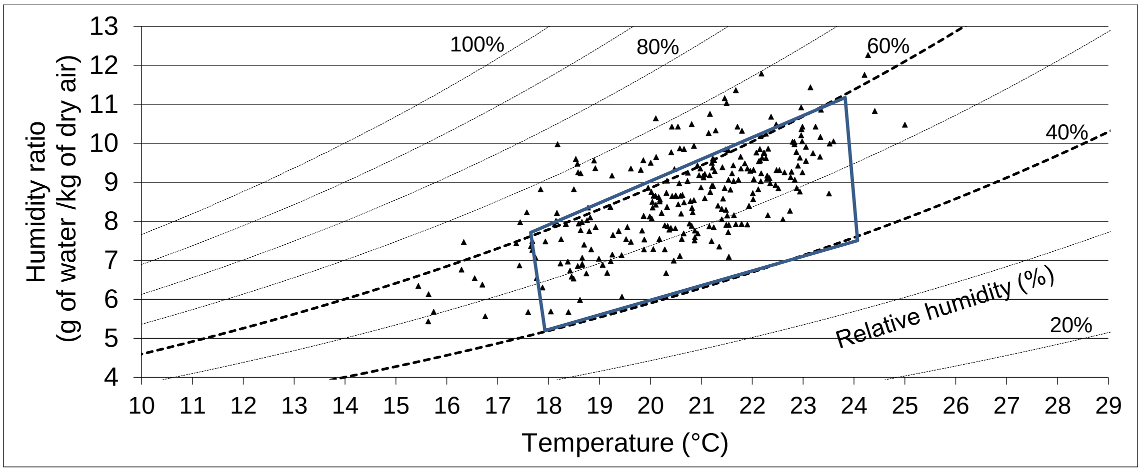
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 2 control classrooms in 2013



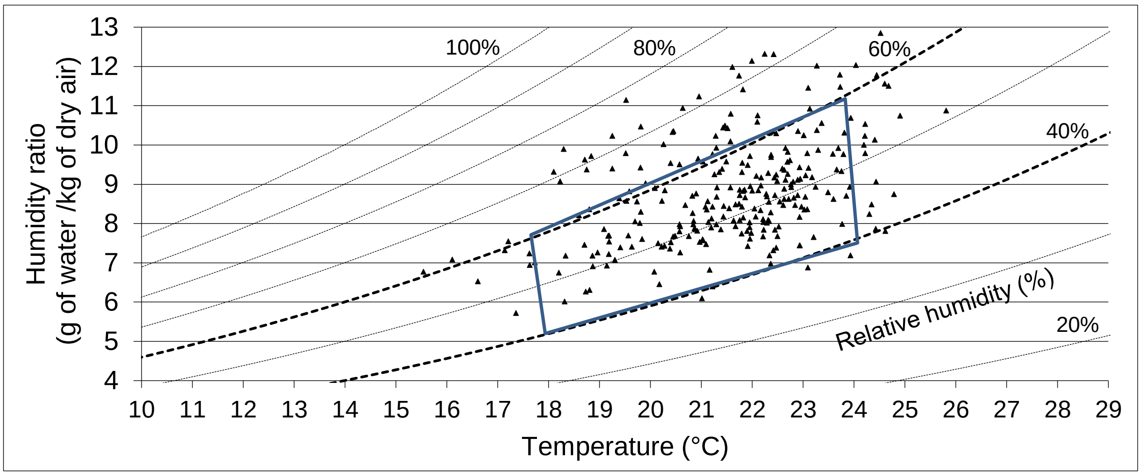
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 2 treatment classrooms in 2013



