Ventilation rates of classrooms as an example of authentic inquiry in STEM

Kenneth Y T Lim[a], Xinyue Wu[b], Yuling Dong[b] and Boon Hian Tan[c]

[a]National Institute of Education, Singapore; [b]Hwa Chong Institution, Singapore ; [c]Nanyang Girls' High School, Singapore

Abstract

Ventilation has always been closely linked to thermal comfort, which affects productivity of building occupants. In view of the COVID-19 pandemic, heightened attention has been brought to the ventilation of classrooms, an important factor in evaluating the risk of school-based transmission of the SARS-CoV-2 coronavirus. This study investigates the ventilation rates of different types of classrooms in a school, located in the Bukit Timah area of Singapore. Using an Arduino sensor with a carbon dioxide sensor and the model of carbon dioxide decay, it was found that the air changes per hour (ACH) is ideal for all classrooms above ground when the windows were open, regardless of whether the fans were turned on. On the other hand, when the only ventilation is the air conditioner, there was low and insufficient ACH for any classroom regardless of its location. For rooms which were partially underground and enclosed, this problem was resolved similarly by turning on the fans and opening the windows, where cross ventilation yields ideal ACH. The exception was the case when two of these partially underground rooms were combined into one, where the ACH was only at a bare minimum even when the windows were opened and fans were turned on.

Introduction

Ventilation refers to the process of introducing and distributing outdoor and/or properly treated recycled air into a building or a room (Etheridge & Sandberg, 1996). The amount of outdoor air circulated per unit time is termed the ventilation rate (Li et al., 2007). In this paper, the unit used for ventilation rate is air changes per hour (ACH).

Ventilation is particularly pertinent to thermal comfort, and the thermal quality of classrooms translates into a positive effect on students' performance (Pepler & Warner,

CONTACT Kenneth Y T Lim, kenneth.lim@nie.edu.sg

1968). Therefore, ventilation in classrooms is especially important in view of the rising temperatures due to climate change and the increased Urban Heat Island (UHI) effect both having a major impact on Singapore's thermal comfort (Opsomer, 2020). Research has reported an average UHI in Singapore of 4°C, even exceeding 7°C at some times of the day (Acero & Ruefenacht, 2017).

Thermal comfort in tropical climates can be achieved by ventilative cooling to reach 5 ACH within buildings (Chandra, 1989).

In addition, ventilation rate is a key factor in the transmission of infectious diseases. An outbreak of an airborne disease could be directly attributed to a lack of outdoor air into and circulation within an enclosed space (Wells, 1955). Specifically, the SARS-CoV-2 coronavirus airborne transmission can be resulted from an inadequate supply of outside air (Man et al., 2020). Besides that, ventilation is a major method for reduction and control of the spread of infectious disease particles via the airborne route (Kaushal, Saini & Gupta, 2004). The ACH for low risk of transmission of the SARS-CoV-2 coronavirus is at least 5 (Allen et al., 2020).

To obtain the ventilation rate of the classrooms, the methodology makes use of the carbon dioxide decay method. The concentration of carbon dioxide is tracked with an Arduino CO2 sensor. The scope of this investigation is the selected classrooms and special rooms in Nanyang Girls' High School. The assumption made in this study is that the concentration of carbon dioxide is uniform throughout the classroom.

Objectives

1. To find out the ventilation rate in the classrooms.
2. To identify the factors affecting ventilation rate and account for the ventilation ability of the respective classrooms.
3. To test out the methods to increase ventilation rate and evaluate their effectiveness.

Literature review

Building Geometry Affects Ventilation

Wind speeds in Singapore are generally rather low due to the city state's proximity to the equator (Acero & Ruefenacht, 2017). The mean surface wind speed is generally lower than 2.5 m/s (Meteorological Service of Singapore, 2019).

Among the Strategies for cooling Singapore (Acero & Ruefenacht, ibid.), the factors of building geometry affecting ventilation identified to be applicable to our research are: variation between building heights, building porosity and building arrangement.

