Enhancing thermal comfort and indoor air quality in Australian school classrooms

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ABSTRACT

The indoor thermal comfort and air quality in classrooms have become of interest worldwide, predominantly because of their influence on children's health, learning performance and productivity. Growing concerns with building energy efficiency emphasize the significance of this topic. This paper illustrates the outcome of a field study conducted in secondary school classrooms in Sydney, Australia, during the school year in 2018/2019. The procedure of the study consists of two approaches to collecting data including survey questionnaires designed for the young population, and measurements of physical variables. The study includes long-term measurements of environmental parameters in two adjacent classrooms (air temperature, relative humidity, CO_2), spot measurements of indoor air quality (PM_{10}, $PM_{2.5}$, and Formaldehyde), and questionnaire surveys designed to match the students' cognitive level. The participants were students aged between 12 and 18. The questionnaire includes questions about thermal perception, air quality and air movement, clothing level, and health condition. Surveyed classrooms used natural ventilation as the main conditioning strategy during the surveys. The infiltration and ventilation rate were studied during the non-occupied period based on the concentration decay method and a ventilation profile was created. In one of the two studied classrooms, a hybrid ventilation system was installed during autumn/mid-season 2019 to improve air quality and ventilation. This study investigates the subjective evaluation of the classroom thermal environment, which includes the analysis of children's subjective assessment and monitoring results. The indoor air temperature reached 29 °C during mid-season and 27 °C during winter. The maximum carbon dioxide (CO_2) concentrations per classroom exceeded 2900 ppm during the occupied period. The mean infiltration rate in air changes per hour (ACH) was 0.87, and ventilation rate with one window open was 2.35 ACH and reached 21.07 ACH when all windows and door were open. Improving the thermal environment and air quality is of importance in school building design, mainly because of the adverse effect of elevated temperature on children's performance. This is an indication that new child-based design guidelines are required to improve the thermal conditions and air quality in future school buildings wherein assessments of students' satisfaction along with energy consumption are undertaken.

KEYWORDS

Indoor environmental and air quality; Thermal comfort; School buildings; Ventilation

1 INTRODUCTION

Schools are an important building category in relation to the effects of indoor conditions on the users' health, learning and performance. Poor indoor air quality (IAQ) and elevated air temperature in classrooms are crucial issues worldwide. This problem is even worse when ventilation rates are insufficient to remove excessive heat or pollutant, especially when teachers keep windows closed to avoid discomfort caused by external noise, weather and/or to prevent drafts. A rise in the reporting of respiratory symptoms has led to an increasing research focus on IAQ in schools (Nissilä et al.). The effects of the ventilation rates and carbon dioxide (CO_2) concentrations on students' learning performance, and positive correlations between the levels of PM and CO_2 and health symptoms (e.g., allergies, nose irritation, and fatigue) are shown in Dorizas et al. (2015). A hybrid ventilation system, in which both natural and mechanical ventilation systems are operated, is an effective strategy for controlling indoor air quality in school buildings. It supplies outdoor air, generally assumed to be clean, to reduce exposures to air pollutants in the indoor environment. Consequently, it helps to reduce risks associated with poor comfort, health and wellbeing, learning performance and productivity. Such risks are well documented in the existing literature (Fisk et al., 2009; Wargocki and Wyon, 2013; Wargocki and Wyon, 2017). Examination of IAQ and thermal comfort for children could improve the design of school buildings and thereby optimize conditions for students' performance and wellbeing. Despite extensive research on comfort and air quality in schools, limited studies have been performed in Australian climatic context to evaluate the effects of ventilation. The main aim of this project was to use and test a hybrid ventilation system to improve indoor air quality, achieve thermal comfort conditions, and at the same time reduce energy consumption and carbon emissions. In order to achieve these objectives, the following activities have been carried out: a) assessment of the thermal comfort conditions and air quality over one year (2018-2019); b) installation and evaluation of a hybrid ventilation system to improve thermal comfort and air quality. The research outlined in this paper helps to develop design solutions for enhanced thermal comfort and low carbon footprint in school buildings.

