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Prototype Development of Modified Roof Turbine Ventilator for Thermal Comfort Enhancement

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ABSTRACT

A mechanical ventilator known as a turbine ventilator harnesses the wind to supply natural ventilation. Due to their high performance and cheap running costs, these devices are increasingly being used to ventilate areas. This study evaluated the impact of a modified turbine ventilator system on thermal comfort and airflow inside a room. The results showed that the natural ventilation system failed to meet the ASHRAE Standard 55-2020 for thermal comfort. The installation of a turbine ventilator decreases the temperature by 1.3°C but still did not meet the standards. The modified turbine ventilator system consisted of a 305 mm diameter inner 12V, 12W exhaust fan installed in a 500 mm diameter ventilator and connected to a 50W, 12V Monocrystalline Solar Panel showed the greatest improvement with a decrease in room temperature of 4.4°C, an increase in airflow, and full compliance with the ASHRAE Standard 55-2020. The study concludes that modifications to the natural ventilation system can significantly improve thermal comfort and airflow, with the modified ventilator system being the most effective solution.

1. Introduction

The building industry is a significant consumer of energy, accounting for 30-40% of global demand. This demand is expected to continue rising in the future [1]. In Southeast Asian countries, particularly in hot and humid tropical regions, the average energy consumption of buildings is 233 kWh/year, with about 50% used for air conditioning [2]. It is frustrating that so much energy is being used for air conditioning, especially since research has shown that people in hot and humid tropical climates tend to be more tolerant of higher temperatures due to acclimatization [3]. To address the negative impacts of air conditioning on the environment and thermal comfort, researchers have been

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exploring alternatives that can provide similar benefits without compromising these factors. Natural ventilation as a passive cooling approach in buildings is one potential solution that has received extensive attention from architects, engineers, and energy-conscious professionals. Unlike air conditioning, which has been linked to greenhouse gases, acidification, and sick building syndrome (SBS) [4] natural ventilation provides various benefits, including lower energy consumption, enhanced indoor air quality (IAQ), natural daylighting, and increased thermal comfort for occupants [5]. Proper ventilation is critical for maintaining a healthy and productive work environment in any enterprise or home. Ventilation is exchanging stale, hot air with fresh, cold air, which helps maintain a regulated temperature, supply more oxygen, and eliminate undesirable things such as moisture, dust, smoke, heat, bacteria, carbon dioxide, and so on. Turbo ventilators use natural wind energy to function, making them both cost-effective and ecologically good because they do not require any external electricity. Meadows initially invented the turbo ventilator idea, which was later refined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)[6]. Edmonds in Australia began commercial manufacturing of turbo ventilators in 1934, and they have been on the market for many years [6]. However, material is scarce in the design and aerodynamics of these units. Natural ventilation and mechanical ventilation are the two basic types of ventilation procedures [7].

The increased usage of air conditioning systems in tropical nations, notably Malaysia, is causing high energy consumption and significant environmental implications [8]. Malaysia's power use is primarily reliant on fossil fuels, and air conditioners are a major source of CO_2 emissions [9]. Energy consumption is rising as Malaysia progresses toward becoming a developed country. According to the International Energy Agency, Malaysia's CO_2 emissions have increased considerably, making it one of Southeast Asia's biggest CO_2 emitters [10]. Air conditioners are no longer a viable option for cooling building interiors, especially with rising energy costs. This issue is exacerbated in modern residential structures, which are frequently built with lightweight materials, have airtight construction, and have inadequate natural ventilation, resulting in a larger reliance on traditional cooling systems [11]. This causes significant levels of heat buildup in Malaysian landed properties, which can have a detrimental influence on the economic expansion of tropical structures. To address these issues, alternative design methods are needed.

Turbine ventilators are one potential remedy for the problem of heat buildup in tropical buildings. Even though these systems have been in operation for a long time, research is always looking for ways to improve ventilation and temperature conditions. This study aims to improve the design of turbine ventilators to enhance thermal comfort in tropical buildings.

2. Materials and Methods

The approach involves developing and testing one design concept to determine the impact on the performance of turbine ventilators. The turbine ventilator with a diameter of 620 mm and a height of 350 mm was used in the testing. The ventilator is made up of 25 curved blades. Curved blades are commonly used in turbine ventilators because they are thought to perform better than straight blades [12]. The experiment results were analyzed to assess the conceptual designs' influence on the turbine ventilator's efficacy.

2.1 Specification of Selected Design for Modification

A turbine ventilator is a device that harnesses the power of the wind to rotate a turbine and generate negative pressure at the downstream end of a pipeline, which aids in the exhaust of airflow

[13]. It is a simple and practical gadget that is extensively used in Malaysia to increase building ventilation [14]. In theory, combining natural ventilation and a turbine ventilator can assist to enhance interior air quality, reduce dependency on air conditioning, and reduce energy usage [15]. Table 1 and Figure 1 shows the dimensions of the modified model.

