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Climate Change Mitigation Through Innovative Solar-Powered Car Ventilation System Design and Evaluation for the Malaysian Context

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Abstract: Automotive carbon emissions, primarily governed by fuel consumption, are closely related to climate change. Parked cars act as inadvertent greenhouses, accumulate heat, requiring increased fuel consumption for air conditioning upon re-entry. Reducing fuel consumption will contribute to sustainable transportation and mitigate climate change by contributing to sustainable transportation. Solar-powered car ventilation is our solution. Study includes comprehensive design, efficiency assessment, and system performance assessment utilizing Solidworks and Creo. Cost analysis, material selection, and market-ready component integration were taken into account. Using the solar-powered ventilation system, interior vehicle temperatures were reduced by 9.10 to 11.63°C. The highest efficiency achieved under ideal conditions was 92.95%. Efficiency calculations under the same simulation parameters on the first day reached 73.44%, while in the real test it reached 62.11%. Simulation and real-world testing differ by 11.33%. This study contributes to sustainable transportation, reducing carbon emissions, and preserving fuel.

Keywords: Solar-powered car ventilation system; Climate change mitigation; Vehicle interior temperature; Energy efficiency; Sustainable transportation.

1. Introduction

The role of ventilation in automobiles for occupant comfort and energy efficiency should not be overlooked. Ventilation is an important aspect to improve the overall driving experience but at the same time it saves energy[1)2)]. Ventilation is inexpensive equipment included to provide better comfort and health for passengers on board. Good ventilation offers the advantage of preventing the build-up of potentially harmful smells, odors and contaminants within the cabin[3)]. It also encourages air circulation, which is very useful for two things - to prevent drowsiness and motion sickness among passengers[4)]. The pleasant and enjoyable interior design leads to comfortable passage, for example, on a long or short trip. Moreover, proper ventilation techniques can significantly reduce vehicle energy costs as reported[5)]. Cars parked in hot weather may quickly heat up due to global warming, forcing passengers to turn on the air conditioners when they re-enter. The same process forces the engine to operate under high load and fuel usage also increases[6)]. When proper ventilation is introduced, the need for excessive air conditioning is thus reduced, ultimately conserving fuel and ultimately prolonging the vehicle's mileage. Moreover, ventilation controls the temperature inside the car to some extent[7)]. While in a warm climate, the car cabin can become very hot inside, because heat builds up over time. This makes the cabin environment uncomfortable. Proper ventilation, for example solar-powered ventilation systems, can be used to remove heat reducing the comfort level of the vehicle and keeping the vehicle at its tolerable temperature even when the vehicle is parked in direct sunlight[8)].

Many researchers initially used traditional methods. For example, Ref.[9)] to reduce the phenomenon of global warming inside the cabin used the passive method such as ventilation holes, sunshades, and window shading. The study concluded that this method caused a decrease in the temperature inside the cabin by an average of 3.3°C. Reference[10)] used a car cover with windows slit up to 1 cm.

The results of the experiments confirmed a decrease in the temperature of the car cabin by 70% compared to the case when no ventilation technique was used. Ref.[11] employed solar shades in parallel with different configurations of closed or open windows and a decrease was reported in the cabin temperature of about 26%.

PV systems are not only emission-free but also offer numerous benefits beyond that. Solar panels can operate under various weather conditions and generate energy for residential or large-scale applications, whether installed on rooftops or in solar farms[12]. The incidence of solar energy in radiance and dispersion enables local electricity generation, reducing the need for long-distance transmissions and associated losses. Moving forward, technological advancements and economies of scale are driving down solar energy prices. Consequently, an increasing number of countries, from developing to developed ones, are transitioning to solar energy [13]. In addition to photovoltaic (PV) applications that aid in reducing greenhouse gas (GHG) emissions, solar energy offers broader advantages such as energy independence, enhanced power system stability through distributed energy, and job creation in the renewable energy sector. A swift transition to solar energy can set an example for other cities striving for a sustainable and resilient future, while also addressing the challenges of climate change[14]. Currently, there is a shift towards photovoltaic/thermal (PVT) systems over traditional PV systems to enhance energy production and efficiency. In contrast to PV systems, PVT systems consist of both photovoltaic modules and heat collectors, operating simultaneously to generate electricity and harness heat[15]. This configuration optimizes sunlight usage, resulting in maximum energy efficiency and utilizing the best resources. It is an ideal solution for areas with limited land or irregular climatic conditions. This further indicates that the world is continuously evolving towards green energy systems that are highly innovative and can efficiently meet various energy requirements[16]. The work of many researchers, such as[17),18)], has embraced the technology of utilizing both PV and PVT systems in ventilating electric cars and reducing the cooling load on the engine.

