CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

Natural Ventilation and Indoor Air Quality in Domestic School Building: CFD Simulation and Improvement Strategies

Adryan Seng Theng Ang[1], Charlie Chin Voon Sia[1,*], Yee Lee Yeu[1], Kok Hing Chong[1], Chin Seng Chia[2], Annie Joseph[3]

[1] Faculty of Engineering, Computing and Science, Swinburne University of Technology (Sarawak Campus), 93350 Kuching, Sarawak, Malaysia
[2] Mechanical Branch, JKR Sarawak Headquarters, 93582 Kuching, Sarawak, Malaysia
[3] Faculty of Engineering, University of Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

ARTICLE INFO

Article history:
Received 22 June 2023
Received in revised form 18 July 2023
Accepted 16 August 2023
Available online 12 December 2023

Keywords:
Natural Ventilation; Solidworks Flow Simulation; Dilapidated School; Thermal Comfort

ABSTRACT

Natural ventilation is a process of replenishing used air from the interior environment with fresh outer air without the use of mechanical equipment. This project aims to investigate the feasibility and performance of implementing natural ventilation in dilapidated classroom designs of actual geometry. Computer models of an existing classroom were created using SOLIDWORKS based on real-scale building floor plans, while the same software was applied to compute flow simulation studies to visualise the airflow pattern, temperature distribution, relative humidity, and the thermal comfort level of occupants in the classrooms. Estimated climate parameters were input in the simulation process to illustrate better the effect of hot and humid climate conditions in Malaysia towards the thermal comfort level of occupants. In this project, a visualised wind tunnel was created to simulate the prevailing wind source that supplies wind to the designed classroom, and the airflow pattern across the designed building was analysed. From the initial simulation results, it was discovered that the airflow into the classroom is uneven, whereby some locations in the building are experiencing extremely low wind breeze, which eventually affects the comfort level of occupants in the room. On the other hand, an internal analysis focusing on the interior comfortability of the classrooms was applied to examine the thermal comfort condition while using the naturally ventilated classrooms. Recommendation optimisation approaches such as the louvre angle and introduction of a windcatcher was presented in this project to improve the natural ventilation performance of the designed classroom.

1. Introduction

Natural ventilation is a process of directing fresh and cool air from outside into the interior environment without the use of mechanical equipment. It offers an alternative way of providing ventilation to an enclosure with less or no energy consumption by eliminating mechanical ventilating machines. Studies have shown that natural ventilation can greatly reduce the amount of energy used and can save up to 25% of overall building energy consumption compared to a mechanical ventilated

---

[*] *Corresponding author.*
E-mail address: cvsia@swinburne.edu.my (Charlie Sia Chin Voon)

https://doi.org/10.37934/cfdl.16.3.114

building [1], while Zhao *et al.,* [2] reported about 40% of building energy consumption is compensated to mechanical ventilation and 35% of carbon dioxide emission in Europe country. The physical environment and thermal comfort level in a classroom could significantly influence the performance of students in terms of their motivation to study as well as their concentration during classes [3, 4]. In relation to this, natural ventilation is attained by purposely built openings around the enclosure, or recently, the wind-assisting device is often applied to facilitate the process [1, 5-7]. While in Malaysia, dilapidated schools, specifically in some rural areas, are not accessible to electricity may greatly impact the learning environment due to the absence of mechanical ventilation. Therefore, the implementation of natural ventilation has become the ideal solution for ventilation requirements in these buildings.

There are several approaches for natural ventilation commonly used in building design considerations. The two most seen natural ventilation type is the single-sided ventilation and cross-ventilation. The former refers to the use of one or more openings at only one of the room façades, whereas the latter mode of ventilation provides airflow through openings at more than one face of a particular room [8]. In addition, natural ventilation is also facilitated by natural phenomena around us, such as wind-driven natural ventilation and stack ventilation. Wind-driven ventilation provides the circulation of air by using natural wind as the driving force. The positive pressure gradient created at the windward side of the building generates a flow to the negative pressure side at the leeward side of the room. With openings on the appropriate façade of the building envelope, a flow can be produced which promotes natural ventilation. On the other hand, stack ventilation is driven by natural air movement due to density differences between hot and cooler air. Openings in this type of ventilation effect usually are located at the top of the building where hot air stacked in the room continues to rise and eventually leaves the building. The negative pressure region created promotes cooler air from the outside to replace the emptied spaces [9].

Implementing natural ventilation system is highly dependent on the weather condition of the location. The hot and humid climate is also perceived as the main challenge in designing naturally ventilated enclosures for cooling purposes [1]. In Malaysia, people experience consistently hot and humid climate conditions in almost all regions. According to the weather data [10], which is shown in Figure 1, the maximum day temperature ranges from approximately 30°C to 33°C, and relative humidity ranges from 83% to 85%. In addition, the number of rainy days constitutes about one-third of the days in a year, which means that temperature discrepancies can be expected. Hence, the local microclimate condition is the deciding factor of the thermal comfort level of occupants in a natural ventilated building.

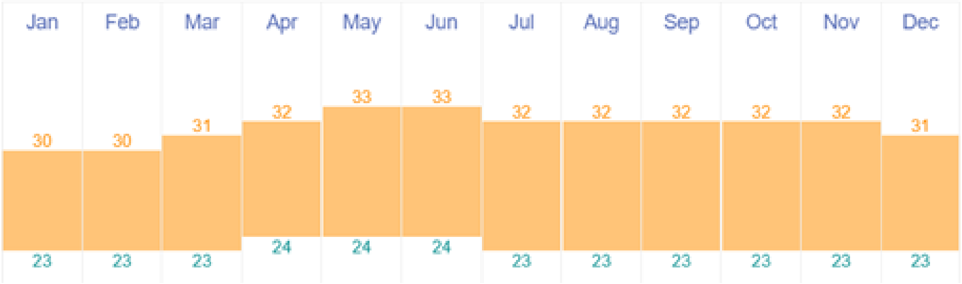


Fig. 1. Average temperature in Kuching, Sarawak [8]