Table 1
The Specification of Turbine Ventilator

Neck Diameter (mm)	Turbine Diameter (mm)	Turbine Height (mm)	Airflow (m^3/h)	Inlet Air Speed (m/s)	Blade No. (pcs)	Weight (kg)	Material
500	620	350	2520	3.4	25	8.5	Stainless Steel

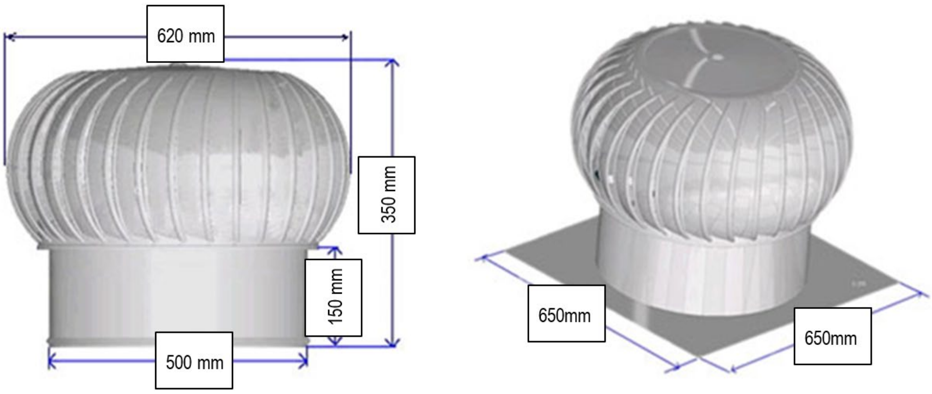


Fig. 1. Turbine ventilator

2.2 Design Concept

This study aimed to enhance the ventilation efficiency of a turbine ventilator without using more power. To accomplish this, a 305 mm diameter inner 12V with12 W power consumption exhaust fan (Figure 2) was inserted in the neck of a 500 mm diameter ventilator without affecting the ventilator's primary construction. A 12V,50W Monocrystalline Solar Panel powered the inside fan (Figure 3). One design proposal was created, including the inner fan and solar panel system in a way that was intended to increase the turbine ventilator's total ventilation efficiency. A previous study has shown that installing roof turbine ventilators may significantly increase building ventilation levels [16,17]. This study aims to build on this work by developing an innovative design concept (Figure 4) that can enhance the performance of turbine ventilators. The next stage was to develop a prototype and bring this concept out (see Figure 5). Table 2 and Table 3 show the specification of the selected solar cell model and DC fan respectively.

(a) (b)

Fig. 2. DC exhaust fan (a) Front view (b) Rear view

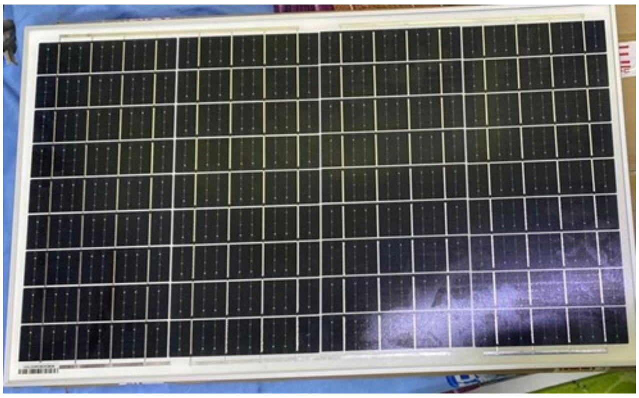


Fig. 3. 50W,12V Monocrystalline solar panel

Table 2
The specification of the selected solar cell model

Solar Cell	Peak Power	Tolerance	Max Power	Max Voltage	Short Circuit Current	Open Circuit Voltage
Monocrystalline	50W +/-	3% +/-	2.78A+/-	18V +/-	3.03A +/-	22.3V +/-

Table 3
The specification of the selected DC fan

AC/DC Type	Fan Type	Fan Size	Number of Fan Blade	Input Voltage	Power Consumption
DC	Exhaust Fan's	305 mm	6	12V	12W