Ventilation is the dominant component of air quality, in essence. Improper ventilation can lead to poor indoor air quality that allows people to breathe in pollutants, allergens, odors, or other contaminants[19),20)]. In addition, this breathing air will hamper healthy functioning especially for people with breathing problems. With ventilation systems that keep clean air recirculating and eliminate indoor pollutants, it is possible to achieve a healthier environment[21]. Implementing measures to increase ventilation leads directly to the automotive sector's broader goals in terms of sustainability. Due to the reduced need for air conditioning and the associated fuel consumption, the vehicle becomes environmentally friendly. Moreover, renewable energy-based ventilation systems such as solar energy system are compatible with the universal design of environmentally friendly transportation[22].

The automotive sector is well covered in scientific investigations covering the application of solar energy mainly in ventilation systems, the use of solar-powered ventilation systems by automobiles, and their efficiency in reducing vehicle temperature rises in direct sunlight[23]. Li et al.[24] presented a methodology frequently used in cars, which involved turning on the ventilation as soon as the car was running. At the same time, this is a method that reaches the state of pre-cooling. However, this will result in long operating periods of the ventilation system which translates into high energy consumption[25]. Meanwhile, an innovative model, which features the introduction of another exhaust fan at the back of the car is also the case [26]. Combined with the car ventilator already installed by the factory, this additional fan cooperates to give the cool air an even greater improvement over the latter. In combination with the built-in fan and internal blower of the car, the solar panels are the power source, which can be charged by solar energy to power both components[27].

Huang et al.[28] looked at using a solar module surrounded by a practically transparent colloidal material. This innovative configuration serves a dual purpose: it prevents solar or thermal radiation from heating the car's interior and preserves the mechanical components at the same time by capturing solar energy and storing it as an additional energy source. In addition, the unit will be able to operate the ventilation system fan which will cool the room as well as prevent global warming. To ascertain the optimal efficacy, the study scrutinized the placement of the air intake through four distinct configurations. CAD and CAE software facilitated precise positioning of the air inlet at various locations: the rear shelf-board, vertically aligned in the midpoint of the top support, laterally positioned at the top support's center, and discreetly placed behind the front windshield. Intriguingly, the investigation revealed that the most advantageous placement was behind the front windshield. This position exhibited superior air-exhausting performance across all scenarios. This excellence can be attributed to the proximity of the air inlet to the steering wheel and its alignment with the hot air's flow direction. Consequently, under the preset pressure differential of -10 Pa at the air inlet, the hot air rapidly evacuates due to the strategic orientation. This is substantiated by the rationale that an air inlet ought to reside within high-temperature or high-pressure zones to facilitate the expeditious release of hot air propelled by local pressure disparities[29].

SehgalMotors[30] presented utilization of solar energy drives the AutoCool system, which effectively maintains a cool and refreshing interior environment within your vehicle. The installation process is remarkably straightforward, involving the simple action of lowering your window, positioning the AutoCool Ventilation System onto it, and subsequently raising the window. Exterior solar panels adeptly capture sunlight, channeling it to power an internal fan that orchestrates the circulation of air. Despite the diminutive total size of a mere 22 cm, the AutoCool fans achieve an impressive rotation speed of 4500 rpm. This pioneering research bridges a critical gap by aligning with the established notion that an ideal parked car interior temperature oscillates between 30 and 35 degrees Celsius—a range optimally conducive to driver and passenger comfort. The temperature sensor is one of the seamlessly functionalities that integrates with the device to help in energy optimization throughout operations. This sensor makes the system work only when needed and rest, greatly contradicting from its operating regimen if it always runs on the car's battery. Similarly, geometry is perfectly thought out to fill up 70% of total window surface area. As the dimension shows 27 cm in its measure. This ensures effective coverage for a broad spectrum of vehicle sizes while adhering to a universal fitment.