Besides the building structure, the type of opening of the room is also a significant factor affecting ventilation. Single-sided ventilation refers to the room where the only obvious openings are positioned along just one side of the room. Single-sided ventilation through a small opening is driven by random turbulent fluctuations, making it unreliable and not recommended as part of a controlled natural ventilation strategy (World Health Organisation, 2009).

On the other hand, cross flow ventilation relies on establishing a clearly defined and unimpeded air flow path between the incoming and outgoing air streams which should pass through the zone of occupancy (Liddament, 1996). Such an air flow pattern is impeded if the building is compartmentalised. Cross flow ventilation is a preferred strategy since it displaces air more effectively in a larger portion of the classroom (Allen et al., 2020).

Carbon Dioxide Decay Method

Carbon dioxide is often used as an indirect measure of ventilation, using the dilution effect of CO2 due to outdoor air flow (Allen et al., ibid.). Outdoor air gets into the classroom due to a pressure differential, caused by bulk motion (wind), a temperature gradient (buoyancy), or a mechanical system (negative pressure due to an exhaust fan). The rate of decay of the CO2 concentration can be used to estimate how fast air from outdoors replaces the indoor volume of air.

Methodology

Materials

- 1* CO2 Arduino sensor with Wi-Fi enabled board connected to the computer;
- 2 boxes of 5kg dry ice pellets for each classroom;
- 1* measuring tape;
- 2* handheld fans (To accelerate the diffusion of CO2)

Setup

Using a measuring tape, measure the room length, width and ceiling height to estimate the volume of the classroom/special room. (Due to the furniture occupation, take the final volume as 90% of the calculated result.) Using the formula:

$$Volume = 90\% * length * width * height$$

Count the number of windows and doors, and measure their dimensions to calculate their openable area.

Connect the CO2 arduino sensor to the computer, and set up the CO2 sensor to log measurements one time per ten seconds.

Measure the outdoor CO2 concentration with the CO2 sensor for five minutes before and after the indoor experiments, to take average to get the background concentration.

Place the CO2 sensor in the classroom away from the dry ice container location and approximately one metre above the floor.

Use dry ice to cause the CO2 concentration to build up in the classroom to approximately 2000 ppm. (Place two open boxes of dry ice in the centre of the classroom and use handheld fans to speed up the mixing of CO2.)

Check the concentration of CO2 on the CO2 sensor. When it reaches 2000 ppm, remove the dry ice container, return airflow to normal condition (with/without fans) and have all people present in the room leave the room.

Allow the CO2 concentration in the classroom to decay to an indicative point of 37% of its original peak concentration above the background concentration.

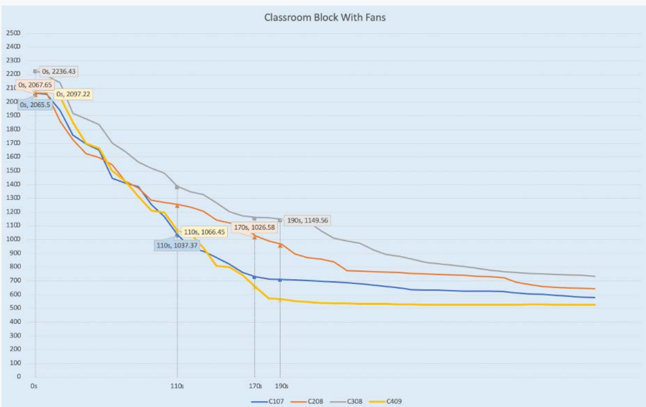
Results

The results are shown in the graphs below. For each graph, the x-axis represents the duration of the experiment (in seconds) and the y-axis represents the concentration of CO2 (in ppm). Both the starting point, and the indicative point (37%) / end point of the experiment, are reflected in each graph.