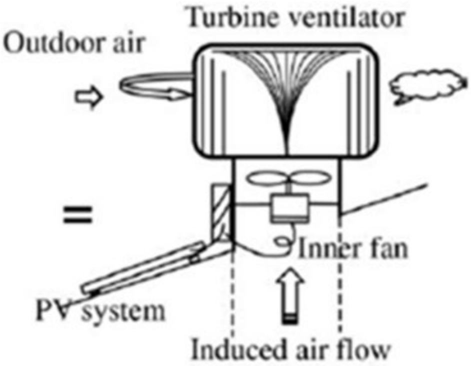


Fig. 4. Design concept

Fig. 5. Prototype development and installation

2.3 Experimental Setup

In this study, measurements were taken using a full-scale model of a building located at the University Tun Hussein Onn Malaysia (latitude 1.8565° N, longitude 103.0822° E). The structure measured 5m x 4m x 3m (L x W x H) and was constructed using typical building materials such as bricks for the walls, plaster boards for the ceiling, and aluminum sheets for the roof (Figure 6). The structure featured a pitched roof with a 30° angle and measurements from the center of 5m × 4m x 1m (L x W x H). The attic space was entered by a gable end inlet and had an exit on the roof. The building's inhabited zone featured six 1m x 1m windows on three sides, and a turbine ventilator with a diameter of 620 mm and a neck diameter of 500 mm was put on the roof. The tests were designed to investigate the effect of the turbine ventilator on the ventilation and thermal performance of the building.

Fig. 6. Actual model

2.4 Research Method

Measurements were made in this study to analyze the influence of a turbine ventilator on a building's ventilation and thermal performance. The measurement process involved performing tests in the building with and without the turbine ventilator installed, under stable outdoor wind conditions. A third set of measurements was also taken after installing a DC inner fan in the neck of the ventilator and connecting it to a photovoltaic system. In addition to these measurements, a walkthrough inspection was conducted to identify potential factors that could affect indoor air quality. Data on inside and outside of the room (air temperature, air velocity, and relative humidity) were collected using KIMO-AMI 310 Multifunction (Figure 7) before input to the Center for the Built Environment (CBE) Thermal Comfort Tool for thermal comfort analysis and compared to the ASHRAE-55[18] standard for further evaluation. The Center for the Built Environment (CBE) Thermal Comfort Tool, a free online tool for calculating and visualizing thermal comfort, complies with all three of the ASHRAE 55-2017, ISO 7730:2005, and EN 16798-1:2019 Standards. It incorporates the most significant thermal comfort models, including dynamic predictive clothing insulation, the Predicted Mean Vote (PMV), Standard Effective Temperature (SET), adaptive models, and local discomfort models [19]. The thermal comfort performance of the original and modified turbine ventilators was also tested and compared. Table 4 lists the instruments and their accuracy.

Table 4
Specification of instrument used

Type of instruments	Measurement parameter	Accuracy
KIMO-AMI 310 Multifunction	- Air Temperature - Relative Humidity - Air velocity	Range of Operation Temperature Range: -20 to 80 °C RH: 0–98% Air Speed: 0-30 m/s Temperature accuracy: 0.3 °C RH: ±3% The velocity must not exceed 0.015 m/s or 3% of the reading. Resolution in degrees Celsius: 0.1 RH: 0.1% Speed: 0.01 m/s

Fig. 7. Measurement of air temperature, velocity, and relative humidity inside and outside of the room using KIMO-AMI 310 Multifunction

2.5 Thermal Comfort Online Tool Description

The CBE Thermal Comfort Tool's home page is as shown in Figures. 8 and 9. ASHRAE 55, EN 16798, Compare, Ranges, Upload, and Other CBE tools are all included in the tool's six pages [20]. Users can browse between pages using the top navigation bar of the website. The user-modifiable input values are located on the left side of each page (except for Upload and Other CBE tools) [21]. On the right side, which frequently has an interactive chart, the results are displayed. There are comments describing the application boundaries and, if relevant, a synopsis of each chart, underneath the main figure. Finally, the footer at the page's bottom includes links to video instructions on how to use the tool as well as information on how to reference the website, get in touch with the author, report issues in the code, and request additional features [22].

