Using a solar air heater to ventilate classrooms during the winter season in New Zealand: a potential alternative solution to assist during COVID 19 outbreaks

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ABSTRACT

Ninety per cent of New Zealand classrooms are naturally ventilated by opening windows. Achieving a suitable ventilation level will rely on teachers. A survey showed that less than half of the teachers opened windows during teaching time. Due to the high occupant density in classrooms and a low natural ventilation rate, it is challenging to provide adequate ventilation during the southern hemisphere winter months (June to September). From 9 am to 3 pm, school hours align well with the optimum solar radiation, providing opportunities for solar ventilation. A crossover intervention study was performed to investigate the effect of operating a 3 m^2 roof-mounted solar air heater (SAH) on classroom ventilation. This study was carried out in six primary schools from June to September 2014. In each school, two adjacent classrooms were randomly assigned to a treatment group (SAH installed and operated) or a control group (SAH installed but not operated). The outlet air velocity from the SAH was monitored at a 10-min interval. Classroom carbon dioxide (CO_2) level was monitored at a 2-min interval. The classroom hourly ventilation rate was estimated using CO_2 as the tracer gas. The hourly CO_2 levels in the treatment classrooms ranged from 551 ppm to 4992 ppm, with a mean (standard deviation) 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. The CO_2 levels in the treatment classrooms were statistically significantly lower than in the control classrooms ($p < 0.01$). The mean volumetric flow rate of the outlet air was around 34.0 m^3/h with a mean incoming temperature of 28.9 °C. The mean air changes per hour (ACH) in treatment and control classrooms ranged from 1.3/h to 3.4/h and 1.1/h to 3.2/h, respectively. Overall, the flow rate coming from the SAH was insufficient to keep a CO_2 level below the 1000 ppm threshold. However, increasing the SAH area could provide alternative classroom ventilation during the COVID 19 pandemic. A follow-up project is currently investigating the use of nanofluid coating and improving the collector design to increase the efficiency of the SAH.

KEYWORDS

Ventilation, solar air collector, primary school, COVID 19 outbreak

1 INTRODUCTION

The inadequate ventilation in schools is of public concern. The level of carbon dioxide (CO_2) can be used as a surrogate to estimate the classroom ventilation rate (ASTM, 2012; Bearg, 1993). The estimation uses tracer gas techniques under a well-mixed[1], single zone[2] and homogeneity[3] assumption (Persily, 1997; Sherman, 1990). Based on ASHRAE (1989), the NZS 4303:1990 (current New Zealand "Ventilation for Acceptable Indoor Air Quality" standard) recommends a minimum ventilation rate of 8 l/s/p, with an assumed maximum occupant density of 0.5 users/m^2). This minimum ventilation rate is required to achieve an indoor CO_2 concentration below 1000 ppm (ASHRAE, 2016; CEN, 2007 Standards New Zealand, 1990). At this ventilation rate, a classroom will have an average ACH of 4/h (BRANZ, 2007).

Ninety per cent of New Zealand (NZ) classrooms are naturally ventilated by opening windows. Achieving a suitable ventilation level will rely on teachers to open windows. A survey showed that less than half of the teachers open windows during teaching time. Inadequate ventilation rates, found in NZ schools during the winter season, could adversely affect occupant respiratory health (Wang et al., 2020a; Smedje et al., 2000) and school attendance (Mendell et al., 2013). Also, it could contribute to a higher virus transmission rate during the COVID pandemic (Morawska et al., 2020). Therefore, solutions to increase ventilation rates in schools are needed. 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 (Cutler-Welsh, 2006; Angelon-Gaetz et al., 2015). Mechanical ventilation systems are not affordable for most NZ schools, especially following the introduction in 2010 of a capped budget for purchased energy[4] (Ministry of Education, 2010). Consequently, an alternative and affordable method is needed to improve the winter ventilation rate in NZ primary schools.

School hours, 9 am to 3 pm, are well aligned with the optimum solar radiation and provide opportunities for solar ventilation (Jaquiery, 2018). This paper aimed to investigate the changes in ventilation rate in twelve NZ primary classrooms from when a roof-mounted solar air heater (SAH) was operating and not operating. Results reported in this paper focus on the change in CO_2 concentration and ventilation rate during occupied school hours (Monday to Friday from 9 am to 3 pm).

This paper is organised as follows: Section 1 introduces the study. Section 2 presents materials and methods to investigate the effects of operating a roof-mounted SAH on CO_2 and ventilation rate in schools. Section 3 presents and discusses the results. Section 4 concludes the paper.