2 DATA COLLECTION PROTOCOL

This study was performed in a secondary school located in a low-traffic area in Sydney. The participating school building was equipped with split systems as the main source for heating and cooling. Two adjacent classrooms (Figure 1) were selected to perform a longitudinal study to investigate indoor air and environmental quality of the classrooms. The main objective of the monitoring campaign was to obtain data before and after the installation of the hybrid ventilation system. Furthermore, this study assessed classroom environmental condition and students' perception of thermal comfort.

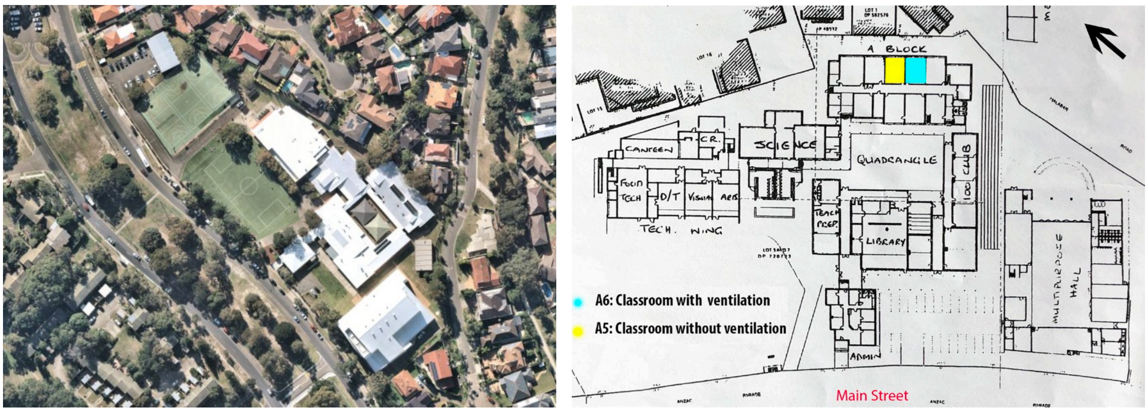


Figure 1: Location of the school and surveyed classrooms.

2.1 Measurement protocol and questionnaire survey

The monitoring campaign involved several stages and measurement protocol in line with the research objectives.

- To determine infiltration and ventilation rates in the classroom (A6) before the installation of the ventilation system, tracer gas measurements were performed using the decay technique in the classroom of about 140 m^3 over one day in October 2018 from 9:00 to 18:00. The classroom was unoccupied for two weeks before the experiment. Innova 1403, and Innova 1412i Photoacoustic Gas Monitor (LumaSense Technology) were used in tracer gas measurements with Sulphur Hexafluoride (SF6).