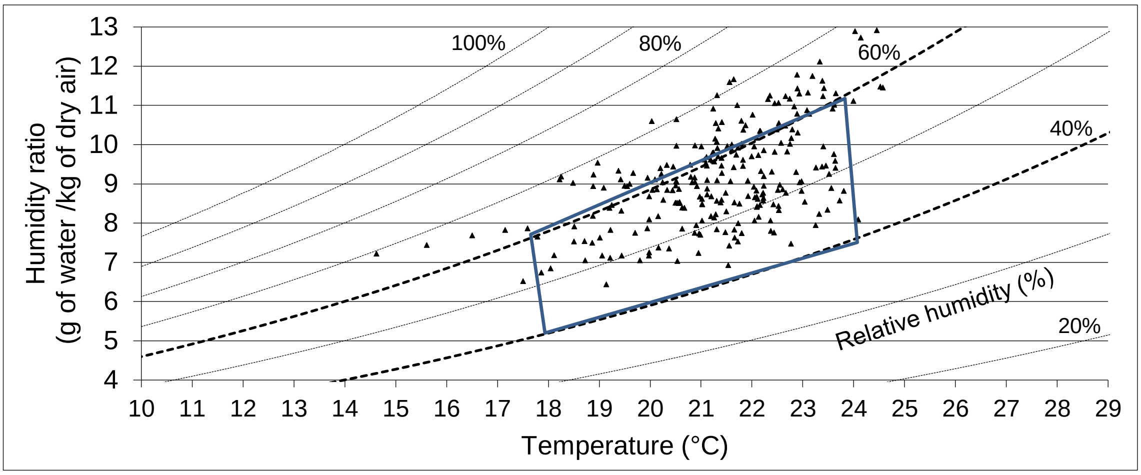
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 3 control classrooms in 2013



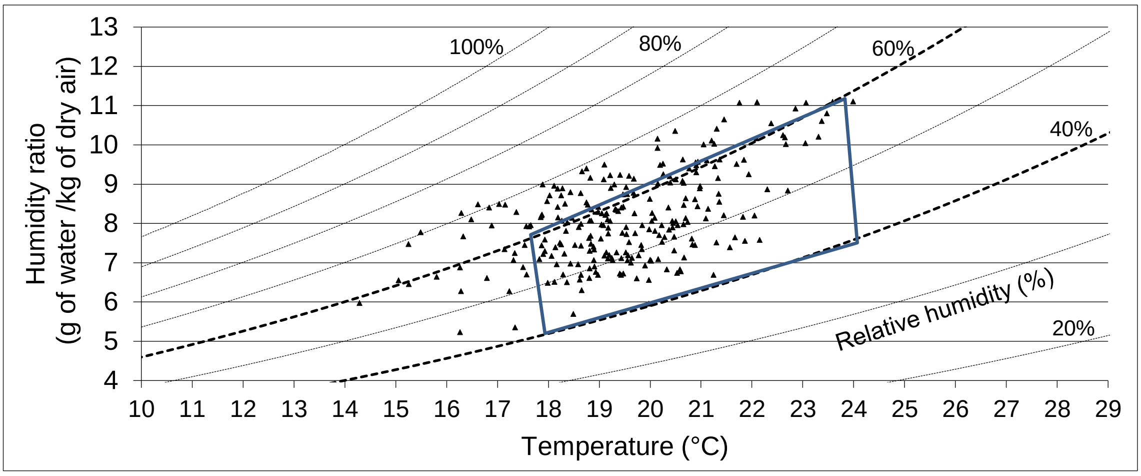
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 3 treatment classrooms in 2013