2 MATERIALS AND METHODS

A crossover intervention study was conducted in Palmerston North (PN), located in the lower North Island. PN (40°S) is close to the midline of NZ (from 34°S to 47°S). During the winter months (June to August), PN's mean solar radiation levels were close to the mean NZ solar radiation levels (77.2 W/m^2 vs 77.9 W/m^2). The mean daily sunshine hours were 0.8 hours

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[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.

[4] The operational funding for N.Z. 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.

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°C vs 7.9°C) (NIWA, 2018). Overall, compared with the mean levels of NZ winter weather, PN has medium solar radiation levels, sunshine hours, and ambient temperature. This means performances of the SAH in PN could be assumed to be at the medium level in NZ.

To be selected in this study, schools were required to meet five criteria: (i) schools have a decile rating from 1 to 6[5], (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 the study. The selected school principals received an invitation to participate. The schools and classrooms were recruited based on principals' and teachers' willingness to participate.

Twelve classrooms from six primary schools (School 1 to School 6) were selected. The schools were all located within a 5 km radius around PN city centre. Before monitoring, the SAH (treatment) was installed on the sun-facing (North in the southern hemisphere) roof of all participating classrooms. The two adjacent classrooms in each school were randomly assigned either to a treatment group (SAH installed and operated) or a control group (SAH installed but not operated). Figure 1 shows the SAH located on the roof of a school building. There was one SAH installed for each participating classroom.

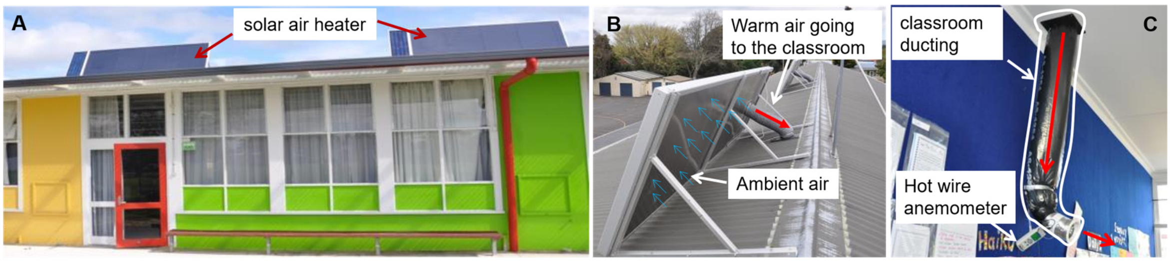

Figure 1: Solar air heater (SAH) located on the roof of the school building

(A: SAH front view; B: SAH backplate; C: Air duct inside the classroom and the location of the hot wire anemometer.

This SAH, from the front to the back, is composed of a transparent cover (double layer polycarbonate with a solar transmission of 0.77 and visible transmission of 0.85), an absorber layer (black felt), a perforated backplate (aluminium) and an aluminium frame. The diameter of the outlet air duct is 125 mm. The air inlet holes in the perforated backplate are 1.5 mm in diameter. These holes are evenly distributed in a grid, 15 mm apart (approximately 4300 holes/m^2). The length, width, and air channel depth of this SAH are 3000 mm, 1020 mm, and 75 mm, respectively. The gross collector area and the absorber layer effective area are 3 m^2. The SAH has a fan with a power consumption of 5.1W, a fan speed and on-off controller, and an outlet duct. An 18W photovoltaic panel powers the fan. The ambient air enters the SAH through the perforated backplate (Figure 1B). The heated air is pushed into the outlet duct by the fan. The velocity of the outlet air is controlled by the fan speed controller (regulator). The fan speed was set at 75%, the maximum fan speed in all classrooms.

The outlet air temperature and velocity were monitored at a 10-min interval, 24/7. The hot wire anemometer was placed centrally at the end of the outlet duct, as shown in Figure 1C. The

[5] 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. School deciles. Wellington, NZ: New Zealand Ministry of Education.

weather data (ambient temperature, solar radiation, wind speed and rainfall) were retrieved from a local climate monitoring station. Table 1 shows the construction characteristics for each classroom and control and treatment status during fieldwork. For privacy, the classrooms were anonymised using the format "S1R1". The first number represented the school (S) identification number from 1 to 6. The second number represented the room (R) identification number and was 1 or 2.