Additionally, a thorough cost-effectiveness analysis has been meticulously conducted, ensuring that the costing evaluation remains within affordable parameters.

Malaysia's climate presents an optimal environment for harnessing solar power and generating electricity. With an average of four to eight hours of daily sunshine, the nation boasts a significant solar energy potential. This abundant solar resource readily facilitates the generation of power through solar panels, thereby establishing Malaysia as a formidable contender in the realm of solar energy[31)].

In the fabric of modern society, automobiles assume a pivotal role, serving as essential modes of transportation for commuting to work, completing errands, and more. However, the scenario of a car parked on a scorching sunny day, particularly under direct sunlight, can lead to the interior temperature soaring to alarming levels of up to 70°C[32),33)]. Even a modest temperature differential of 15°C can prove pivotal, as instances of temperatures surpassing 38°C have tragically demonstrated the peril posed to children and pets inadvertently left within cars. The phenomenon of a greenhouse effect is conspicuously evoked when a car is parked under direct sunlight. Sunrays infiltrating the car's windows initiate a greenhouse-like mechanism, causing an elevation in the temperature of enclosed elements such as seats and dashboards[28)]. The moment one enters the vehicle, an oppressive atmosphere prevails, accompanied by an intense sensation of stifling heat. Besides the evaporative cooling system which has to work overtime before the interior ambiance can be comfortably thermally regulated. Moreover, it causes unloading of the altogether mechanism of air conditioning and increase in fuel consumption, thus it promotes the environmental problems[34),35)].

The current research seeks to provide a pioneering solution: a solar-powered ventilation system designed to suit the needs of vehicles in the Malaysian context. Here is the advanced technology used to harvest solar energy and produce low voltage electricity that effectively meets the needs of fans. These fans redistribute good air thus expelling hot and cold air from inside the car while at the same time improving the outside ambient air conditions. Furthermore, this may only be powered by solar electricity and does not detract from the energy saving of the vehicle's main battery. It is an essential component of the system that serves the purpose of monitoring the internal temperature of the vehicle through the control unit. The study aims to activate the solar ventilation system in Malaysian vehicles in a suitable manner for the purpose of use in cases where the temperature exceeds the specified ceiling by a certain degree. Therefore, this solution eliminates integration into the main frame of the vehicle making it compatible, portable and adaptable to a wide range of diverse vehicles while at the same time maintaining vehicle safety standards.

2. Methodology and materials

It describes the approach taken for the study, giving an account of the material, parameters, circumstances, and design scheme which were used in the experiment. This study's methodology is primarily comprised of five phases: data preparation, design, modelling, material alternative and cost estimation, fabrication and/or simulation and data analysis.

2.1 Phase 1: Data Preparation Phase

The fact that the development of main design principles and equations being determinant for data preparation is highlighted draws attention of readers to importance of this process. Initial data configuration encompasses crucial parameters such as the initial temperature of the vehicle subsequent to being parked under direct sunlight, a value typically approximating 50 degrees Celsius. Distinctly, the research culminates at the optimal temperature of 32.4 degrees Celsius, a benchmark deemed ideal and comfortable for drivers. The vehicle chosen as the subject of this study is the Honda City ZX. The essential summarized initial data is succinctly presented in Table 1.

Table 1. Initial data preparation.