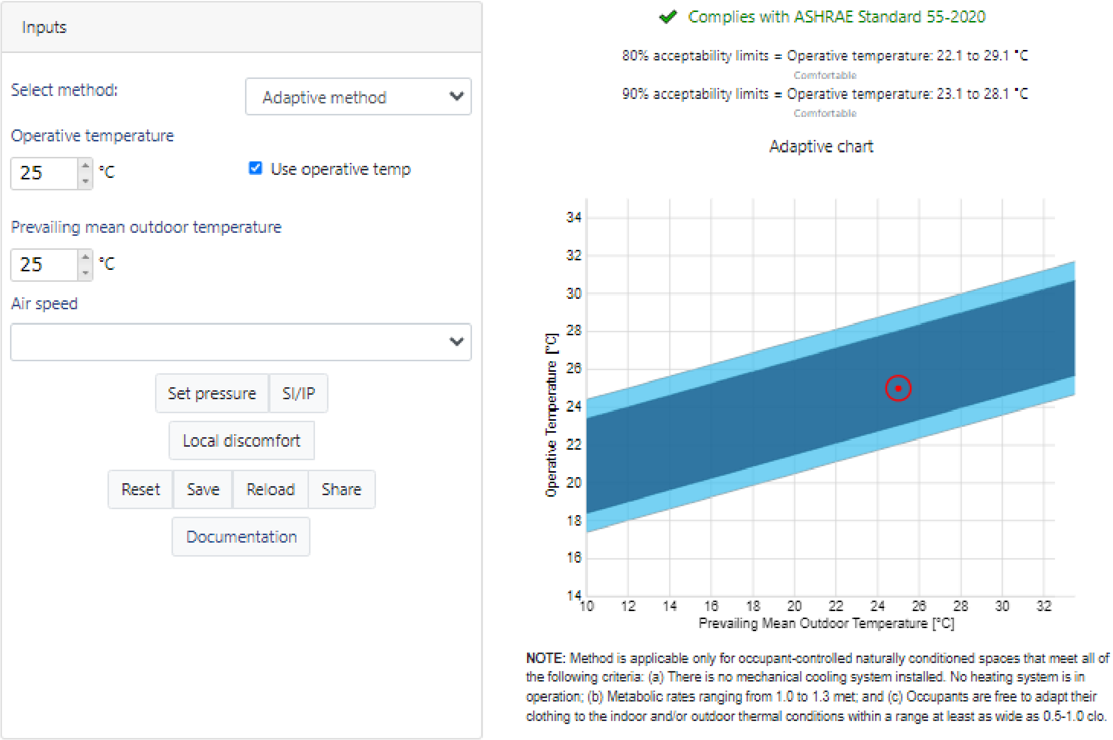
International standards (ASHRAE standard 55-2017) employ two thermal comfort models: the heat balance model (laboratory-based) created by Fanger [18] in 1970 (also known as the PMV/PPD model) and the adaptive thermal comfort model [23,24]. The first model is best suited for air-conditioned buildings where occupants have no control over their immediate surroundings, whereas the latter model is dynamic and the occupant's behavioral, physiological, and psychological adaptations are broader than in conditioned buildings [23,25]. The outside temperature (Tout), which is a crucial aspect in determining thermal comfort, is ignored by Fanger's PPD/PMV model. Field research has been done in naturally ventilated buildings by researchers from all over the world. The ASHRAE 55-2004 standard adaptive comfort model was created by analyzing the database of 21,000 samples that had been collected from buildings all around the world. Eq. (1), which establishes a direct relationship between indoor comfort temperature and external air temperature, is the adaptive model of thermal comfort.

$$Tc = 0.31Tpm + 17.8 \tag{1}$$

Where Tc is indoor comfort temperature (°C); Tpm (out) is the prevailing mean outdoor dry bulb temp (°C). Figure 9 depicts an ASHRAE 55-2017 adaptive thermal comfort chart. This model is only relevant to naturally conditioned occupant-controlled rooms that fulfill all the following criteria: (a) No mechanical cooling system is fitted. There is no heating system in use; (b) metabolic rates of 1.0 to 1.3 are met; and (c) occupants are free to adjust their clothes to the interior and/or outdoor temperature conditions within a range of at least 0.5-1.0 clo. The adaptive model of thermal comfort naturally ventilated buildings, the following equation.

$$Top = 0.54Tout + 12.83 \tag{2}$$

Where Top is Indoor operative temperature (neutral temperature) in °C; Tout is 30 days Outdoor running mean temperature in °C [23].



Select method: Adaptive method

Operative temperature: 25 °C

☑ Use operative temp

Prevailing mean outdoor temperature: 25 °C

Air speed:

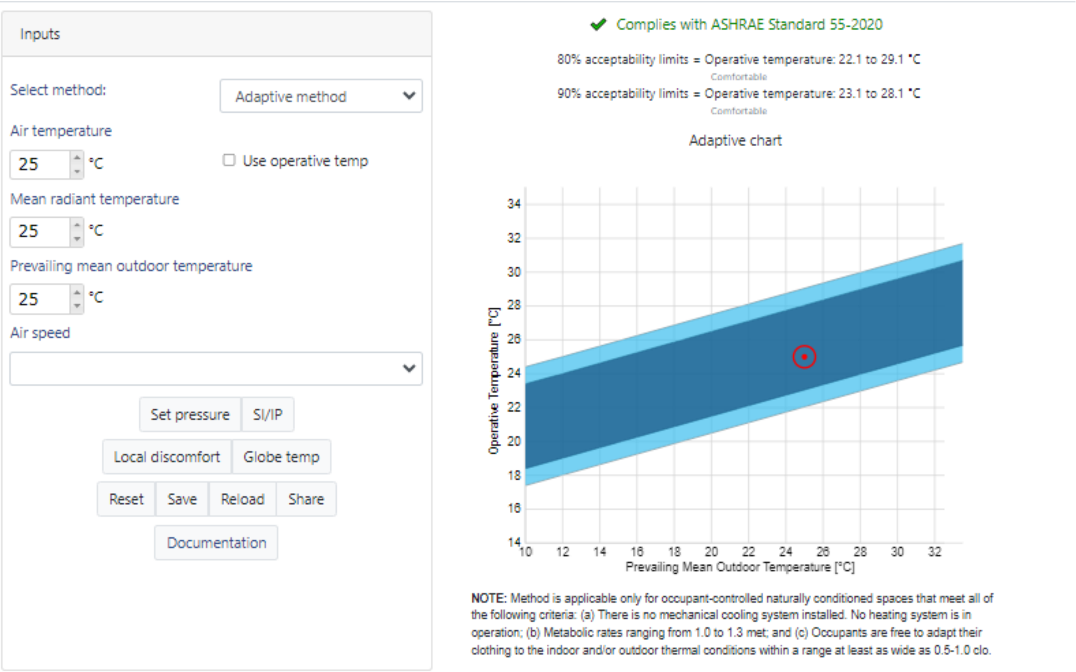
✓ Complies with ASHRAE Standard 55-2020

80% acceptability limits = Operative temperature: 22.1 to 29.1 °C
Comfortable

90% acceptability limits = Operative temperature: 23.1 to 28.1 °C
Comfortable

NOTE: Method is applicable only for occupant-controlled naturally conditioned spaces that meet all of the following criteria: (a) There is no mechanical cooling system installed. No heating system is in operation; (b) Metabolic rates ranging from 1.0 to 1.3 met; and (c) Occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5-1.0 clo.

Fig. 8. CBE Thermal Comfort Tool home page



Inputs

Select method: Adaptive method

Air temperature: 25 °C

☐ Use operative temp

Mean radiant temperature: 25 °C

Prevailing mean outdoor temperature: 25 °C

Air speed:

✓ Complies with ASHRAE Standard 55-2020

80% acceptability limits = Operative temperature: 22.1 to 29.1 °C
Comfortable

90% acceptability limits = Operative temperature: 23.1 to 28.1 °C
Comfortable

NOTE: Method is applicable only for occupant-controlled naturally conditioned spaces that meet all of the following criteria: (a) There is no mechanical cooling system installed. No heating system is in operation; (b) Metabolic rates ranging from 1.0 to 1.3 met; and (c) Occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5-1.0 clo.

Fig. 9. CBE Thermal Comfort Tool home page.

3. Results and Discussion

The study was carried out on a hot sunny day during a 12-day period, to gather air temperature, relative humidity, and air velocity data. The data collection was carried out in three stages. Monitoring the temperature, relative humidity, and air velocity inside and outside the room without installing any ventilators in the first phase. This served as a baseline against which the other two stages of the experiment could be compared. A typical turbine ventilator was erected on the room's roof (Figure 10) in the second phase and the temperature, relative humidity, and air velocity were monitored once more. This allowed for a comparison of the performance of the modified ventilator with the traditional ventilator. In the last step, the turbine ventilator was changed by installing a 305mm diameter inner DC 12V,12W exhaust fan in the neck of a 500mm diameter ventilator (Figure 11) and connected to a12V,50W Monocrystalline Solar Panel to the inner fan to boost the turbine ventilator's efficiency. The air temperature, relative humidity, and air velocity were then monitored again to assess the performance of the redesigned ventilator.

Fig. 10. Prototype development and Installation

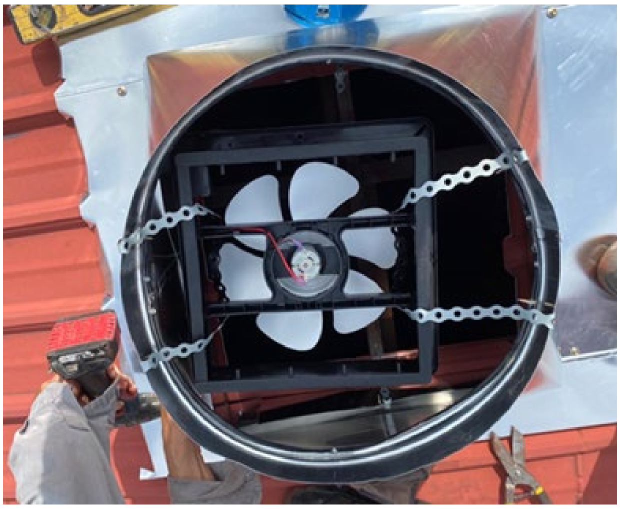


Fig. 11. 305mm diameter inner12W DC 12V exhaust fan in the neck of the Ventilator