Table 1: Construction characteristics for each classroom and control and treatment status during fieldwork

School (S) Room (R)	**Volume (m^3)**	**Term 2**	**Term 3**	**Student number and age (years)**	**When school buildings built**	**Roof**	**Windows (type and glazing)**	**Heaters**
S1R1	221.0	Control (C)	Treatment (T)	21, 8 – 10	1963	Skillion roof	Awning, single	Central radiator
S1R2	221.0	Treatment (T)	Control (C)	21, 8 – 10				
S2R1	212.5	T	C	28 (10 – 13)	1913[1]	Skillion roof	Awning, single	Inverter heat pump
S2R2	230.6	C	T	27 (10 – 12)				
S3R1	227.7	C	T	27 (9 – 11)	1958	Skillion roof	Louvre, single	Unflued gas heater, Inverter heat pump
S3R2	227.7	T	C	20 (9 – 12)				
S4R1	313.6	T	C	26 (8 – 10)	1928	Gable roof	Awning, single	Inverter heat pump
S4R2	295.2	C	T	22 (8 – 10)				
S5R1	175.8	T	C	30 (12 – 13)	1953	Skillion roof	Awning, sliding, single	Electric heater
S5R2	175.8	C	T	21 (10 – 12)				
S6R1	182.8	C	T	21 (7 – 8)	1975	Skillion roof	Awning, single	Central radiator
S6R2	182.8	T	C	22 (7 – 9)				

These classrooms were all light timber-framed single-storey buildings and naturally ventilated. The classrooms kept the same control or treatment status for the entire school Term 2[6]. During Term 3, the treatment classrooms became control classrooms and vice versa. In the control classrooms, the SAH fan was off, and the outlet air duct was sealed to avoid air coming into or out of the classroom. The fieldwork was carried out from June to September 2014.

[6] NZ 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).

The classroom CO_2 levels were monitored at a 2-min interval, 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 (TSI Incorporated, USA) or a Model 7545 IAQ-Calc Meter (TSI Incorporated, USA). These devices were placed inside a custom-made support structure at 1.1 m above the floor (average height when students were seated at desks). The devices were located in the best available location in classrooms. All instruments were away from the doorway and direct sunlight. All monitoring devices involved in this study were calibrated and checked before and after the fieldwork.

Data analysis focused on NZ school hours, from 9 am to 3 pm. During the occupied (Monday to Friday) school hours, the hourly average values of the CO_2 were calculated. Results were presented with a mean (SD) and 95% CI. The difference in CO_2 levels between treatment and control classrooms was compared (t-test). All classrooms' ventilation rates (air changes per hour, ACH, /h) were estimated using the tracer gas technique (ASTM, 2012; Bearg, 1993). The CO_2 level has been used in different studies to evaluate the ventilation rate (Gao et al., 2014).

The volume of each classroom was measured (Table 1). The number of occupants in all classrooms was the enrolment (Table 1). 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 PN ambient air CO_2 concentration was 400 ppm. This level was also assumed in the European Standard EN13779 (CEN 2007). Table 2 shows the number of occupied fieldwork days for each school.

Table 2: The number of unoccupied and occupied days

School (S)	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
The number of school days	70	82	82	73	72	74

All calculations were conducted using the statistical computing and graphics platform programming language R version 4.1.3 (R Core Team, 2021). The statistical significance was defined at a level of 0.05.

3 RESULTS AND DISCUSSION

3.1 Temperature and volumetric flow rate of the outlet air

Table 3 shows the mean (SD) and 95% CI of the SAH outlet air temperature and the mean (SD) and median (minimum-maximum) volumetric flow rate of the SAH outlet air in different schools.

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, the ambient temperature was 5.6°C, and the 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.

Table 3: Air temperature coming from the solar air heater (°C), flow rate (m^3/h), mean (SD) and 95% CI

Schools (S)	Temperature (°C)		Volumetric flow rate (m^3/h)	
	Mean (SD) [95% CI]	**% of the time with temperatures above 18 °C**	**Mean (SD) [95% CI]**	**Median (minimum-maximum)**
S1	32.2 (10.4) [30.0–34.3]	85.4%	25.0 (7.7) [23.4–26.6]	26.2 (4.3–43.6)
S2	28.9 (10.8) [26.7–31.1]	75.6%	31.5 (9.8) [29.5–33.6]	32.7 (4.7–46.4)
S3	29.2 (11.4) [26.5–31.9]	76.1%	30.0 (13.9) [26.7–33.2]	25.7 (8.0–61.1)
S4	27.3 (11.7) [22.6–32.0]	62.5%	37.1 (8.6) [33.6–40.5]	39.3 (21.0–49.2)
S5	26.4 (9.8) [23.7–29.0]	68.5%	30.7 (11.7) [27.6–33.8]	29.9 (7.4–55.7)
S6	27.9 (10.8) [25.8–29.9]	73.8%	33.7 (13.1) [31.2–36.2]	33.3 (6.0–63.4)

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. 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 a velocity of 0.8 (0.3) m/s. This flow rate 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 of fresh air are required for a classroom occupied by 30 pupils (Standards New Zealand 1990)[7].