Figure 1 shows the graph of CO2 decay rate of classrooms in classroom block when fans are turned on. In the classroom block when fans are turned on, C107, C208, C308, C409 take 110s, 170s, 190s and 110s respectively to return the carbon dioxide level

Figure 1

Classroom Block with fans

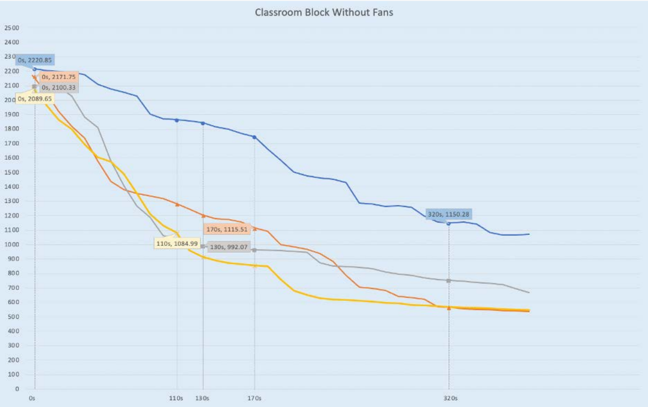


to the indicative point.

Figure 2 shows the graph of CO2 decay rate of classrooms in classroom block when

Figure 2

Classroom Block without fans



fans are turned off:

Figure 3 shows the graph of CO2 decay rate of classrooms in science block when fans are turned on:

Figure 3

Science Block with fans

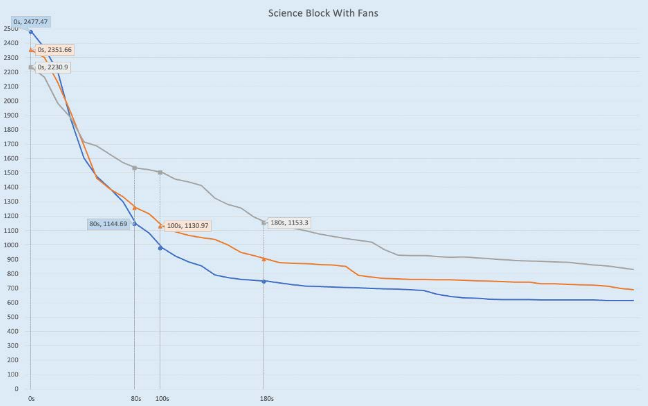


Figure 4 shows the graph of CO_2 decay rate of the classrooms in science block when fans are turned off:

Figure 4

Science Block without fans

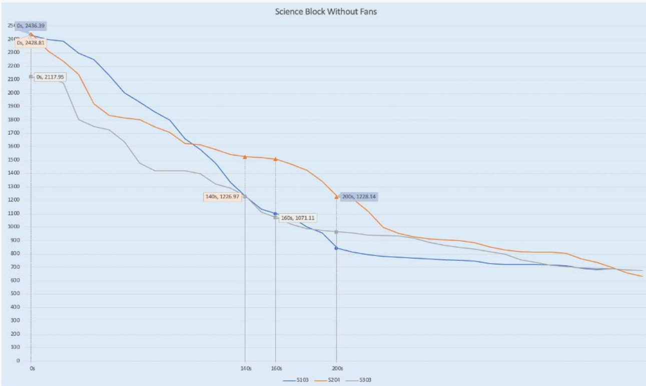


Figure 5 shows the graph of CO_2 decay rate of room S407:

Figure 5

Room S407

Figure 6 shows the CO2 decay rate of the Special Rooms:

Figure 6

Special Rooms

The following table shows the dimensions and designs of rooms experimented. The result (ACH) and the level it is corresponded to are also reflected in the table.

According to the chart for different levels of ventilation, all the classrooms in both science block and classroom block reach or exceed the ideal level, which is 6 ACH, under both fans-on and fans-off conditions, excluding room S407 when the air conditioner is turned on. For rooms with the air conditioner turning on, all the ACH are below 3 ACH.

Discussion

From the results, it shows that there is no significant difference in the final values of ACH between fans on and fans off condition for the classroom block and science block (excluding room S407), but they all reach the highest level of ACH (ideal). As for room S407, its ventilation rate reaches ideal level only when fans are on and windows are open. When the air conditioner is on and windows are closed, room S407's ACH is only 1.5, which is at low level (less than 3 ACH). As for special rooms, when the air conditioner is on and windows are closed, all the special rooms tested (including SPR1, SPR1 and 2 combined and SPR4) only achieve the 'low' level for ACH. When fans turn on and windows are open, SPR reaches 14 for ACH, which is at the ideal level. However, SPR 1 and 2 combined only have 3.4 for ACH, which is at the 'bare minimum' level.