Initial Temperature	50 ºC
Ideal Temperature	32.4 ºC
Vehicle Type	Honda City ZX

Enhancing the efficacy of heat transfer across the system constitutes a fundamental objective of this design endeavor. Consequently, to precisely gauge and quantify the efficiency of the airflow, it necessitates the application of pertinent equations. Notably, the equation to ascertain heat recovery efficiency emerged in lieu of the originally sought heat ventilation efficiency. This strategic adjustment yields a consequential outcome in terms of heat recovery, which subsequently serves as the cornerstone for deriving the system's ventilation efficiency. The equations underpinning this evaluation are presented in Eq. 1 and Eq. 2[36)]. The formula dictating temperature transfer efficiency for heat recovery is expressed as follows:

$$\mu\_h = ((t\_2 - t\_1))/((t\_3 - t\_1)) \times 100\% \quad (1)$$

Where:

μ_h= Temperature transfer efficiency for heat recovery

t_1= Temperature outside air before entering system

t_2= Temperature inside air after system heat transfer has occurred

t_3= Temperature inside air before system is switched on

From the temperature transfer efficiency for heat recovery equation, the efficacy of the ventilation system can be calculated using the temperature transfer efficiency for heat loss equation, as shown in Eq. 2.

$$\mu_v = 100 - \mu_h \quad (2)$$

Where:

μ_v= Temperature Transfer Efficiency for Heat Loss

2.2 Phase 2: Design and Modelling Phase

In this research, the proposed system takes the form of a portable unit, strategically affixed to the dashboard in close proximity to the driver's seat and the steering wheel. This innovative design encompasses a triad of axial fans, harnessed by a direct current propeller mechanism, orchestrating heightened airflow to effectively displace hot air. The crux of this investigation revolves around augmenting both the air movement efficiency and the heat transfer capacity of the internal hot air within the vehicle, facilitating its transition to the ambient external temperature.

Furthermore, the overarching objective of this study is to maintain the interior temperature of the vehicle at a steadfast 32.4°C, aligning with the standard ambient air temperature prevalent in Malaysia. Augmenting this endeavor, the integration of a temperature sensor significantly enhances the efficiency of heat transfer operations. This sensor-driven augmentation dictates that the system solely activates and expels hot air when the interior temperature breaches the 50-degree Celsius threshold. This dynamic feature effectively curtails power consumption by engaging and disengaging the system solely as necessitated by prevailing conditions.

Another significant enhancement of the new design is that it has a length of 270 mm, which allows it to cover approximately 70% of the car's side window. This will increase the surface area of the air exposed, which will result in a significant rise in the efficiency of the air flow in space. The fan speed for the design model is faster and has a higher power output when compared to the fan speed for the previous study's design, all of which contribute to improving the efficiency of air flow.

A 3D model of the solar ventilation system as shown in Fig. 1 and Fig. 2, was created using the Creo 7.0 software during this phase, which will be shown to give an idea of what the model looks like. In order to create the final result, the software was utilized to draw each individual component of the system as well as the entire system as a whole. The measurements chosen are a close approximation of the actual dimensions of the automobile.

The stress-strain analysis of the design model was done using Solidworks 2021 software. The analysis was done to determine the stresses and strains in materials and structures that are subjected to forces. According to the results of the analysis, the maximum Von Mises Stress of the model is 221.8 MPa, as appears in Fig. 3.