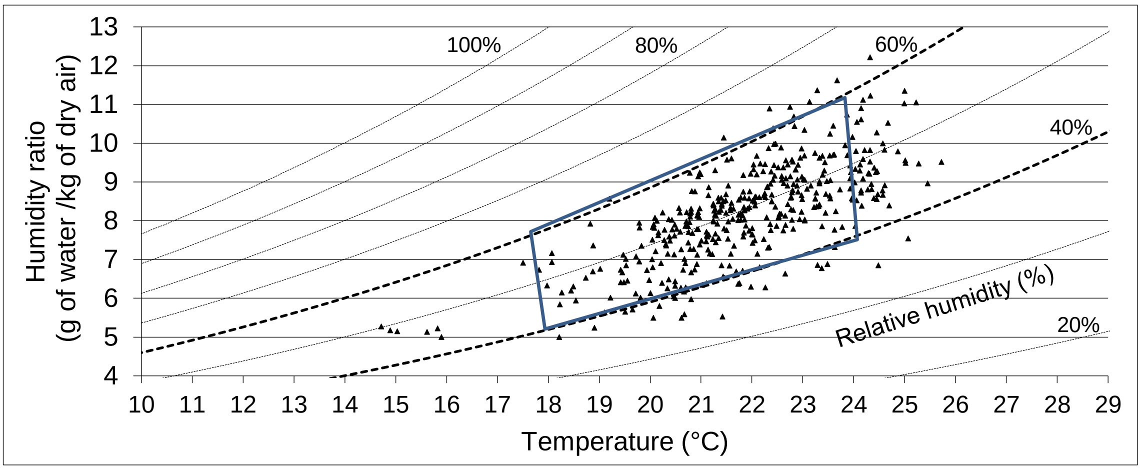
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 4 control classrooms in 2013



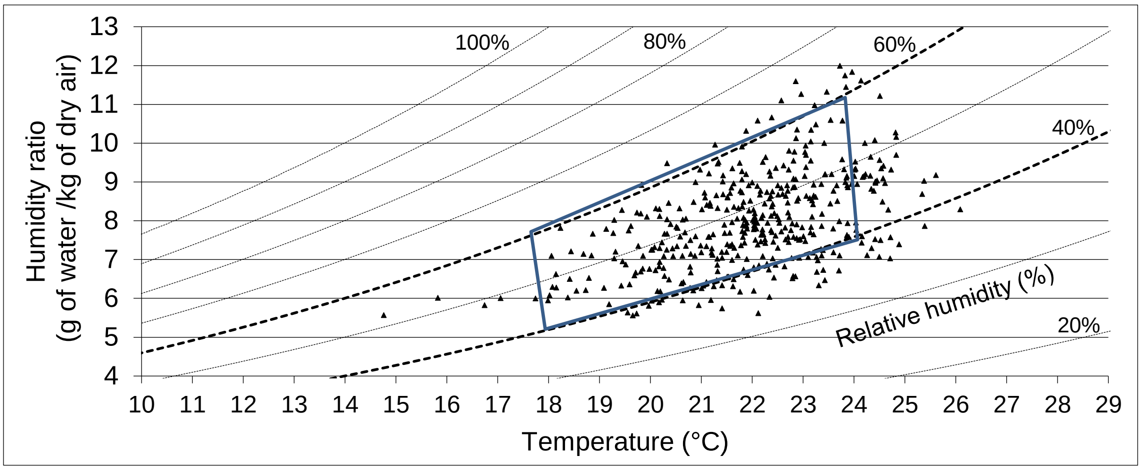
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 4 treatment classrooms in 2013



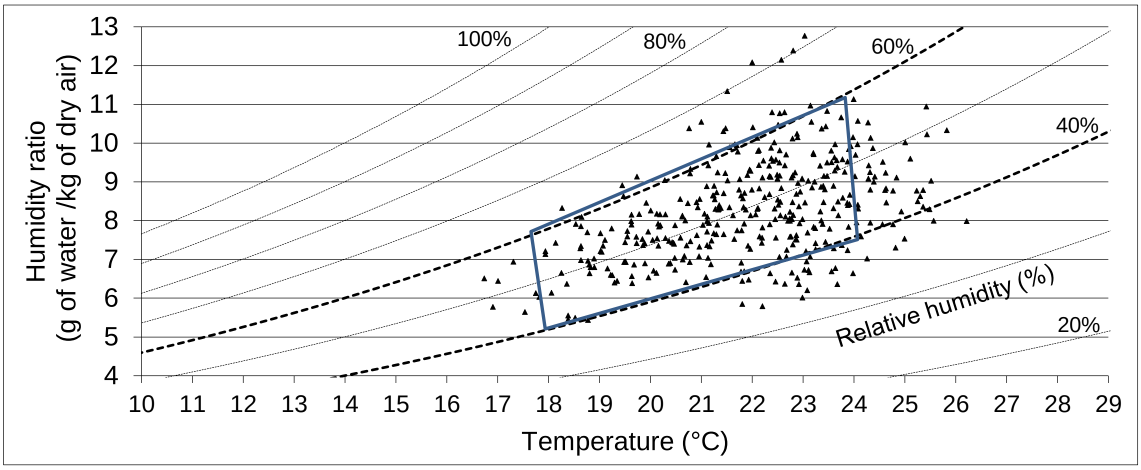
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 1 control classrooms in 2014