- To evaluate the effectiveness of the ventilation and assess indoor thermal and air quality condition, indoor air temperature (T_a), relative humidity (RH), and carbon dioxide (CO_2) were monitored in two adjacent classrooms from April 2018 to May 2019 using Air Quality Eggs version 2 Model D (Wicked Device LLC, New York). Sensors were wall-mounted about 2.3 m above floor level in each classroom and connected to the internet. They placed in a well-ventilated position away from direct sunlight and excessive moisture exposure. The indoor air quality Egg sensors had the capability of transferring 1-minute data over the school's wireless network enabling monitoring of the data in real time.
- Aeroqual Air Quality Monitor (series 500) was used to perform spot measurements of PM_{10} and $PM_{2.5}$, and Formaldehyde before the installation of the ventilation system.
- The outdoor air temperature was recorded every 30 minutes during the long-term monitoring period using Logtag® TRIX-16 temperature recorder with a resolution of 0.1 °C and accuracy of ± 0.5 °C. The sensor was shielded from solar radiation by a Stevenson screen mounted on a pole 1.8 m high, placed in the coastal site with 4.8 km distance from the school.
- To understand students' comfort and classrooms thermal and environmental conditions, fieldwork procedures combined measurements of physical variables of the classrooms with a survey of subjective responses, which recorded students' perceptions of the immediate thermal environment conducted on 'right here, right now' basis over one week during mid-season and winter. During the survey period, all subjects were asked to perform as they do routinely to stay comfortable in the classroom. Questionnaires were specifically designed for the target age group based on developmental psychology (Haddad et al., 2012). During the 'right-here-right-now" survey, a thermal comfort meter (Heat Shield, by LSI) was used in the classroom to measure globe temperature, dry bulb temperature, relative humidity, and air speed. It was located near the centre within the vicinity of the students' desks away from heat-emitting devices (e.g., laptop or monitor) to avoid any interference in the readings. The Heat Shield was placed in one of the two classrooms at the time of the survey to measure thermal condition at the height of seated students.
- To improve ventilation, Healthbox 3.0 and Invisivent window ventilator by RENSON® were installed in one of the selected classrooms (A6) before the mid-season survey in February 2019 (Figure2).

a) b)

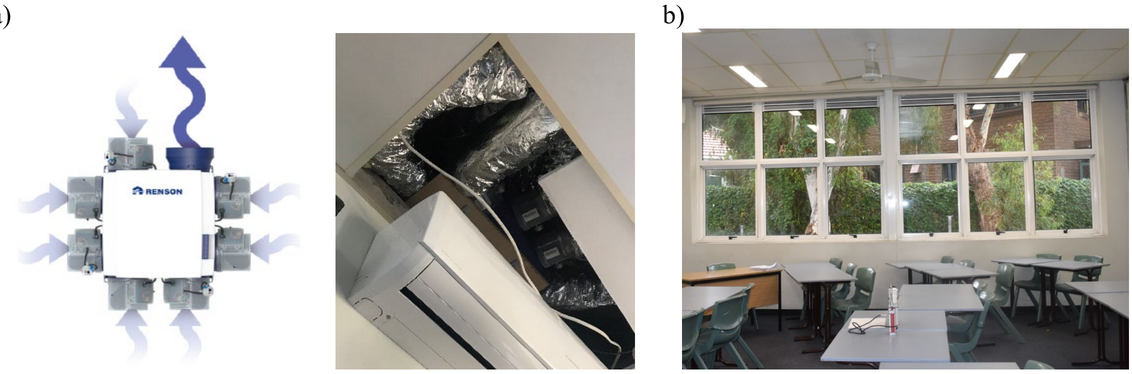
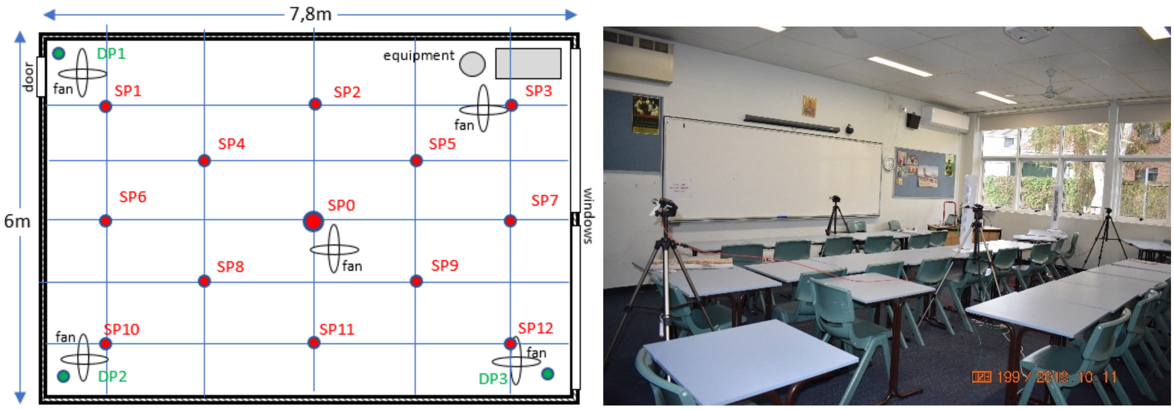


Figure 2: Ventilation system: HEALTHBOX® 3.0 (a), INVISIVENT® Ventilator (b).