3.1 Alloy Comfort Conditions for the Experiment Zone without a Ventilator (WO)

Based on the data from our experiment (Table5), the thermal comfort conditions within the room were not in compliance with the standards set by ASHRAE Standard 55-2020. The prevailing mean indoor air temperature measured 34.6°C, which was higher than the prevailing mean outdoor air temperature of 34.2°C, and the Indoor Operative Temperature is 32.29 °C. This indicates that the room was not being cooled effectively by the natural ventilation system. Additionally, the air velocity within the room was measured at 0.00 m/s, while the air velocity outside the room was measured at 0.50 m/s. This suggests that the air movement within the room was not sufficient to provide thermal comfort. The results of the experiment were analyzed using the CBE Thermal Comfort tool website, and the adaptive method was used to evaluate the acceptability of the thermal conditions within the room. According to the adaptive method, the operative temperature within the room should be between 24.9 to 31.9 °C for 80% acceptability and between 25.9 to 30.9 °C for 90% acceptability. However, the measured operative temperature of 34.6°C falls outside of these limits, indicating that the room was too warm. Furthermore, when comparing the operative temperature to the prevailing mean outdoor temperature, as shown in Figure 12, it can be seen that the room does not comply with the ASHRAE Standard 55-2020. This suggests that the room's thermal comfort conditions were not optimal and that improvements to the natural ventilation system and/or additional cooling methods may be necessary to bring the room into compliance with the standard.

Table 5
Environmental parameters of the experiment zone without ventilator (WO)

Environmental Parameters	Inside Room	Outside Room
Indoor Operative Temperature (°C)	32.29	-
The prevailing mean air temperature(°C)	34.6	34.2
Airspeed (m/s)	0.00	0.50
Relative Humidity (%)	62.5	56
Sensation	Too warm	Too warm
Compliance With ASHRAE-55	No	No

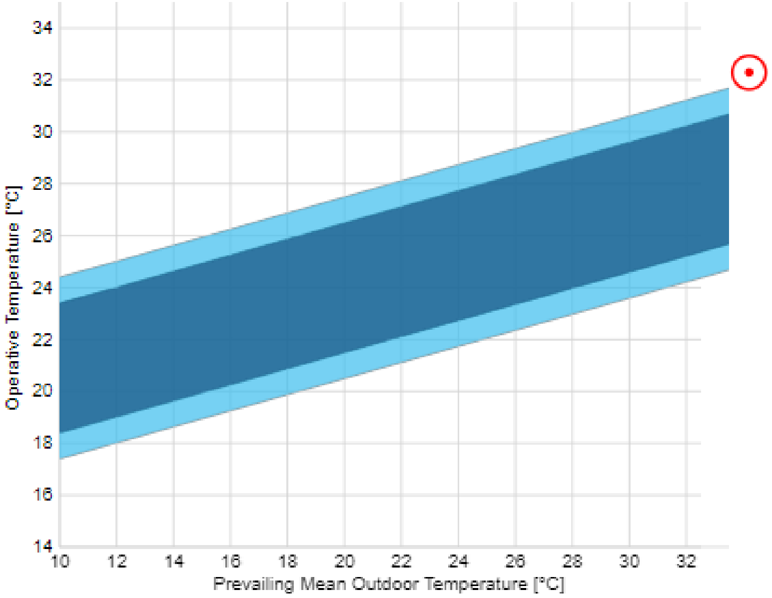


Fig. 12. Operative temperature vs prevailing mean outdoor temperature for the experiment zone without ventilator (WO)

3.2 Comfort Conditions for the Experiment Zone with Turbine Ventilator (TV)

The study was conducted to determine the impact of installing a turbine ventilator on the thermal comfort conditions inside a room. During the experiment (Table 6), the outside prevailing mean air temperature was recorded as 32.9°C and the inside prevailing mean air temperature was recorded as 31.6°C. and the Indoor Operative Temperature is 31.59 °C. After the installation of the turbine ventilator, the temperature inside the room decreased by 1.3°C, while the air velocity increased to 0.15 m/s from 0.00 m/s. To evaluate the thermal comfort conditions within the room, the results of the experiment were analyzed using the CBE Thermal comfort tool website and the adaptive method. The adaptive method provides an evaluation of thermal comfort based on the prevailing mean outdoor temperature and indoor operative temperature. According to the adaptive method, for 80% acceptability, the operative temperature within the room should be between 24.5 to 31.5°C, and for 90% acceptability, the range should be between 25.5 to 30.5°C. In this case, the operative temperature was near the acceptability limit. However, according to the ASHRAE Standard 55-2020, which sets guidelines for thermal comfort, the room was still considered to be in a warm condition. The results of the experiment are displayed in Figure 13, which shows the relationship between the operative temperature and the prevailing mean outdoor temperature for the experiment zone with the turbine ventilator installed. Overall, the experiment concluded that installing a turbine ventilator in a room decreases the temperature inside the room and increases air velocity, but the results are near the limit of acceptability as determined by the adaptive method.