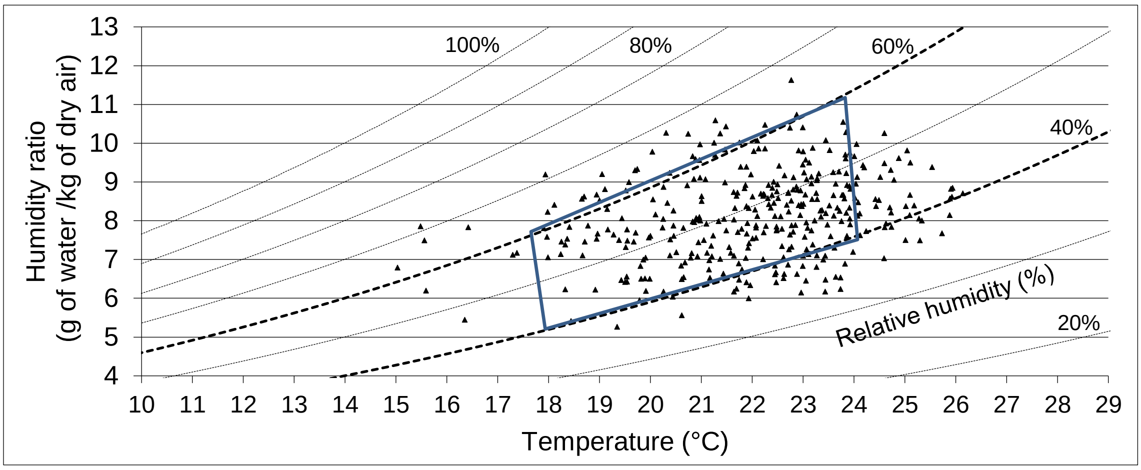
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 1 treatment classrooms in 2014



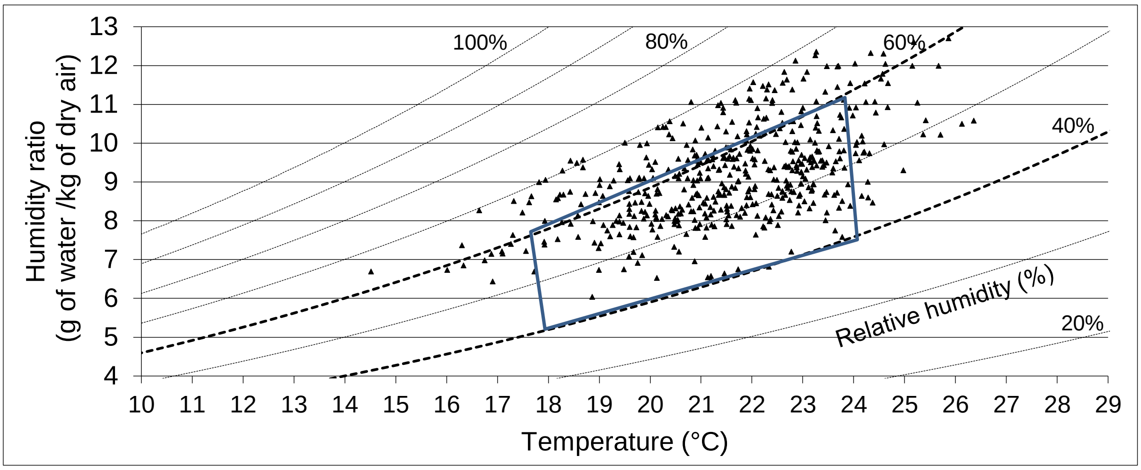
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 2 control classrooms in 2014