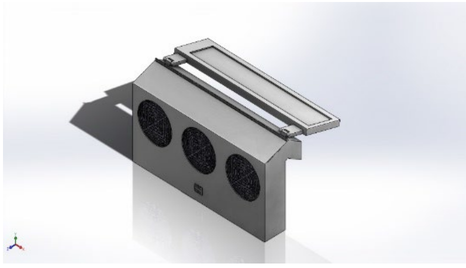


Fig. 1: Full assembly of solar ventilation system model

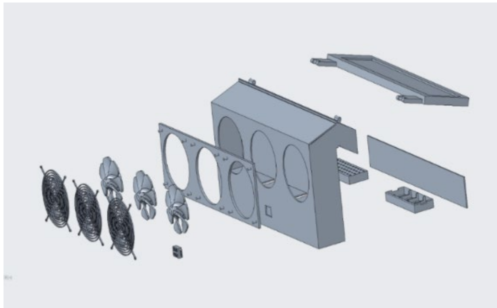


Fig. 2: Exploded view of solar ventilation system model

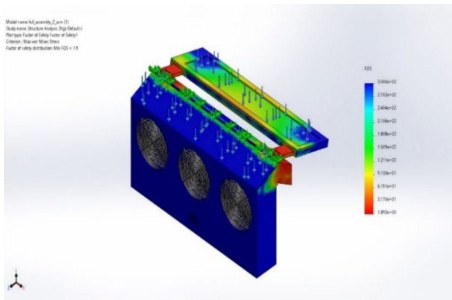


Fig. 3: The stress-strain analysis of the proposed system

2.3 Material Selection and Cost Analysis Phase

Material selection is one of the most important steps in product design and development. The selected materials must be characterized by their high quality and moderate and acceptable cost. The material used in the design was ABS plastic. ABS plastic has a low melting point, making it ideal for use in the injection molding process as well as 3D printing applications. The main components of the design made of ABS plastic are the main body, solar panel holder and axial fan blade. Table 2 summarizes the specifications and costs for the various material selections made using the cost-effective approach.

Table 2. The summary of the material selection with its cost.

Parts	Price (RM)	Quantity	Total (RM)
Solar Panel Polycrystalline Silicon 2.2 W	11.90	1	11.90
18650 3.7V Rechargeable Battery	4.87	1	4.87
Axial Propeller Fan 5 V 8025 DC	13.50	3	40.50
18650 Battery Holder	2.20	1	2.20
DHT 11 Temperature Sensor	4.90	1	4.90
Arduino Breadboard	2.50	1	2.50
Arduino Switch Relay Module	3.90	1	3.90
Arduino Breadboard Wire	6.00	1	6.00
Rubber Window Seal	9.00	1	9.00
Arduino Nano	19.50	1	19.50
TP 4056 Module	4.90	1	4.90
XL6009 Booster	6.90	1	6.90
3D Printing	200	1	200.00
Total			317.07

Based on the stress strain analysis, the factor of safety was determined. The analysis was carried out in accordance with the materials chosen for each component as well as their respective material attributes. Calculated from the data analysis, the factor of safety was 1.9, which is suitable for usage in the circumstances of the study and preventing the model from experiencing failure. The factor of safety was calculated using Eq. (3)[37].

$$F.O.S = (Yield\ strength)/(Maximum\ Von\ Mises\ Stress) = 421.142/221.8 = 1.9 \quad (3)$$

The stress and strain analysis were also performed on the windows of the vehicle to determine whether or not they are able to withstand the force that will be applied when mounting the solar ventilation system. As can be seen from the fig, the mounting force is not dangerous and will not result in any damage to the glass used in the vehicle's windows.

3. Climate Analysis for Malaysia

In this investigation, data collected over a span of 30 days in November 2022 in Kuala Lumpur serve as the foundation. Specifically, the 22nd of November 2022 was chosen due to its marked clarity in sky conditions. The minutely recorded dataset encompasses ambient temperature and global solar radiation, visually represented in Fig. 5. Notably, the solar radiation profile reveals an atypical distribution curve, a phenomenon attributed to the intermittent rainy and cloudy weather patterns characteristic of Malaysia. Despite these irregularities, exclusively clear sky days were considered for analysis. The calculated averages for daily ambient temperature and total global solar energy stand at 38.89°C and 4062 Wh/m², respectively. These figures underscore the remarkable solar energy potential in Kuala Lumpur, with both radiation levels and temperatures conducive to effective photovoltaic system implementation[38].