3 RESULTS

3.1 Results of tracer gas measurement

To perform tracer gas measurement, a grid of 13 sampling points was organized in the classroom. The reference sampling point was in the centre of the classroom as shown in Figure 3. The equipment was located in a corner of the classroom and three dosing points were placed in the other three corners. Each dosing tubing was mounted to a mixing fan which helped to diffuse the gas concentration in the classroom. Fans were used during the dosing stage and stopped when the decay concentration sampling started. Figure 3 shows the location of sampling and dosing points. Sampling was started when the gas concentration was completely diffused and homogeneously distributed in the classroom.



DP: dosing points; SP: sampling points

Figure 3: Tracer gas measurement

The experiments were performed under two conditions a) all windows closed, b) windows opened, including two sub-cases, namely with one window opened and all windows opened. When the window was closed (air infiltration), the mean air exchange rate through the envelope of the classroom was 0.86 ACH at the reference sampling point. The ventilation rate with one window open was 2.35 ACH in the reference point. When all windows and door were opened, the ventilation rate of 21.07 ACH was obtained.

3.2 Results of long-term monitoring

Figure 4 shows the results of monitoring during cold and autumn/mid-season with an overlay of two periods in 2018 and 2019 when the questionnaire surveys were conducted. During the monitoring period, the indoor temperature varied between 10.2 °C and 30.0 °C, while the outdoor temperature ranged from 5 °C to 37.9 °C from April 2018 to May 2019. Relative humidity spanned from 20.1 % to 80.9 %. During the measurement period, semi-hourly CO_2 concentration in the classrooms exceeded 2900 ppm. Split-system air-conditioners were used occasionally outside the questionnaire survey campaign, which induced slight differences between the temperature and humidity of the investigated classrooms. During the winter period, windows were often closed due to the weather conditions, which caused CO_2 concentration exceeding the recommended thresholds of 1000 ppm (ASHRAE 62.1, 2016) and 850 ppm (Australian Building Codes Board ABCB, 2018).

After the installation of the hybrid ventilation system in the classroom A6, CO_2 concentration was significantly reduced. Figure 5 compares CO_2 concentrations in classrooms with and without ventilation system. During winter, both classrooms show similar CO_2 levels. It should be noted that boxplots included data obtained during school holiday or hours when classrooms were not occupied. Sample t-test shows that the difference between the mean value of CO_2 concentration in the classroom with the ventilation system and the classroom with no means of ventilation is statistically significant ($p < 0.001$). Elevated CO_2 levels may lead to headache, changes in respiratory patterns, and concentration loss (Australian Building Codes Board ABCB, 2018). Then, the indoor air temperature was slightly higher in the classroom without ventilation (A5) than in the classroom where the ventilation system was installed (A6).