Thermal comfort is defined as the state of mind where thermal satisfaction in the environment is achieved. According to ASHRAE Standard 55, the thermal comfort level is determined by six primary factors, i.e., metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity level [11]. A thermal sensational scale derived from the heat balance principle relating to the factors mentioned above is used to measure the thermal comfort condition of occupants in a designed space as proposed in ASHRAE Standard 55. It levels the thermal comfort of occupants by using the Predicted mean vote (PMV) model, which ranges from hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (-1), cool (-2) and cold (-3). On the other hand, the Predicted Percentage of Dissatisfied (PPD) index related to the PMV model estimates the percentage of occupants dissatisfied with the thermal environment. The thermal comfort level in a hot and humid country varies. Malaysian Standard MS1525 recommends a comfortable cooling condition in a mechanical ventilated building with 24°C to 26°C dry bulb temperature, 50% to 70% relative humidity and 0.15 m/s to 0.50 m/s air velocity while naturally ventilated enclosure should be acceptable at a range slightly higher than the mentioned specification. Taib *et al.,* [12] reported that the thermal comfort temperature in Malaysia is estimated to lie between 24°C to 30°C. A similar range of thermal comfort temperature was supported by Aynsley [13], but the comfort temperature will be adjusted lower with higher relative humidity (greater than 60%), but airflow raises the thermal comfort range significantly as it increases (0.55°C for each 0.15 m/s). Furthermore, Shahrom *et al.,* [14] stated that a temperature range from 23°C to 30.9°C is acceptable in naturally ventilated classrooms. Hence, this shows that the thermal comfort perception may vary from time to time, location, and the micro climatic condition in an enclosure.

Flow around a building is one of the key design considerations, particularly in naturally ventilated buildings. According to ASHRAE [15], external flow around the building is essential to identify the environmental impact, such as pollutant dispersion, pedestrian wind comfort and safety, and wind-driven rain building. It was mentioned that the contaminants are likely to follow the airflow, but there is also the possibility that the recirculating region will reverse the direction, bringing the pollutants back to the enclosure or contaminating the wake region. Also, safety concerns usually are omitted when designing a building. In fact, the high wind speed at the downflow of high-rise buildings may be dangerous at pedestrians' level.

Due to its energy-saving benefits, wind-driven ventilation is a topic of interest in naturally ventilated design buildings. While experimental investigation on the performance of wind-driven ventilation is viable through wind tunnel experiments, it is often that researchers use Computational Fluid Dynamics (CFD) as an alternative method to perform virtual experiments as it is more cost-effective and it provides accurate results analogous to model testing. For example, Bangalee *et al.,* [16] used CFD to simulate the flow pattern inside and around a full-scale single-story building with multiple windows, mimicking the actual wind tunnel experiments using the virtual computational domain, Cheng *et al.,* [17] suggested using CFD to find the relationship between ventilation coefficients and building parameters and form empirical equations that anticipate the natural ventilation potential, while Tai *et al.,* [18] investigated the effect of louvres window position and the angle of louvres affecting the performance of natural cross ventilation.

Although tropical climate condition is a major issue for natural ventilation, thermal comfort studies on naturally ventilated buildings in tropical countries show that the people living in these countries can better adapt to the thermal environment. In the thermal comfort field study [19-22], they concluded that a higher range of thermal comfort parameters is determined in naturally ventilated classrooms in tropical climate countries.

The utilisation of natural ventilation in domestic schools located in rural areas with limited electricity access presents an intriguing engineering research opportunity. Sekolah Daif serves as a compelling case study for implementing the concept of natural ventilation due to the absence of electricity infrastructure in most of these schools. Consequently, it becomes imperative to investigate whether the existing natural air ventilation strategies effectively cater to the occupants' thermal comfort requirements or if supplementary ventilation systems are necessary to optimise students' learning experience and environmental conditions. Hence, this research will analyse the airflow pattern and thermal comfortability in the current classroom design in Sekolah Daif and propose an alternative to improve natural ventilation performance.

2. Methodology

Figure 2 shows the computed 3D model of a classroom in *Sekolah Daif* from the provided floor plan, where the compartment dimension is 9 m × 7.5 m × 3.3 m. The six openings, i.e., four windows and two doors, facilitate natural ventilation in the designed classroom. The front section is allocated at the building façade where one window and two door openings (2.55 m × 1.5 m) are placed. The window opening (1.8 m × 1.65 m) of the classroom is equipped with a horizontal Altair Louvres Window, where occupants are allowed to control the amount of airflow entering the enclosure. The operable angles of openings enable different amounts of airflow and direction, which may be desirable in different microclimate conditions. On the other hand, it was mentioned that the classroom walls are made up of lightweight concrete panels with generally lower thermal transmittance or high resistance to heat. Hence, it obstructs an amount of heat flowing into the interior through the conduction of solids which eventually regulates a portion of the internal temperature (but not infiltration).

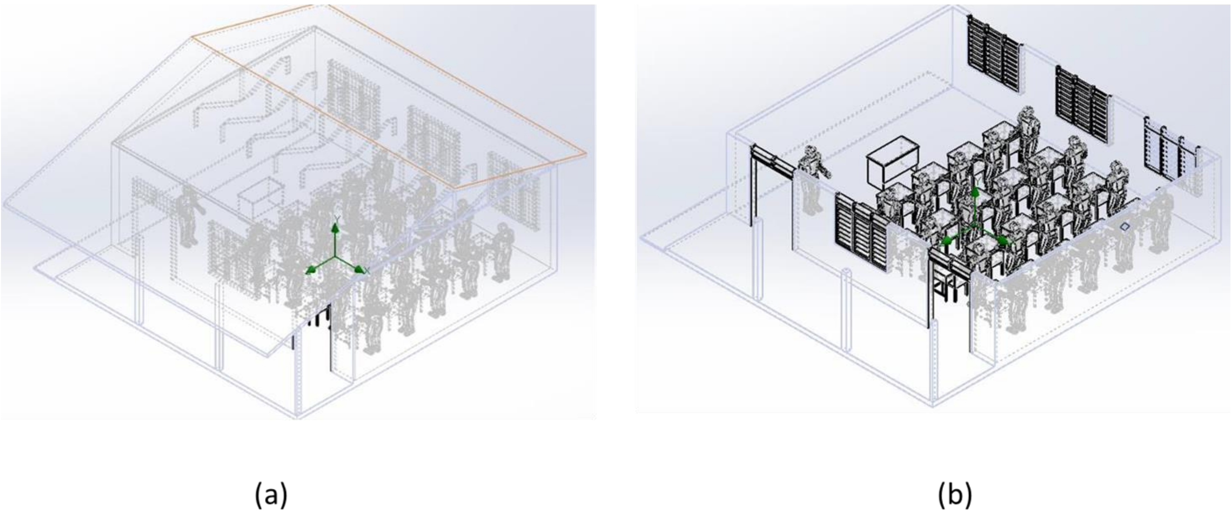

(a) (b)