Table 1

A summary for the information of classrooms measured

classroom	C107	C208	C308	C409	S103	S204	S303	S407	SPR1	SPR1+2	SPR4
Dimension (length* width*height)	8.0m *8.0m *3.8m	8.0m *8.0m *3.4m	8.0m *8.0m *3.4m	8.0m *8.0m *2.8m	8.0m *8.0m *3.8m	8.0m *8.0m *3.4m	8.0m *8.0m *3.4m	8.0m *8.0m *2.8m	9.3m *7.2m *3.5m	18.6m *7.2m *3.5m	9.3m *7.2m *3.5m
volume/m3	243.2	217.6	217.6	179.2	243.2	217.6	217.6	179.2	234.4	468.7	234.4
unoccupied volume/m3	218.88	195.84	195.84	161.28	218.88	195.84	195.84	161.28	210.96	421.83	210.96
opening area/m2	17.45	16.33	16.33	18.83	17.45	16.33	16.33	11.24	2.40	4.80	6.20
ACH (with fans)	33 (ideal)	21 (ideal)	19 (ideal)	33 (ideal)	45 (ideal)	38 (ideal)	20 (ideal)	15 (ideal)	NA	3.4 (Bare minimum)	14 (ideal)
ACH (without fans)	11 (ideal)	21 (ideal)	28 (ideal)	33 (ideal)	26 (ideal)	18 (ideal)	26 (ideal)	1.5 (low) (with aircon)	low	low	low

There are numerous reasons causing the ventilation ability of the classrooms to vary. After comparing across these classrooms, the following are selected as the most significant factors affecting the ventilation rates of the classrooms in this particular school.

Building design and structure

Classrooms in both the Classroom block and Science block are designed in semi-open structure, with the top part of the corridor side having a gap with the ceiling, as shown in Figure 7.

This allows air to circulate in and out of the classroom. Moreover, according to the online meteorological service MyForecast, the average wind direction in Bukit Timah region (location of the school) is North East between November and April, and it is South wind between May and October. Since both buildings are north-south designed, the wind can pass directly through the classroom, resulting in a preferable condition for ventilation. Furthermore, classrooms that have a structure with two openings on the opposite walls have cross flow ventilation, which is preferable. Cooler air from outside can push the hot air inside out more easily compared to single opening structures.

As for room S407, it is specially designed. Different from other rooms in the science block and classroom block with a semi-open structure, room S407 is sealed with air conditioning. Hence, when the air conditioner is turned on (which means all its windows and doors are closed), the ventilation ability of S407 is significantly lower than other classrooms in the same block.

For special rooms, they are compartmentalised, thus impeding air flow. Figure 8 shows that SPR 4 has two openings (excluding the door side) on the adjacent walls, making it cross flow ventilation. Figure 9 shows that SPR 1 and 2 combined only have a single opening, and hence has single-sided ventilation. (The door side is connected to a sealed corridor, and would not help much in diffusing carbon dioxide out of the special room. Hence, it is not considered as an opening). SPRs have fans on top of the ceiling, which is similar to classrooms in the classroom block and science block. However, the

Figure 7

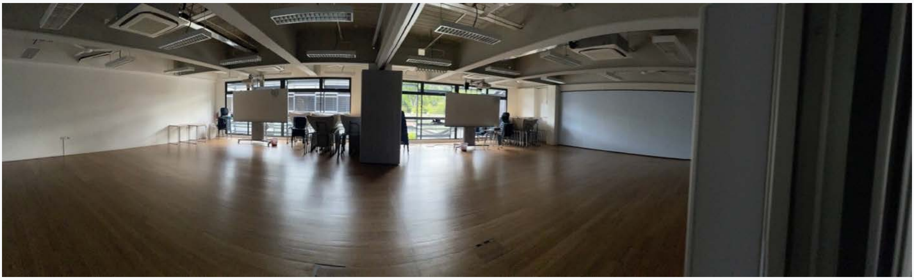
A typical classroom in the classroom / science block