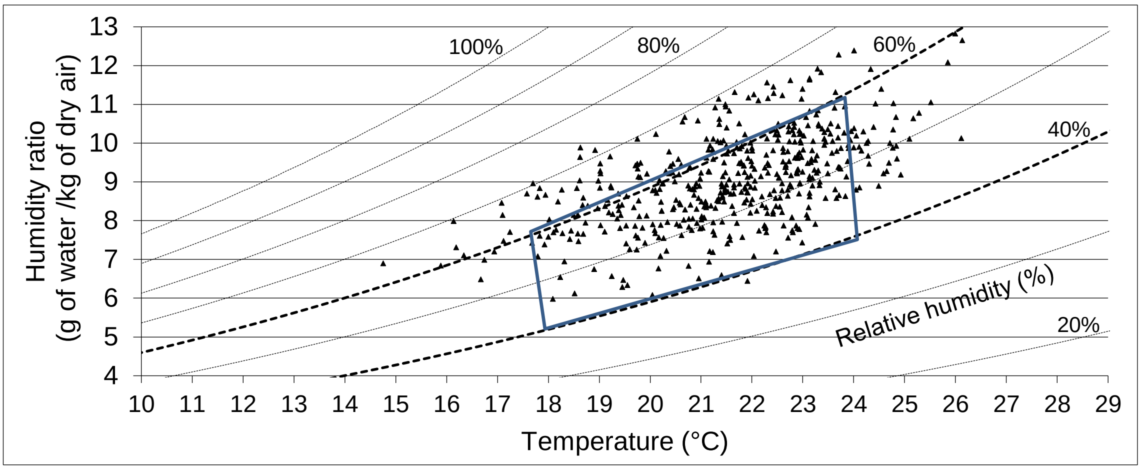
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 2 treatment classrooms in 2014



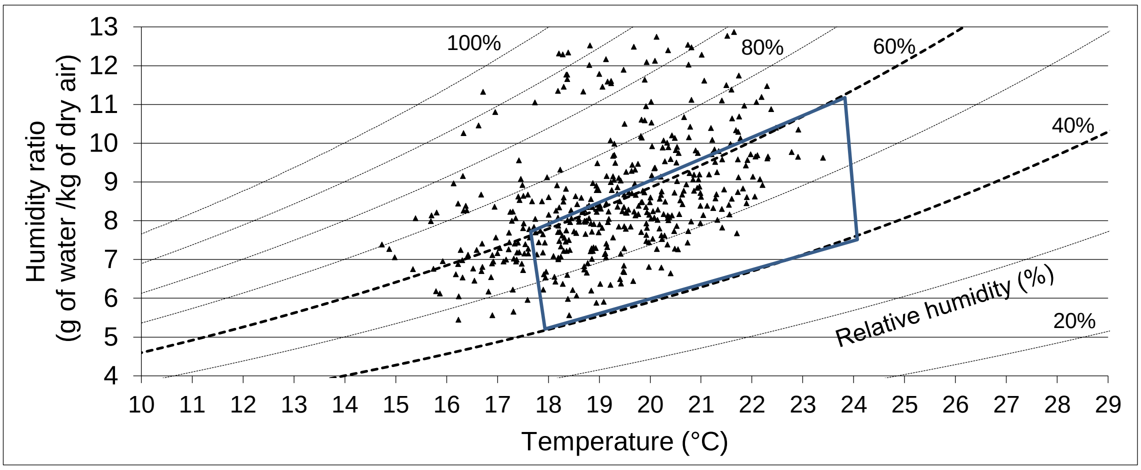
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 3 control classrooms in 2014