Fig. 2. 3D model of dilapidated school classroom

2.1 Method I: Visualised Wind Tunnel Analysis

This simulation approach analyses the wind flow around the buildings and identifies the airflow pattern formed when a source of the prevailing wind is typically directed to the classroom model's openings. The analysis mimics the test section area of a wind tunnel with the assumed direction of the prevailing wind source. It is crucial to identify the flow pattern as inappropriate building geometry may cause contamination of pollutants. In addition, it was observed that the magnitude of prevailing wind supply is not necessarily the same as the wind velocity received at the openings of the building envelope, e.g., door and windows. In fact, the air velocity entering an opening may be affected by the building geometry or obstacles. Therefore, this method provides more accurate readings on the wind velocity approaching the designed classroom and will be used as the input velocity in the subsequent analysis method.

2.2 Method II: Internal Thermal Comfort Analysis

In accordance with the previous simulation, the average wind velocity approaching the door and window openings is collected from near the surface of the openings, and the information is used as the average air velocity input in this analysis. Internal thermal comfort analysis focuses more detail on the airflow pattern in the designed classroom and the temperature fluctuations with time. In this analysis, the human model that is the main source of heat is implied into the simulation model and the thermal comfort level is assessed in Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). In this sense, the thermal comfort level can be studied, and the performance of natural ventilation in the existing design of the classroom can be justified.

2.3 Boundary Conditions

To cater for all cases, the design of simulation in this research project will consider the worst-case scenario, which is during the peak cooling load requirement at the maximum temperature and average wind speed. According to the weather report [8], the maximum ambient temperature recorded in Kuching, Sarawak, is approximately 33℃ with an average wind velocity of 1 m/s. It is assumed that the initial ambient temperature is at its peak value, and it is maintained throughout the simulation case. On the other hand, a value ranging from 0.25 to 1.0 m/s with an interval of 0.25 m/s is used as the wind velocity input to investigate how wind magnitude affects the thermal comfort level of occupants and temperature distribution in the current design of the classroom. These values are input as the boundary condition of the prevailing wind source in Method I.

An average approaching wind velocity near the openings of window and doors are simulated from the software, and it is used as the subsequent wind speed input for Method II. On the other hand, the computed human model is specified as a heat source with a temperature of 37℃. An estimated heat gain by ambient air surrounding the human model is expected. Solid Materials for the indoor classroom with an initial temperature of 26℃ are specified, and heat gain is expected. For the existing simulation case, the outlet is defined at the other end of the enclosure to simulate a cross-ventilation case. The outlet is set to be under environmental pressure. The boundary conditions are summarised in Table 1. Figure 3 shows an example of the boundary condition that was applied for the simulation study.

Table 1
Initial boundary condition

Method	Initial boundary condition	Description
I	Prevailing wind speed (method I)	0.25 – 1.0 m/s
	Pressure Outlet	Environment pressure
II	Indoor temperature	33 °C
	Heat source (human body)	37 °C
	Initial solid temperature	26 °C
	Pressure outlet	Environment pressure
	Relative humidity	83%
	Simulation time	360 s

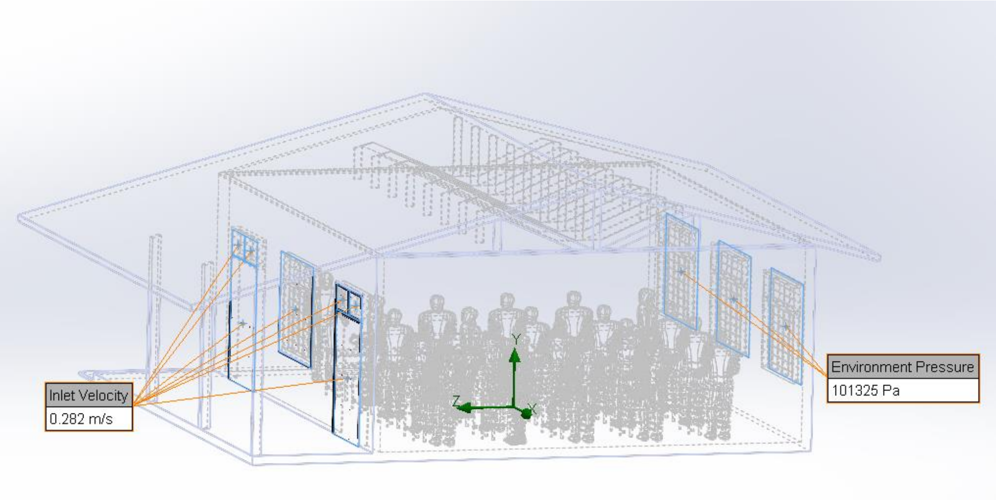


Fig. 3. Boundary conditions in the simulation model

3. Results

3.1 Wind Tunnel Analysis

Figure 4 illustrates the airflow pattern across the building geometry computed in the middle section of the classroom. The simulation result showed that a few areas are prone to forming a vortex. This can be observed at the front part, where the flow is developed at the ground level, downstream of the downward inclined roof, and also the region after the outlet. This vortex formed can also be known as the standing vortex, whereas the downstream region represents the flow recirculation region [15]. In addition, there is a recirculating region and wake formation near the outlet of the classroom.