Table 6
Environmental parameters of the experiment zone with Turbine ventilator

Environmental Parameters	Inside Room	Outside Room
Indoor Operative Temperature (°C)	31.59	-
The prevailing mean air temperature(°C)	31.6	32.9
Airspeed (m/s)	0.15	0.50
Relative Humidity (%)	60.2	57.4
Sensation	Warm	Warm
Compliance With ASHRAE-55	No	No

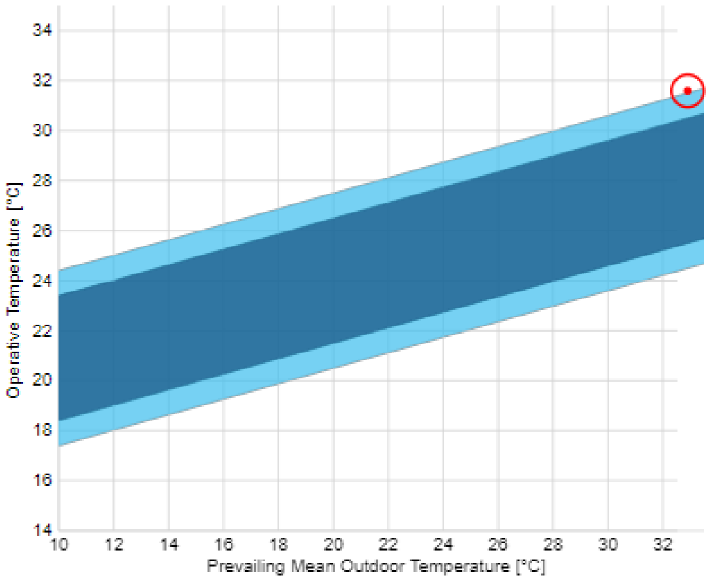


Figure 13. Operative temperature vs prevailing mean outdoor temperature for the experiment zone with turbine ventilator (TV)

3.3 Comfort Conditions for the Experiment Zone with Modified Turbine Ventilator (THTV)

After installing a 305mm diameter inner DC 12V,12W exhaust fan in a 500mm diameter ventilator and connecting it to a 12V,50W Monocrystalline Solar Panel we conducted some tests to evaluate the performance of this modified ventilator in terms of thermal comfort and airflow. The experiment aimed to evaluate the impact of a modified ventilator system on thermal comfort and airflow inside a room. The modified ventilator system consisted of a 305mm diameter inner DC 12V,12W exhaust fan installed in a 500mm diameter ventilator and connected to a 12V,50W Monocrystalline Solar Panel. When the outside prevailing mean air temperature was recorded as 32.5°C, the inside prevailing mean air temperature was recorded as 28.1°C and the Indoor Operative Temperature is 28.00 °C (Table 7), which demonstrates a decrease of 4.4°C in the room temperature due to the modified ventilator. Additionally, the airflow inside the room was recorded as 0.21 m/s compared to the outside airflow of 0.31 m/s, showing an increase in the airflow inside the room due to the modified ventilator. The results were analyzed using the CBE Thermal Comfort Tool website and the Adaptive method, which is used to evaluate the acceptability of the thermal conditions within a room. According to the Adaptive method, the operative temperature within the room should be between 24.4°C to 31.4°C for 80% acceptability and between 25.4°C to 30.4°C for 90% acceptability. With an operative temperature of 28.1°C, the room condition was deemed comfortable according to the ASHRAE Standard 55-2020. The results are illustrated in Figure 14, which shows the relationship between the operative temperature and the prevailing mean outdoor temperature for the experiment zone with a turbine ventilator (TV). The figure demonstrates that the modified ventilator is effective in improving the thermal comfort of the room and meets the requirements set by ASHRAE-55. In conclusion, the modified ventilator was successful in improving both thermal comfort and airflow inside the room and was found to meet the standards set by ASHRAE-55 for thermal comfort.