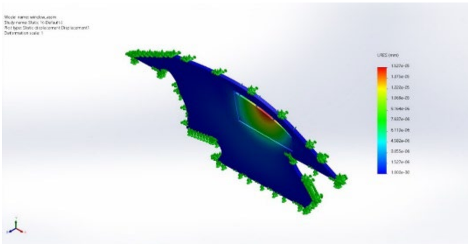


Fig. 4: Stress-strain analysis on Car's window

Consequently, this scenario implies the feasibility of investments in PV systems. Nevertheless, the relatively high ambient temperature aligns favorably with the thermal aspects of PV systems, yet simultaneously dampens the power generation efficiency of photovoltaic panels. This distinction manifests in the divergence between PV power generation at standard test conditions (25°C ambient temperature) and the current study's conditions (39°C ambient temperature). The outcome is a discernible 7% reduction in peak power output.

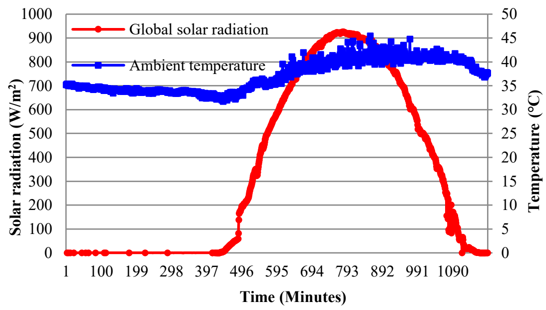


Fig. 5: solar radiation and temperature measurements encompassing solar energy profiles in Kuala Lumpur

4. System Design

4.1 SPVS electrical setup

The electrical configuration of the solar-powered ventilation system can be broken down into two primary components. The first configuration is the operating part of the system in which an Arduino and a DHT 11 temperature sensor will work together to regulate the operation of the fans in a direct manner. If the DHT 11 temperature sensor determines that the interior of the vehicle has reached a temperature of 50 ºC or more, it will send a signal to the relay, which will then cause all three fans to turn on at the same time automatically. This is shown in Fig. 6.

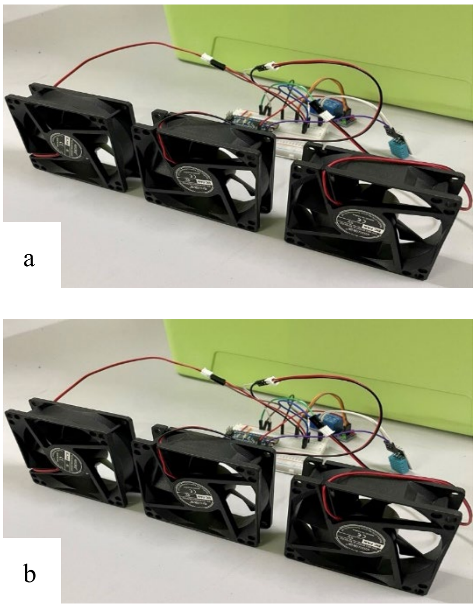
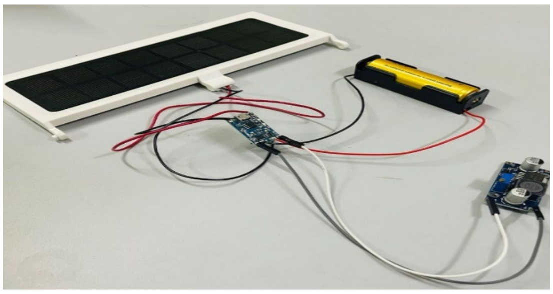
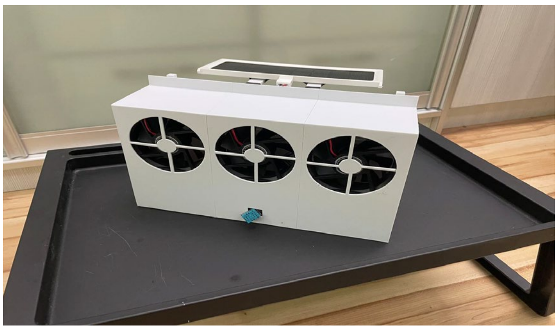


Fig. 6: (a) front view for operating part of SPVS, (b) side view for the wiring setup

The second part is the power input setup, in which the solar panel is connected to a TP4056 chip, which is a lithium-ion battery charger that protects the battery from overcharging and undercharging. The TP4056 chip is then connected to an 18650 rechargeable battery with a rated voltage of 3.7V, which is also connected to a voltage regulator that will increase the voltage up to 5V in order to power the Arduino. The third connection is made between the voltage regulator and the Arduino as shown in Fig. 7(a).