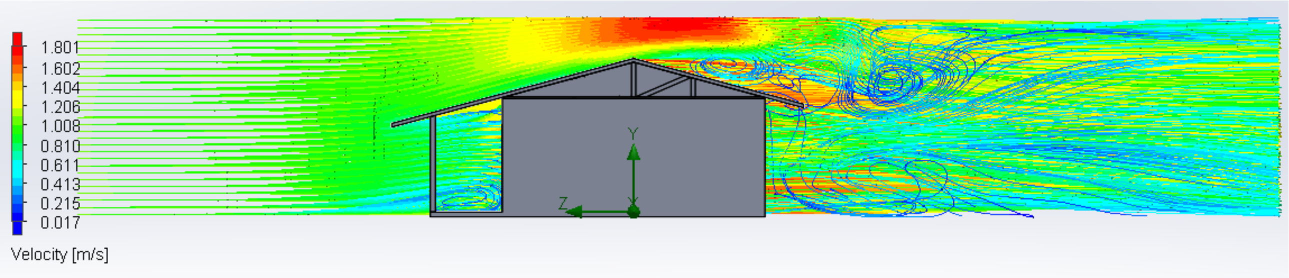


Fig. 4. Airflow pattern across classroom

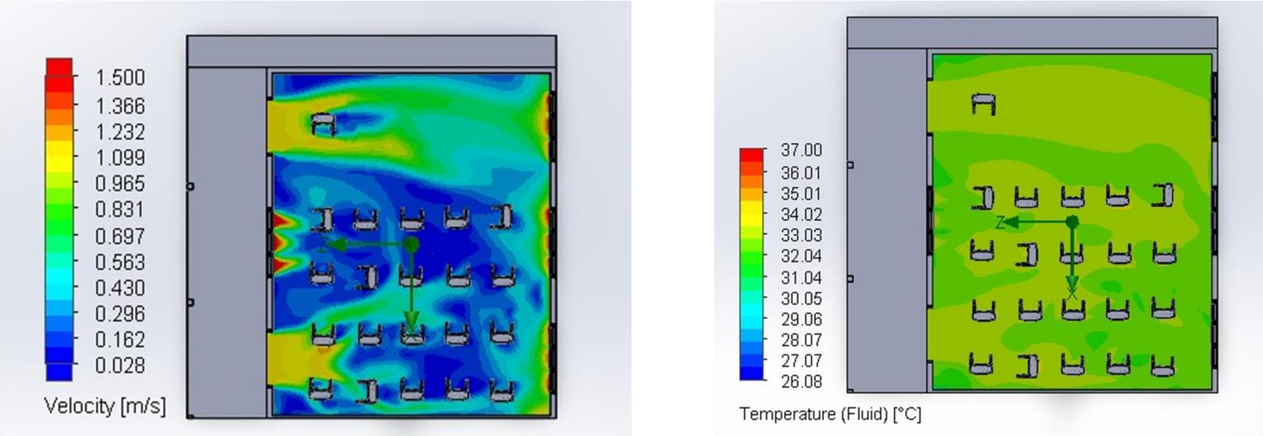
Table 2 shows the corresponding wind speed approaching the inlet of the opening of the existing classroom design. It was found that the wind speed is slightly more significant than the prevailing wind velocity as it approaches the openings of the classroom.

Table 2
Corresponding inlet velocity at different wind velocities

Prevailing wind speed (m/s)	Surface wind speed (m/s)
0.25	0.282
0.50	0.558
0.75	0.836
1.00	1.113

3.2 Internal Thermal Comfort Analysis

Figure 5 shows the simulated results for air distribution at which inlet velocity is the maximum (1.13 m/s). The maximum wind velocity was recorded at the opening area, which is comparable with simulation results obtained by Shak *et al.,* [23]. In addition, Shak *et al.,* [23] also reported that only a slight temperature difference of about 0.22°C is recorded for indoor and ambient temperature, which is comparable to the current simulation, which has a temperature difference of about 0.37 °C. This reasoning is also supported by Driss *et al.,* [24] findings, where only a slight temperature decrease was observed throughout the computational domain. This is mainly due to the assumptions made for simulation and also the presence of a heat source (human) in the current simulation setting. On the other hand, the air velocity is decreased and evenly distributed inside the room, which is shown in Figure 5(a). In addition to the temperature distribution, the temperature is also distributed unevenly due to the uneven airflow where these regions experience a similar climate as the outdoor [23, 26].



(a) (b)

Fig. 5. a) Velocity, and b) Temperature distribution contour at 1.1 m height from floor

Figure 6 illustrates the static pressure distribution in the classroom. Similar finding on the pressure contour where the static pressure will decrease slightly as the airflow and identical compression region was discovered at the window opening [24].

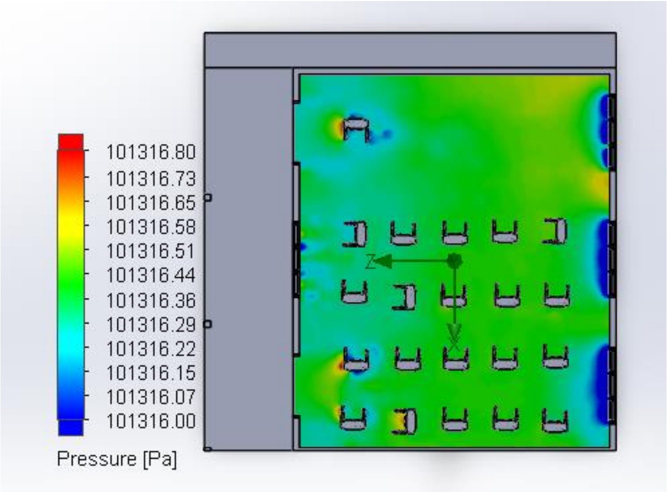
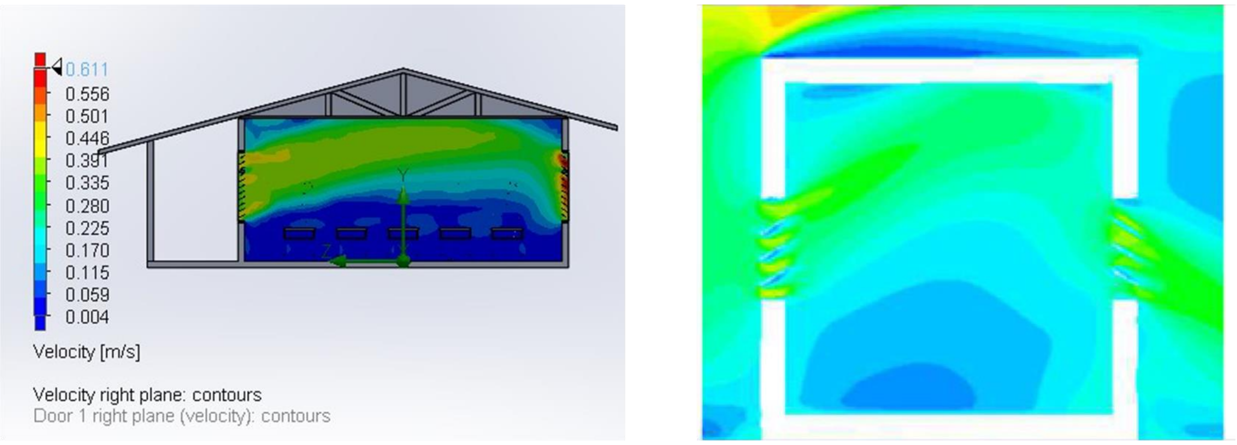