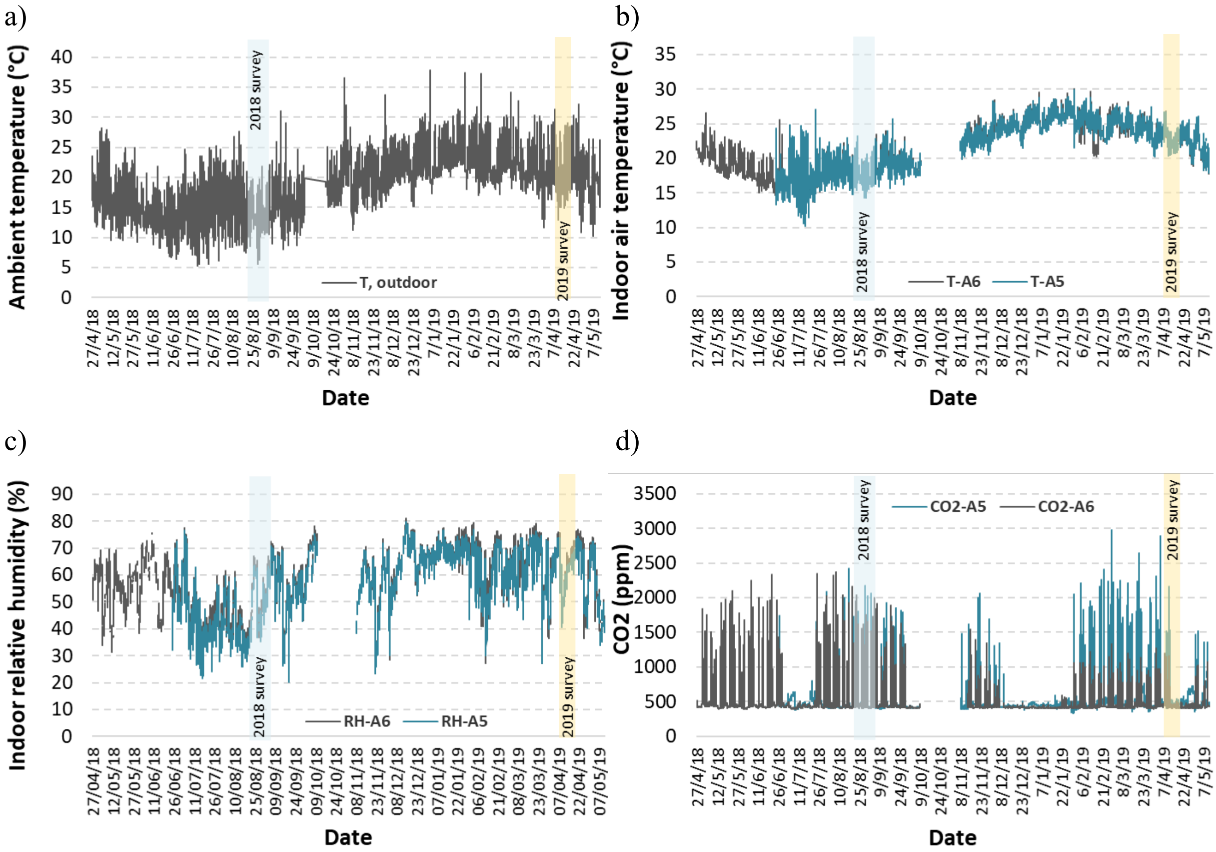


Figure 4: Results of monitoring during cold and mid-season: outdoor temperature (a), indoor air temperature (b), indoor relative humidity (c), CO_2 (d) in A6 (classroom with ventilation system) and A5 (classroom without ventilation system)

Formaldehyde was measured in the classrooms during different periods of the school year: a) over one week in December 2018 (including weekend and unoccupied condition), b) over 8 hours in three normal school days. The 8-hours average of the formaldehyde concentration varied between 0.1 ppm to 0.14 ppm. While the World Health Organization (2010) sets a limit of 0.1 mg/m^3 (0.08 ppm) to prevent sensory irritation, an indoor air level of 0.1 ppm formaldehyde has been considered safe based on Golden (2011). Indoor level of particulate matter (PM) was measured during school days (about 8 hours) for two different days. During the first day, PM_{10} varied between 5 to 39 μm/m^3 (8-hour mean: 16±6 μm/m^3) and $PM_{2.5}$ was within a range of 2 to 11 μm/m^3 (8-hour mean: 7±2 μm/m^3). A 24-hour average of 25 μg/m^3 and 50 μg/m^3 is specified as the maximum contaminant limits for $PM_{2.5}$ and PM_{10}, respectively (Australian Building Codes Board ABCB, 2018). The 8-hour mean urban background levels of $PM_{2.5}$ and PM_{10} were 10.8 μg/m^3 and 17.7 μg/m^3, respectively, based on the measured data obtained from a station within 2 km distance from the school (Office of Environment and