3.2 Classroom carbon dioxide and ventilation rates

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. The 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 4 shows the mean levels of CO_2 in all classrooms.

Table 4: Mean (standard deviation) and 95% CI of carbon dioxide (ppm) in control and treatment classrooms

School (S)	Control classrooms	Treatment classrooms	Difference[1]	p
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

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

School (S)	Control classrooms	Treatment classrooms	Difference[1]	p
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 4 out of 6 schools, the CO_2 levels in the treatment classrooms were significantly lower than in the control classrooms. It was found that the 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 attained 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 higher levels of CO_2 in S3. Firstly, S3 was built to the Dominion Basic Plan, consisting 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's 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.

The small volume of the S5 classroom and the high density of the occupants caused a high level of CO_2. The classroom volume 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 and treatment classrooms (mean 29 students per room) was higher than in the other classrooms (mean 25 students per room). Additionally, the students in S5 classrooms were from 10 to 13 years old and older than in the other classrooms, who were 5 to 10 years old. Children aged 10 to 13 generate higher levels of CO2 than students aged 5 and 10, assuming the same physical activities (Persily and de Jonge, 2017).

Table 5 shows air changes per hour (ACH, /h) in all control and treatment classrooms. The results include mean (SD) and 95% CI. The ACH was estimated using the tracer gas (CO_2) technique.

Table 5: Mean (standard deviation) and 95% CI of air changes per hour (ACH, /h) in all classrooms

School (S)	Control classrooms	Treatment classrooms	Difference[1]	p
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] Difference between the treatment classroom and the control classroom.

The mean ACH in treatment classrooms ranged from 1.3 /h to 3.4 /h and from 1.1 /h to 3.2 /h in control classrooms. In 2 out of 6 schools (S1 and S4), the ACH levels in treatment classrooms were significantly higher than in control classrooms. However, the contrasting result was obtained in S5, where the ACH level in the treatment classroom was significantly lower than in the control classroom. 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.

High levels of CO_2 in classrooms indicate 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) in 51 French classrooms (17 schools). Batterman et al., 2017 found that, in 147 classrooms of 37 schools, 90% of the median level of 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 school hours exceeded 1000 ppm in most 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.

NZ Ministry of Education requires a minimum ACH of 4 /h during the winter (Ministry of Education 2017). The mean ACH ranged from 1.1 /h to 3.4 /h, not meeting this ventilation requirement. Across all these classrooms, the occupants were exposed to ACH above 4 /h for 15% of school hours. Of this, 46% and 54% occurred in the control and treatment classrooms. This means operating the SAH increased the ventilation rate in the classrooms, although there was insufficient 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 accurate for some schools. Second, the ventilation rate was estimated using CO_2 as a tracer gas. The source strength number (the student number) was the enrolment in each classroom rather than in the attendance report or the class curriculum. This might potentially overestimate the ventilation rate.
A side project has investigated the efficiency of the SAH. The thermal efficiency increased from 34% at the airflow between 0.021 kg/s and 0.023 kg/s to 47 % at the airflow ranging from 0.032 kg/s to 0.038 kg/s, to 71% at the airflow of 0.056 kg/s. The maximum thermal efficiency of 75% was obtained at the airflow of 0.057 kg/s (Wang, 2020b).

4 CONCLUSION

This paper investigated the ventilation performance of a SAH roof-mounted on 12 classrooms. The results showed that the outlet air temperature was above 18 °C for at least 62% of school hours. The CO_2 levels in the treatment classrooms were significantly lower than in the control classrooms, with a mean difference of 96 ppm. In 4 out of 6 schools, CO_2 levels in the treatment classrooms were significantly lower than in the control classrooms.

Operating the SAH increased the classroom ventilation rate (a valuable supplement to natural ventilation). However, there was insufficient airflow to satisfy the NZ Ministry of Education ventilation requirements. We are currently investigating using nanofluid coating and improving the collector design to potentially increase the SAH's efficiency. In addition, another study is closely monitoring the opening and closing of windows and doors (sensors) to better inform on ventilation behaviour in NZ classrooms.

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