Fig. 6. Static pressure distribution

An identical airflow pattern was obtained for louvres opening at the inlet and outlet, as shown in Figure 7, where the wind is directed upward, and a region of low velocity is formed just under the airflow path [18, 25].



(a) (b)

Fig. 7. Velocity contour at louvre opening for a) simulated results, b) referenced case [18]

3.2.1 Temperature distribution

The mean temperature value is obtained as an average of the air volume in the classroom. Table 3 below summarises the temperature for each different wind velocity measured from Method I.

Table 3
Average fluid temperature (air) at different wind speed

Inlet wind speed	Average temperature (**°C**)
0.282	32.26
0.558	32.38
0.836	32.50
1.113	32.64

In general, the results showed that as the wind velocity increases, the average temperature of global air increases. The temperature gradually decreases with time because heat transfer occurs from indoor air to other objects of lower temperature, such as the wall, wooden tables, and chairs, through conduction. The slow speed of wind ventilated through the room provides more time for the heat transfer process to occur. Hence, under the same simulation time, it was observed that the wind speed and its corresponding temperature would dominate the temperature distribution inside the classroom, and thus the temperature appeared to be higher at high wind velocity. This can be better illustrated in Figure 8, which shows the temperature change with simulation time at different wind velocity inputs. As referred to Ishak *et al.,* [23] data, only a slight difference (about 0.22°C) in average temperature is found when simulating wind across a naturally ventilated classroom at an inlet velocity of 1 m/s. In contrast, the temperature difference obtained in the current simulated case was approximately 0.37°C (32.64°C to 33°C). The value discrepancy may result from the specified inlet wind speed.

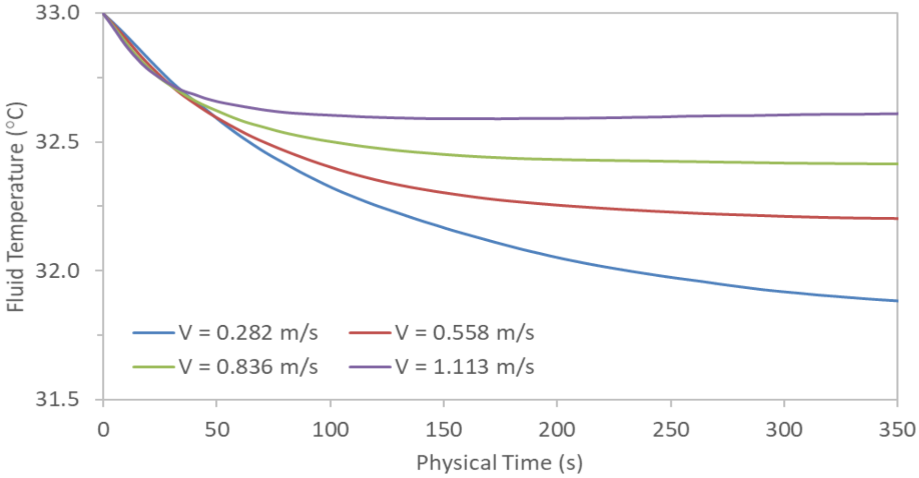


Fig. 8. Graph of average fluid temperature against Time at different wind speed

3.2.2 Air velocity

Based on the simulation results, the average velocity distribution is consistently increasing with higher inlet wind speed, as shown in Figure 9. The average velocity distribution in the room indicates that the wind can effectively reach its mean state, which supplies constant and steady wind to the interior environment after 10 or 20 seconds of physical time.

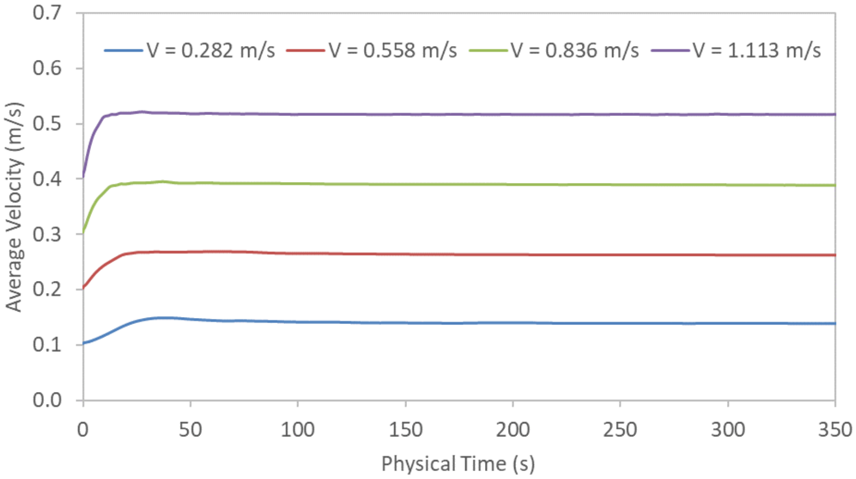


Fig. 9. Graph of average velocity against time at different wind speed

3.2.3 Relative humidity

Figure 10 shows the relationship between average relative humidity and inlet wind speed. The average relative humidity decreases as the wind speed increase because the higher wind speed removes the moisture level at a greater rate. In addition, this difference in relative humidity at different wind speeds can be related to the average temperature distribution of the interior, as obtained from Figure 8. When the water content in the air remains constant, the temperature rise will decrease relative humidity as warmer air needs more moisture to reach its saturation point and vice versa. However, the high relative humidity level is not ideal for the recommended relative humidity level as specified in ASHRAE standard 55, contributing to thermal discomfort.