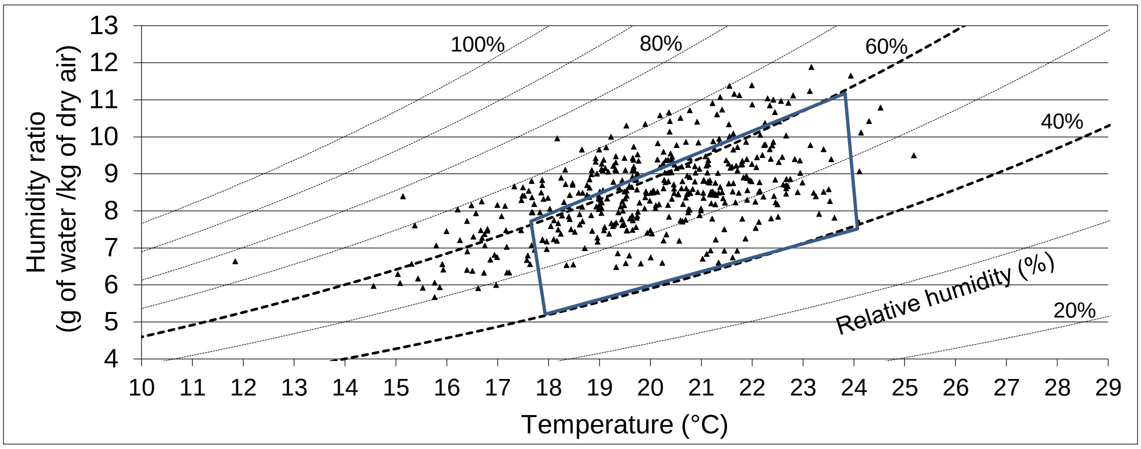
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 3 treatment classrooms in 2014



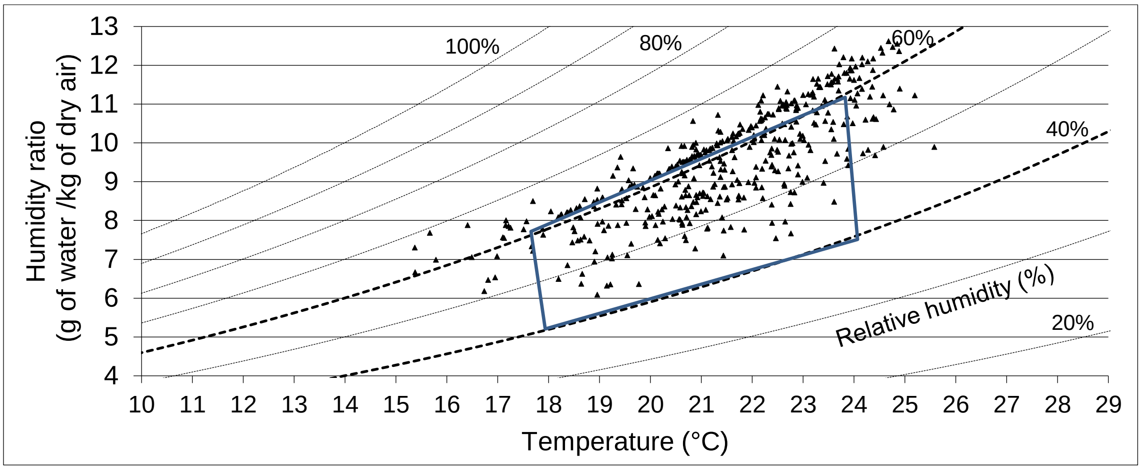
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 4 control classrooms in 2014