Heritage, 2019). In the second day, indoor PM_{10} varied from 1 to 50 µm/m^3 (mean: 26±7 µm/m^3) and $PM_{2.5}$ was within a range of 3 to 12 µm/m^3 (mean: 6±1 µm/m^3). The 8-hour average outdoor PM_{10} was 16.9 µm/m^3. No $PM_{2.5}$ was available for this day.

a) b)

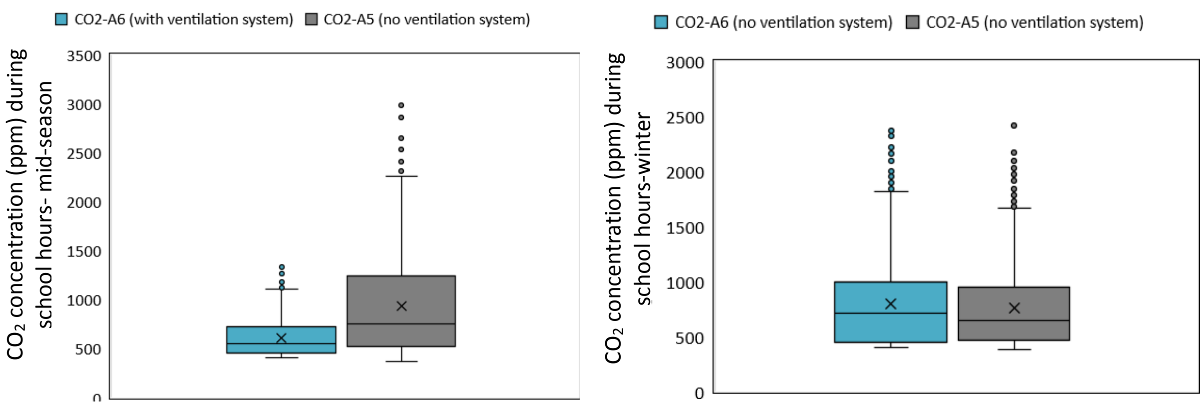


Figure 5: Box plot of CO_2 after (a) and before (b) installation of the ventilation system

3.1 Results from subjective survey and simultaneous measurements of physical parameters

The indoor air temperature varied between 20.7 °C and 26.4 °C with the mean value of 23.7 °C during mid-season questionnaire survey (2019). During the winter survey period, the indoor temperature fell in the range between 17.3 °C and 22.4 °C since no heating system was used in the classrooms. The average CO_2 concentration during the winter survey period was higher than that during mid-season survey period ranging between 718 ppm and 2114 ppm and from 442 ppm to 1510 ppm, respectively. The actual occupancy profile of the classrooms was not monitored. Therefore, data from unoccupied hours was retained in this analysis. In total, 376 and 306 responses to the questionnaires were pooled during winter and mid-season/autumn, respectively. During the winter survey period, the percentage of female and male students were similar (about 44 %), while during mid-season a higher percentage of participants were female (56 %). Based on the results of the right-here-right-now thermal sensation survey, the acceptable range of temperature for students was derived. Comfort zone refers to conditions falling within a range from -0.5 to +0.5 in which the predicted percentage of dissatisfied people is expected to be 20 %. The 20 % rate of dissatisfaction corresponds to 10 % dissatisfaction for general thermal discomfort, when $-0.5 <$ predicted mean vote (PMV) of occupants < 0.5, and an additional 10 % dissatisfaction due to local discomfort (ASHRAE 55, 2017). The overall rate of dissatisfaction (20 %) is related to the limits of ±0.85, which assumes 80 % of votes falling inside the central three categories of the ASHRAE scale. To find the empirical limits of acceptable thermal environments for 80 % satisfaction, the indoor temperature was calculated for the mean thermal sensation votes (TSV) of ± 0.85 using the linear regression model (Figure 6). The neutral temperature for the sampled students was derived for the entire survey period (combined winter and mid-season) using mean thermal sensation votes of students and air temperature per survey; i.e., 23.4 °C. The operative temperature was not used in the regression analysis due to a lack of simultaneous measurement of globe temperature in both classrooms. School children who participated in the surveys felt comfortable within an indoor temperature range of 19.5 °C to 27 °C. Moreover, they demonstrated considerable adaptability to classroom indoor air temperature variations, with one thermal sensation unit equating to approximately 4.6 °C difference in air temperature. A similar study in classrooms found an acceptable range of operative temperature from 19.5 to 26.6 °C for Australian students (de Dear et al., 2015).