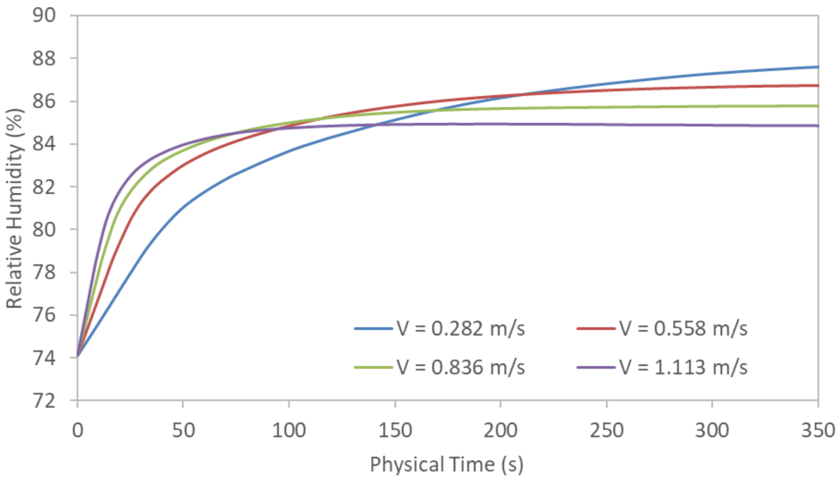


Fig. 10. Graph of relative humidity against time at different wind speed

3.2.4 Thermal comfort level: PMV and PPD

Table 4 shows the average PMV and PPD levels at different inlet wind velocities. The simulation results showed that the higher wind speed could improve the PMV and PPD levels of the interior room. During which the inlet wind speed is 0.282 m/s, the average PMV is valued at 1.71, which is close to warm and hot according to ASHRAE thermal sensation scale. The corresponding PPD value of 61.81% showed that more than half of the occupants would be expected to dissatisfy while staying in the room. However, the high wind velocity can efficiently improve the thermal comfort level based on the predicted model. This may be due to the windchill effect that eventually creates the sensation of a cooling effect on occupants staying in the enclosure.

Table 4
Thermal comfort level at different wind speed

Inlet wind speed	Average PMV	Average PPD (%)
0.282	1.71	61.81
0.558	1.53	53.04
0.836	1.35	44.70
1.113	1.27	41.53

3.2.5 Thermal comfort level at various heights from floor

Figure 11 illustrates the thermal comfort level (PMV) at three different heights from the floor as suggested by ASHRAE standard 55 for standing occupants. The results showed that the PMV value increases as the height from the floor increases. For all three heights at which the velocity is the minimum, the simulated PMV is considered as warm, while the thermal sensation is improved as the inlet wind speed is gradually increasing. This also indicated that higher wind velocity could improve the thermal comfort level measured from the height of the floor.

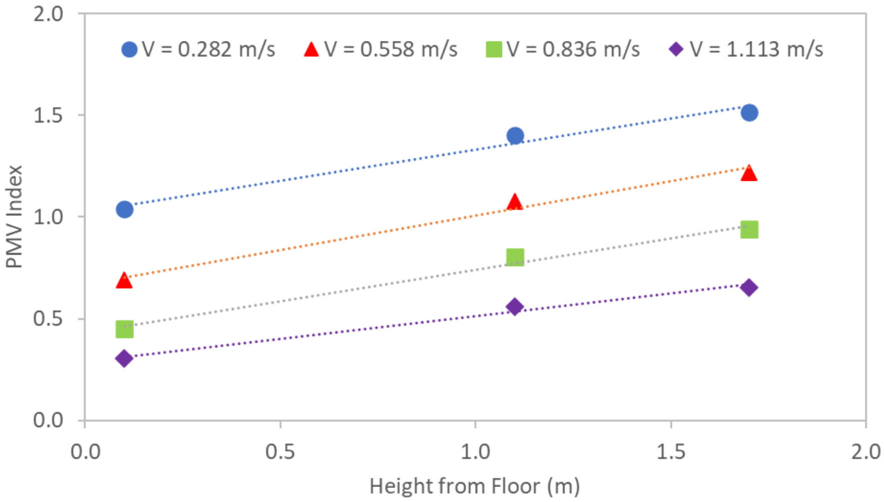


Fig. 11. PMV index at various height from floor

3.3 Design Optimisation

3.3.1 Operable window and its angle

The altair window offers an operable function that can help improve the wind flow across the room. Adjusting the opening is proven to increase the average velocity of air entering the classroom from the simulation, as shown in Figure 12. By changing the louvre's angle, the more extensive opening area promotes airflow into the classroom, which eventually helps to provide an even wind distribution into the room . Figure 12 shows the air velocity contour at the mid-plane of the classroom at 0° louvre (fully open). The simulation results are supported by Vin Cent *et al.,* [18]. Hence, a greater thermal comfort level can be achieved as this provides an even distribution of wind to the occupants in the room.