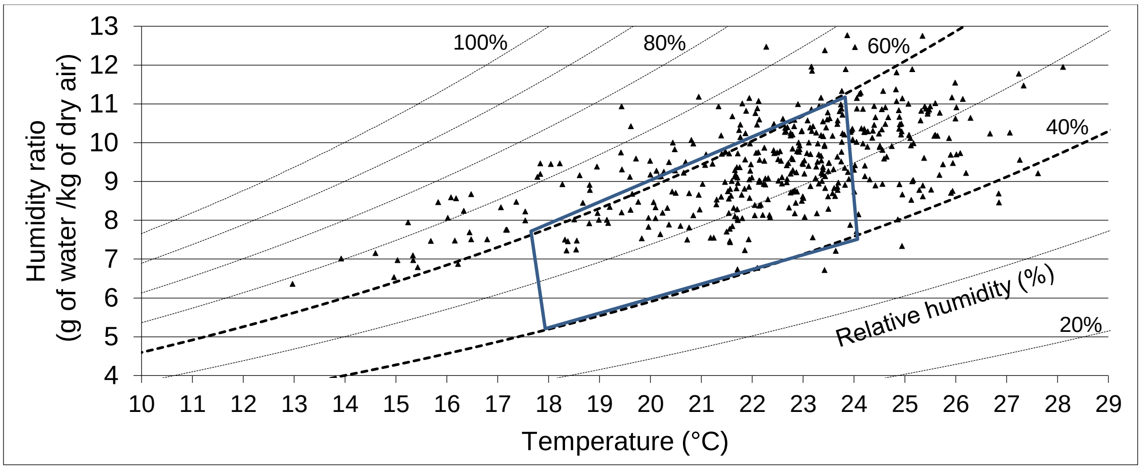
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 4 treatment classrooms in 2014



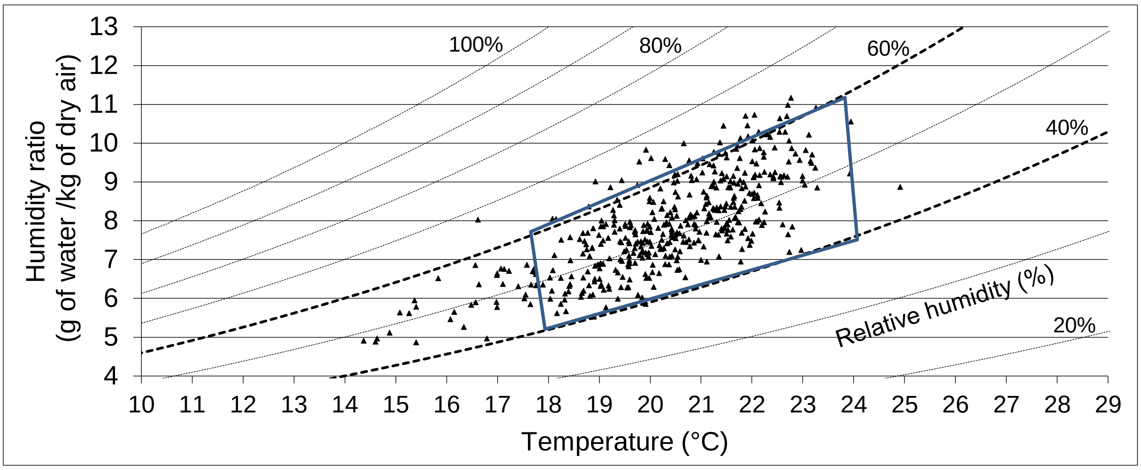
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 5 control classrooms in 2014