Figure 8

Special Room 4 (SPR 4)

Figure 9

Special Rooms 1 (left) and 2 (right) combined (SPR 1+2)



ACH of SPR 1 and 2 combined still only reached 'bare minimum' level when windows are open and fans are on, while the ACH of SPR 4 reaches the ideal level. The cross ventilation structure provides SPR 4 an advantageous condition for ventilation.

Outside environment of the building

Outside environment refers to the location the building is present, as well as obstructions around the building. With less obstructions, the air can move inside and out freely, providing a better condition for ventilation to happen. For the classroom block, in front of it is a quadrangle as shown in Figure 10. There is a grass patch between the classroom block and the science block, as shown in Figure 11.

A road is behind the Science Block, with no blockage by tall buildings within 20 metres around it. This also provides an advantageous condition for ventilation to happen in these two buildings.

Figure 10

The quadrangle in front of the classroom block

Figure 11

The grass patch between the science block and the classroom block

As for special rooms, directly opposite to the single opening of SPR 1 is another building (shown in Fig 6.3), which can block the air coming out, leading to a slower ventilation rate. As for SPR 4, since when the back facing the door of SPR 4, the right window and the front window face the grass patch and the field respectively, and are not blocked by large buildings, the air inside it can move out freely without obstacles. This provides an advantageous ventilation condition for SPR 4 as well.

Presence of fans and openable areas

Although it has been mentioned that there is no significant difference in the final values (ACH) between fans on and fans off condition for the classroom block and science block (excluding S407), the presence of fans and openable areas leave a significant impact on the ACH for special rooms and S407. The reason why the presence of fans does not have a great impact on the classrooms in the classroom block and the science block (excluding S407) is because these classrooms have a semi-open structure. Their special structure plays a more crucial role in determining the ventilation ability of these classrooms compared to the presence of fans and opening areas, which is sufficient to keep ACH at the ideal level.

When the structure is sealed, fans and openable areas (windows and doors) play a significant role in improving the ACH. When fans are on and windows are open, S407 reaches the ideal level for ACH, significantly better than the low level when the air conditioner is turned on and windows are closed. Same for SPR 1 and 2 combined and SPR 4, fans-on and windows-opened condition significantly improve their ventilation performance, from low to bare minimum, even to ideal.

Limitations

First, data for a particular classroom were captured on a single day, which will reflect only the weather on that day. The infiltration rate for air entering the building from the outside is highly dependent on the outdoor weather conditions (Allen et al., 2020). Hence, the ventilation ability of each room may vary on different days due to different weather conditions.

Second, not all parts of the room are equally well mixed with carbon dioxide. For example, as carbon dioxide is denser than air, it will sink to the lower part of the classroom. This means the data collected may not be fully representative of the concentration of carbon dioxide of the whole room and the ventilation ability calculated may not comprehensively reflect the actual ventilation ability of the whole room.

Lastly, the scope of the experiment is very narrow, focusing on only one school in Singapore. Hence, the results cannot be generalised to apply to other schools.

Conclusion

In conclusion, there are various methods that can affect the ventilation rate of a building, including the structure of the building, the type of opening it has, the outside environment around it, and the presence of fans and openable areas. Generally, a semi-open structure increases building porosity, maximising air permeability and hence, air flow (Acero & Ruefenacht, 2017). Additionally, the cross-flow ventilation design, with two openings adjacent or opposite to each other, is advantageous for increasing the ventilation rate due to its ability to displace more air. However, the semi-opened structure is uniquely applicable to tropical areas such as Singapore. For countries with four distinct seasons, this structure is not suitable for their winter. As an alternative method, they can consider implementing mechanical systems.