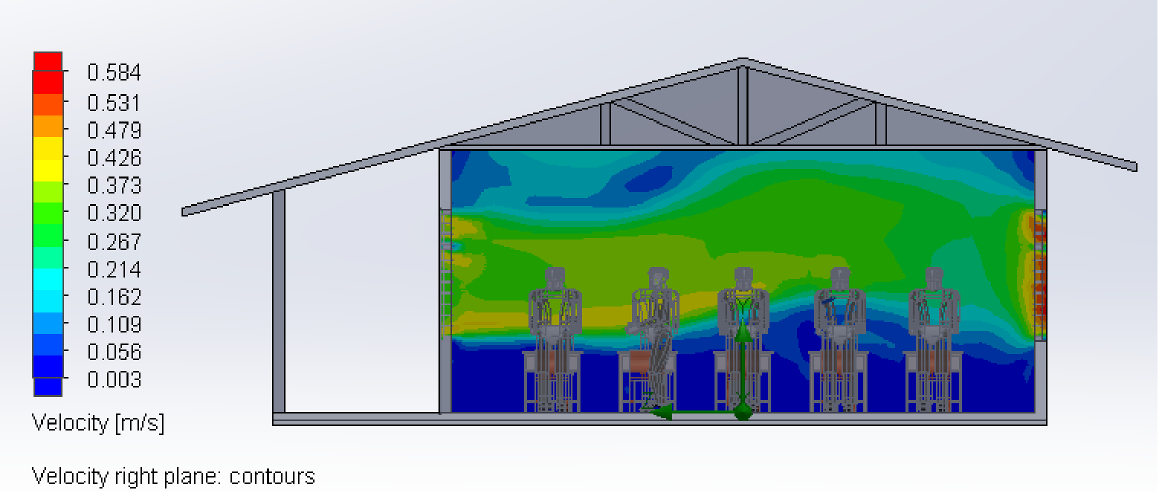
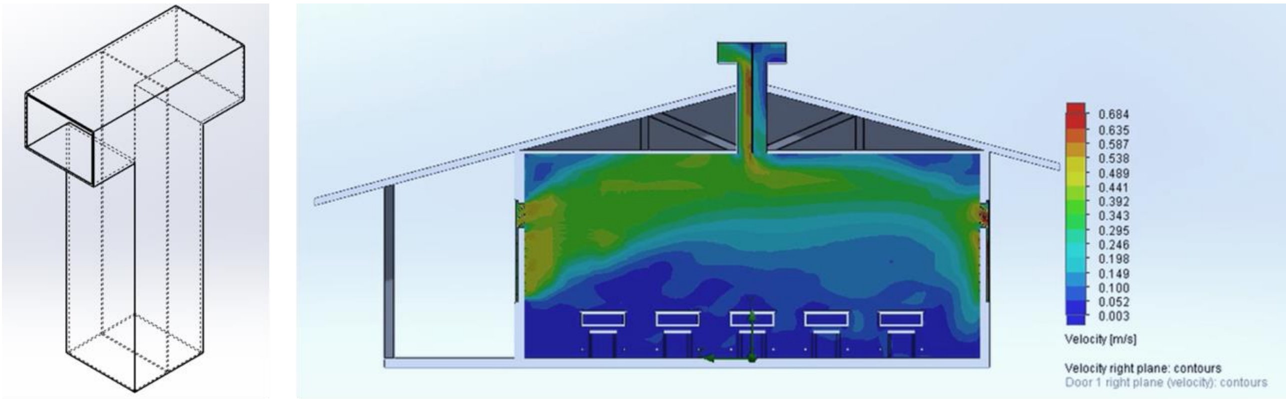


Fig. 12. Wind distribution at 0° louvre angle

3.3.2 Windcatcher

Windcatcher or wind tower is a type of passive cooling architectural design used widely in hot countries such as Egypt. The major concern of designing a windcatcher is the direction of the wind and the number of openings on the windcatcher device. Figure 13(a) shows an example of a two-sided windcatcher where it is used, mainly if one direction of the wind is dominant. Figure 13(b) presents the velocity distribution contour of using a windcatcher in the existing classroom design. It can be seen that the windcatcher traps some of the air from the environment and directs them into the classroom interior. This dramatically improves the magnitude of average air velocity moving into the classroom, enhancing the room's thermal comfort level.



(a) (b)

Fig. 13. (a) Windcatcher design, and (b) Implementing windcatcher to the classroom

4. Conclusions

In conclusion, Computational Fluid Dynamics (CFD) study using Flow Simulation SOLIDWORKS has been done to investigate the airflow pattern, temperature distribution, and relative humidity and thermal comfort level in a real-scaled dilapidated school classroom. The simulation results showed that the existing design of the classroom might not be ideal to rely entirely on natural ventilation. The simulated thermal comfort level suggested that the environment is slightly warm, and only a minor decrease in temperature will be expected due to the heat transfer process occurring from hotter fluid to the colder surface. However, it was also shown that increasing inlet velocity could greatly improve the thermal comfort level due to the wind chill effect. Hence, recommendation and optimisation of the existing classroom is proposed. It was found that a windcatcher can effectively enhance the performance of wind intake that provides chillness to the occupants in the room. In addition, a suggested louvre window configuration was stated to maximise the entrainment of air into the room and provide an even cooling effect to the occupant.

Acknowledgement

The authors would like to acknowledge Ir. Jong Fung Swee from the Public Works Department, Sarawak, for providing the details of the *Sekolah Daif* project, Sarawak, in this numerical analysis.

References

[1] Etheridge, David. *Natural ventilation of buildings: theory, measurement and design*. John Wiley & Sons, 2011. https://doi.org/10.1002/9781119951773

[2] Zhao, Hai-xiang, and Frédéric Magoulès. "A review on the prediction of building energy consumption." *Renewable and Sustainable Energy Reviews* 16, no. 6 (2012): 3586-3592. https://doi.org/10.1016/j.rser.2012.02.049

[3] Norazman, Norsafiah, Adi Irfan Che Ani, Wan Norisma Wan Ismail, Afifuddin Husairi Hussain, and Khairul Nizam Abdul Maulud. "Indoor environmental quality towards classrooms' comforts level: Case study at Malaysian secondary school building." *Applied Sciences* 11, no. 13 (2021): 5866. https://doi.org/10.3390/app11135866

[4] Wang, Yang, Fu-Yun Zhao, Jens Kuckelkorn, Di Liu, Jun Liu, and Jun-Liang Zhang. "Classroom energy efficiency and air environment with displacement natural ventilation in a passive public school building." *Energy and Buildings* 70 (2014): 258-270. https://doi.org/10.1016/j.enbuild.2013.11.071

[5] Montazeri, Hamid, and Ruhollah Azizian. "Experimental study on natural ventilation performance of one-sided wind catcher." *Building and Environment* 43, no. 12 (2008): 2193-2202. https://doi.org/10.1016/j.buildenv.2008.01.005