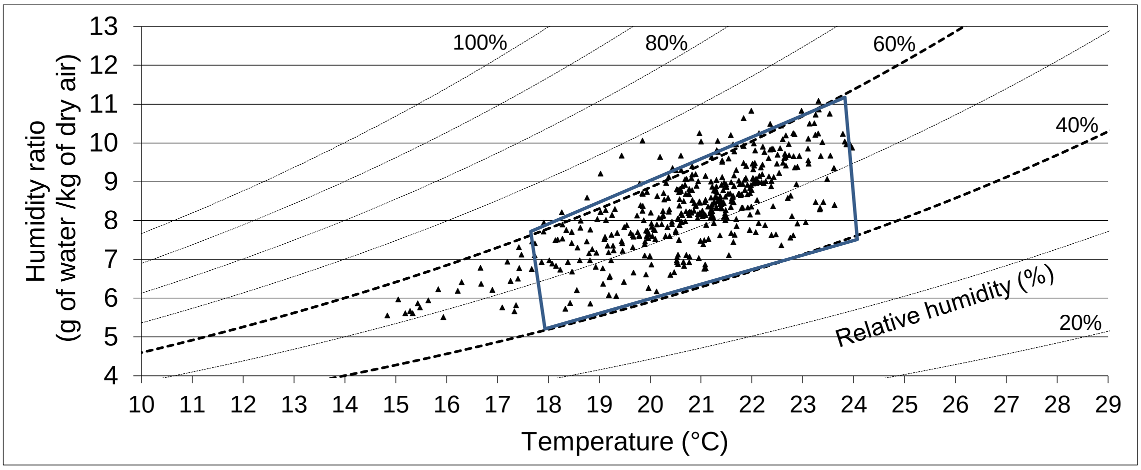
Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 5 treatment classrooms in 2014



Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 6 control classrooms in 2014



Hourly averaged temperature, relative humidity and humidity ratio during occupied school hours in School 6 treatment classrooms in 2014



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We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Yu Wang
Name/title of Primary Supervisor:	Professor Robyn Phipps
Name of Research Output and full reference:	
Wang Y., Boulic M., Phipps R., Plagmann M., Cunningham C., (2020). Experimental Performance of a Solar Air Collector with a Perforated Back Plate in New Zealand. Energies. 13(6), 1415	
In which Chapter is the Manuscript /Published work:	Chapter 3
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	85%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Yu Wang, Mikael Boulic and Robyn Phipps conceived and designed the experiment; Yu Wang performed the experiment, analyzed the data and wrote the manuscript. Co-authors reviewed the manuscript and provided the useful feedback.	
For manuscripts intended for publication please indicate target journal:	
Candidate's Signature:	Yu Wang Digitally signed by Yu Wang Date: 2021.01.05 15:14:27 +13'00'
Date:	05/01/2021
Primary Supervisor's Signature:	Phipps, Robyn Digitally signed by Phipps, Robyn Date: 2021.01.06 09:38:19 +13'00'
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Name of candidate:	Yu Wang
Name/title of Primary Supervisor:	Professor Robyn Phipps
Name of Research Output and full reference:	
Performance of a solar air heater used for space heating and ventilation – a case study in New Zealand primary schools in winter	
In which Chapter is the Manuscript /Published work:	Chapter 4
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	85%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
R. Phipps and M. Boulic conceived the research concept; M.B. and Y. Wang collected data in 2013 and in 2014 respectively; Y.W. analysed data and wrote the paper. Other co-authors reviewed the paper and provided the useful feedback.	
For manuscripts intended for publication please indicate target journal:	
Energies	
Candidate's Signature:	Yu Wang Digitally signed by Yu Wang Date: 2021.01.05 15:24:10 +13'00'
Date:	05/01/2021
Primary Supervisor's Signature:	Phipps, Robyn Digitally signed by Phipps, Robyn Date: 2021.01.06 09:40:52 +13'00'
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Name of candidate:	Yu Wang
Name/title of Primary Supervisor:	Professor Robyn Phipps
Name of Research Output and full reference:	
Effects on classroom indoor air quality in winter from the use of a solar air heater - A case study in 6 Palmerston North primary schools	
In which Chapter is the Manuscript /Published work:	Chapter 5
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R. Phipps and M. Boulic conceived the research concept; M.B. and Y. Wang collected data in 2013 and in 2014 respectively; Y.W. analysed data and wrote the paper. Other co-authors reviewed the paper and provided the useful feedback.	
For manuscripts intended for publication please indicate target journal:	
Indoor Air	
Candidate's Signature:	Yu Wang — Digitally signed by Yu Wang Date: 2021.01.05 15:24:10 +13'00'
Date:	05/01/2021
Primary Supervisor's Signature:	Phipps, Robyn — Digitally signed by Phipps, Robyn Date: 2021.01.06 09:42:19 +13'00'
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