The same study showed between-school differences in thermal sensitivity. Students in locations exposed to variable weather condition showed greater thermal adaptability than those in areas with more equable weather (de Dear et al., 2015).

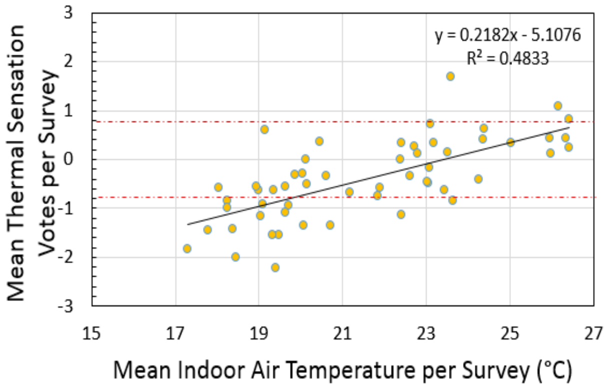


Figure 6: Linear regression analysis of thermal sensation against classroom temperature

As it concerns the thermal preference of students, a larger percentage of participating students wanted to feel warmer (57 %) than those who preferred a cooler or no change in the classroom during the winter survey. During autumn/mid-season, the percentage of 'No change' votes (42 %) was higher followed by the percentage of students wanted to be 'Cooler' (37 %).

4 CONCLUSIONS

This paper presents the results of the study performed to implement, monitor and evaluate the performance of hybrid ventilation technologies to provide indoor air quality and comfort. To achieve the objectives, detailed experimental investigations were performed in two adjacent classrooms of a private secondary school in Sydney, Australia. The long-term experimental campaign was conducted from April 2018 to May 2019 to monitor indoor air quality and thermal parameters continuously. Infiltration and Ventilation rates were measured equal to 0.86 ACH and 2.35 ACH, respectively. A hybrid ventilation system equipped with a window ventilator and Healthbox 3.0 were installed in February 2019 in one of the two classrooms. The system communicated with smart devices to enable real-time monitoring of the classroom air quality, temperature and humidity. The system supplied fresh air and removed the polluted air from the classroom based on CO_2 and VOCs detection. Analysis of indoor air quality and thermal comfort shows significant improvements in reducing CO_2 concentration in the classroom with ventilation compared to the classroom without a ventilation system. This will ultimately help to reduce the adverse health impacts of the environmental condition on children and improve productivity and performance. Furthermore, it was found that Australian students feel comfortable at a neutral temperature of 23.4 °C. This is consistent with previous literature and highlights that children feel comfortable at slightly lower thermal environments compared to adults. Further research should be proposed and implemented with a larger sample of schools to develop health-based ventilation guidelines for schools in Australia. Future research is needed to determine the discrepancies between the schools and classrooms exposures, which are not tested here.

5 ACKNOWLEDGEMENTS

Authors acknowledge CRC for Low Carbon Living, RENSON®, and St Spyridon College to support this study. Special thanks go to all students and teachers who participated in this research.

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