[6] Hughes, Ben Richard, John Kaiser Calautit, and Saud Abdul Ghani. "The development of commercial wind towers for natural ventilation: A review." *Applied energy* 92 (2012): 606-627. https://doi.org/10.1016/j.apenergy.2011.11.066

[7] Zhang, Haihua, Dong Yang, Vivian WY Tam, Yao Tao, Guomin Zhang, Sujeeva Setunge, and Long Shi. "A critical review of combined natural ventilation techniques in sustainable buildings." *Renewable and Sustainable Energy Reviews* 141 (2021): 110795. https://doi.org/10.1016/j.rser.2021.110795

[8] Ahmed, Tariq, Prashant Kumar, and Laetitia Mottet. "Natural ventilation in warm climates: The challenges of thermal comfort, heatwave resilience and indoor air quality." *Renewable and sustainable energy reviews* 138 (2021): 110669. https://doi.org/10.1016/j.rser.2020.110669

[9] Khan, Naghman, Yuehong Su, and Saffa B. Riffat. "A review on wind driven ventilation techniques." *Energy and buildings* 40, no. 8 (2008): 1586-1604. https://doi.org/10.1016/j.enbuild.2008.02.015

[10] "Climate & Weather Averages in Kuching, Sarawak, Malaysia," *www.timeanddate.com*.

[11] Standard, A. S. H. R. A. E. "Standard 55-2010, Thermal environmental conditions for human occupancy." *American Society of Heating, Refrigerating and Air Conditioning Engineers* (2010).

[12] Taib, Noor Syazwanee Md, Sheikh Ahmad Zaki, Hom Bahadur Rijal, Azli Abd Razak, Aya Hagishima, Waqas Khalid, and Mohamed Sukri Mat Ali. "Associating thermal comfort and preference in Malaysian universities' air-conditioned office rooms under various set-point temperatures." *Journal of Building Engineering* 54 (2022): 104575. https://doi.org/10.1016/j.jobe.2022.104575

[13] Aynsley, Richard. "Estimating summer wind driven natural ventilation potential for indoor thermal comfort." *Journal of Wind Engineering and Industrial Aerodynamics* 83, no. 1-3 (1999): 515-525. https://doi.org/10.1016/s0167-6105(99)00098-7

[14] Shahrom, Farah Arisha, and Mohd Azuan Zakaria. "A study of thermal comfort in classroom under natural ventilation and air-conditioner condition in hot and humid climate country." *Recent Trends in Civil Engineering and Built Environment* 2, no. 1 (2021): 8-16.

[15] American Society of Heating, Refrigerating and Air-Conditioning Engineers. *2021 ASHRAE Handbook: Fundamentals*. American Society of Heating Refrigerating and Air-Conditioning Engineers Incorporated (ASHRAE), 2021.

[16] Bangalee, M. Z. I., S. Y. Lin, and J. J. Miau. "Wind driven natural ventilation through multiple windows of a building: A computational approach." *Energy and Buildings* 45 (2012): 317-325. https://doi.org/10.1016/j.enbuild.2011.11.025

[17] Cheng, Jun, Dahai Qi, Ali Katal, Liangzhu Leon Wang, and Ted Stathopoulos. "Evaluating wind-driven natural ventilation potential for early building design." *Journal of Wind Engineering and Industrial Aerodynamics* 182 (2018): 160-169. https://doi.org/10.1016/j.jweia.2018.09.017

[18] Tai, Vin Cent, Joseph Wu Kai-Seun, Prasath Reuben Mathew, Lip Kean Moey, Xinwei Cheng, and David Baglee. "Investigation of varying louver angles and positions on cross ventilation in a generic isolated building using CFD simulation." *Journal of Wind Engineering and Industrial Aerodynamics* 229 (2022): 105172. https://doi.org/10.1016/j.jweia.2022.105172

[19] Talukdar, Md Sarwar Jahan, Tahmid Hassan Talukdar, Manoj Kumar Singh, Md Abdul Baten, and Md Shahadat Hossen. "Status of thermal comfort in naturally ventilated university classrooms of Bangladesh in hot and humid summer season." *Journal of building engineering* 32 (2020): 101700. https://doi.org/10.1016/j.jobe.2020.101700

[20] Mishra, Asit Kumar, and Maddali Ramgopal. "A thermal comfort field study of naturally ventilated classrooms in Kharagpur, India." *Building and Environment* 92 (2015): 396-406. https://doi.org/10.1016/j.buildenv.2015.05.024

[21] Jindal, Aradhana. "Thermal comfort study in naturally ventilated school classrooms in composite climate of India." *Building and Environment* 142 (2018): 34-46. https://doi.org/10.1016/j.buildenv.2018.05.051

[22] Bayoumi, Mohannad. "Improving indoor air quality in classrooms via wind-induced natural ventilation." *Modelling and Simulation in Engineering* 2021 (2021): 1-14. https://doi.org/10.1155/2021/6668031

[23] Ishak, Muhammad Taufik, Baharuddin Hamzah, Z. Gou, R. Rahim, and Sahabuddin Latif. "Thermal Performance of Naturally Ventilated Classroom in the Faculty of Engineering Hasanuddin University, Gowa Campus." *International Journal of Engineering and Science Applications* 5, no. 1 (2018): 23-36.

[24] Driss, Slah, Zied Driss, and Imen Kallel Kammoun. "Computational study and experimental validation of the heat ventilation in a living room with a solar patio system." *Energy and Buildings* 119 (2016): 28-40. https://doi.org/10.1016/j.enbuild.2016.03.016

[25] Kouhirostami, Maryam. "Natural ventilation through windows in a classroom (CFD analysis crossventilation of asymmetric openings: Impact of wind direction and louvers design)." PhD diss., 2018.

[26] Ibtissame, Benoudjafer, Benoudjafer Imane, and Laoufi Salima. "Towards Low Energy and Thermal Comfort of Buildings Through Passive Cooling or Heating Strategies in Hot Arid Climates." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 93, no. 2 (2022): 173-182. https://doi.org/10.37934/arfmts.93.2.173182