Table 7
Environmental parameters of the experiment zone with modified turbine ventilator (THTV)

Environmental Parameters	Inside Room	Outside Room
Operative Temperature (°C)	28.00	-
The prevailing mean air temperature(°C)	28.1	32.5
Airspeed (m/s)	0.21	0.31
Relative Humidity (%)	50	60.2
Sensation	Comfortable	Warm
Compliance With ASHRAE-55	Yes	No

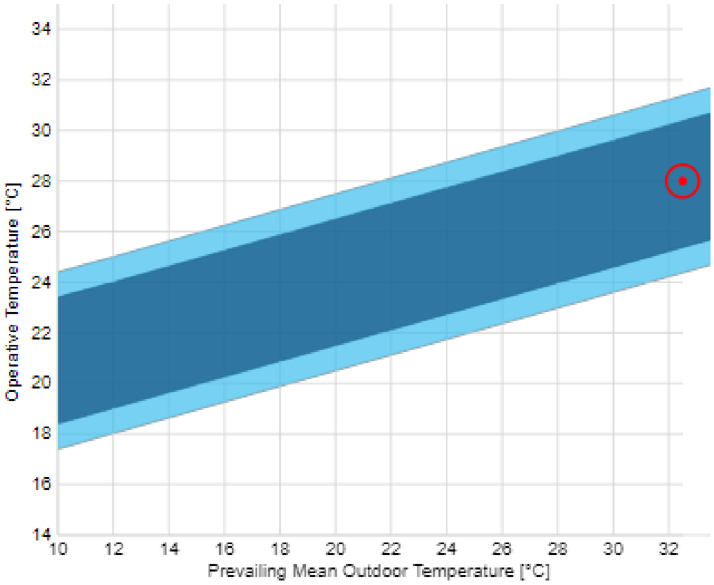


Fig. 14. Operative temperature vs prevailing mean outdoor temperature for the experiment zone with modified turbine ventilator (THTV)

3.4 Overall Analysis of Three Situations

The overall analysis of the results shows that the performance of a natural ventilation system in terms of thermal comfort and airflow can be improved with modifications such as installing a turbine ventilator or a modified ventilator system. In the first experiment, the indoor temperature was recorded as 34.6°C and the air velocity was measured at 0.00 m/s, indicating that the natural ventilation system was not effectively cooling the room and providing sufficient air movement. The results of the analysis using the Adaptive method showed that the room was too warm and did not meet the standards set by ASHRAE Standard 55-2020 for thermal comfort.

In the second experiment, the installation of a turbine ventilator improved the temperature inside the room by 1.3°C and increased the air velocity to 0.15 m/s. The results showed that the room was near the limit of acceptability as determined by the Adaptive method, but still considered to be in a Warm condition according to ASHRAE Standard 55-2020.

The third experiment, with the modified ventilator system consisting of a 305mm diameter inner DC 12V,12W exhaust fan installed in a 500mm diameter ventilator and connected to a 12V,50W Monocrystalline Solar Panel, showed the greatest improvement in thermal comfort and airflow. The inside temperature was recorded as 28.1°C, a decrease of 4.4°C from the outside temperature, and the airflow inside the room was recorded as 0.21 m/s, an increase from the outside airflow of 0.31

m/s. The results of the analysis using the Adaptive method showed that the room was comfortable and met the standards set by ASHRAE-55 for thermal comfort.

Overall, the experiments demonstrated that modifications to a natural ventilation system can improve thermal comfort and airflow inside a room, but the modified ventilator system was found to be the most effective solution in meeting the standards set by ASHRAE-55.

4. Conclusion

In conclusion, our experiment aimed to evaluate the impact of different ventilation systems on thermal comfort and airflow in a room. The results showed that the thermal comfort conditions within the room were not in compliance with the ASHRAE Standard 55-2020 when the natural ventilation system was used. However, when a turbine ventilator was installed, the temperature inside the room decreased, but the conditions were still not in compliance with the standard. After installing a modified ventilator system (305 mm diameter inner DC 12V,12W exhaust fan in a 500mm diameter ventilator and connected to a 12V,50W Monocrystalline Solar Panel), the results showed a decrease of 4.4°C in the room temperature, an increase in airflow, and the room was found to be in compliance with the ASHRAE Standard 55-2020. Overall, the modified ventilator system was found to be effective in improving thermal comfort and airflow in the room. For future research, here are some recommendations for wind turbine ventilators. Using a battery to store energy for use during times when the sun is not available is a good idea. This can help to ensure that the DC fan has a constant power supply and can operate continuously, even at night or on cloudy days.

Lead-acid batteries, lithium-ion batteries, and nickel-metal hydride batteries are among the several types of batteries that might be used for this function. Each kind has advantages and disadvantages, and the ideal option will be determined by several considerations such as cost, performance, and durability.

It might also be worth considering other ways to improve the efficiency and performance of the system, such as using more efficient solar panels or optimizing the design of the wind turbine ventilator to maximize efficiency. Additionally, incorporating smart control systems or energy management technologies could help to optimize the use of the stored energy and ensure that it is used as efficiently as possible.

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