The ventilation rate for most classrooms in the school, which are generally located in the science block and classroom block, are far exceeding the ideal ACH level. This is because the different blocks in the school have uniform building arrangements parallel to each other and to the prevailing wind, avoiding sea breeze obstruction. Improper building arrangements can reduce wind speeds (Acero & Ruefenacht, ibid.) and as a result, ventilation rates. Even though the blocks have no variation in building heights, which is unfavourable for wind capture and increasing wind velocity, there is little impact on ventilation due to the low wind speeds in Singapore. Therefore, the ventilation of the classrooms aboveground are ideal, and no further action is needed to increase their ventilation. For the special rooms with single openings, the school can introduce more portable fans, which would increase air flow. Mechanical systems would not be advisable due to operational cost and maintenance, as the classrooms in the tropical climates are able to open the windows and turn on fans all year round.

References

Acero, J.A., & Ruefenacht, L.A. (2017). *Strategies for cooling Singapore. A catalogue of 80+ measures to mitigate urban heat island and improve outdoor thermal comfort (Cooling Singapore 2017).* Retrieved from Cooling Singapore website: https://www.coolingsingapore.sg/catalogue-of-strategies

Allen J., Spengler, J., Jones, E., Laurent C. J. (2020). *5-step guide to checking ventilation rates in classrooms.* Retrieved from Schools For Health website: https://schools.forhealth.org/wp-content/uploads/sites/19/2020/10/Harvard-Healthy-Buildings-program-How-to-assess-classroom-ventilation-10-30-2020.pdf-EN.pdf

Chandra, S. 1989.Ventilative cooling. In Cook, J,. Ed. *Passive cooling: Fundamentals and applications.* Cambridge, MA: MIT press

Etheridge D, Sandberg M. *Building ventilation — theory and measurement.* Chichester, UK: John Wiley & Sons; 1996.

Kaushal V, Saini PS, Gupta AK (2004). Environmental control including ventilation in hospitals. *JK Science, 6*: 229 232.

Li, Y., Leung, G.M., Tang, J.W., Yang, X., Chao, C.Y.H., Lin, J.Z., Lu, J.W., Nielsen, P.V., Niu, J., Qian, H., Sleigh, A.C., Su, H.-J.J., Sundell, J., Wong, T.W. and Yuen, P.L. (2007), Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systematic review. *Indoor Air, 17*: 2-18. https://doi.org/10.1111/j.1600-0668.2006.00445.x

Liddament M.W. (1996). *Guide to Energy Efficient Ventilation.* Retrieved from: https://www.aivc.org/resource/gv-guide-energy-efficient-ventilation

Man P., Paltansing S., Ong D.S.Y., Vaessen N., Nielen G., Koeleman J.G.M. Outbreak of coronavirus disease 2019 (COVID-19) in a nursing home associated with aerosol transmission as a result of inadequate ventilation. *Clinical Infectious Diseases. 2020* doi: 10.1093/cid/ciaa1270.

Meteorological Service Singapore. (2019). *Climate of Singapore.* Retrieved October 30, 2019, from http://www.weather.gov.sg/climate-climate-of-singapore/ Meteorological Service Singapore. (2017). Annual Climatological Report 2017. Retrieved from Meteorological Service Singapore website: http://www.weather.gov.sg/climate-annual-climate-reports/

Opsomer, A. (2020). *Exploring the Effects of Void Decks on Urban Ventilation in Singapore: A Computational Design & Simulation Approach for Wind Microclimate-Informed Urban Planning.* Retrieved from: http://resolver.tudelft.nl/uuid:97304da6-8938-48eb-8117-ca53321b1e34

Pepler, R.D.; Warner, R.E. Temperature and learning: An experimental study. *ASHRAE Trans. 1968, 74*, 211–224.

Wells, W.F. (1955) *Airborne Contagion and Air Hygiene: an Ecological Study of Droplet Infection,* Cambridge, MA, Harvard University Press.

World Health Organization. Regional Office for Europe. (2009). *WHO guidelines for indoor air quality: dampness and mould.* World Health Organization. Regional Office for Europe. https://apps.who.int/iris/handle/10665/164348