(a)



(b)

Fig. 7: (a) side view for power input setup of the proposed system, (b) full design of proposed SPVS

The full setup of the solar ventilation system consists of the electrical setup with its full body and operating system is shown in Fig. 7(b).

4.2 The Arduino Program

The Arduino program can be used as both a measuring instrument and a switch at the same time. When the inside ambient temperature of the vehicle exceeds 50 degrees Celsius, the DHT 11 temperature sensor will send a signal to the relay labelled 'LOW' and begin turning on the three DC axial propeller fans. This will allow the car to be ventilated with air from the ambient outside environment. The programming code is shown in Fig. 8.

```
File Edit Sketch Tools Help
Open
second_try §
#include "DHT.h"
#define DHTPIN 12
#define DHTTYPE DHT11
DHT sensor(DHTPIN, DHTTYPE);
int relay_pin = 9;

void setup() {
Serial.begin(9600);
sensor.begin();
pinMode(relay_pin, OUTPUT);
digitalWrite(relay_pin, HIGH);
}
void loop() {
float t = sensor.readTemperature(); //reading the temperature from the sensor
// Checking if the sensor is sending values or not
if (isnan(t)) {
Serial.print("Failed");
delay(1000);
return;
}
Serial.print("Temp: ");
Serial.print(t);
Serial.print(" C");
if (t > 50){
  digitalWrite(relay_pin, LOW);
  Serial.print("Fan is ON ");
  delay(10);
}
else{
  digitalWrite(relay_pin, HIGH);
  Serial.print("Fan is OFF ");
}
delay(2000);
}
```

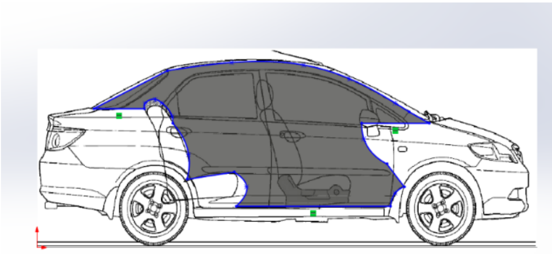
Fig. 8: SPVS programming code

4.3 Simulation phase

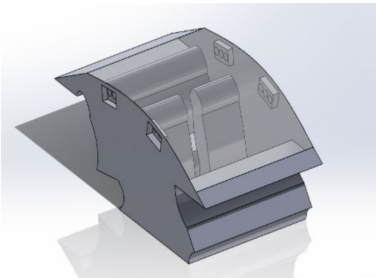
The CFD ANSYS FLUENT 2021 R2 software was the one that was utilized in order to perform the flow simulation. Two distinct types of simulations were carried out in order to model the functioning of the system which is simulating the velocity of the air and the heat transfer that takes place within the car. The actual dimensions of the ventilation system and the car model, Honda City ZX, were used as the basis for the simulations that were run.

The outline of the car was sketched and drawn in the Solidworks software based on a picture of the model car, and then the model was extruded to correspond to the actual measurements of the car. After that, the four models of the solar ventilation system were also sketched and extruded on the left and right sides of the car in order to have only the operational systems and their essential boundary conditions for the heat transfer system as shown in Fig. 9.

After the geometry has been designed using the Solidworks software, it is exported to a STEP file and imported into the Ansys FLUENT software as an external geometry. The meshing process was carried out on the model using an element size of 0.2, which had an orthogonal quality of 0.77 and a skewness of 0.23. These values are regarded as very good in the size for meshing. The total number of elements that make up the model is 686842. The inlet and outflow areas of the zone types were determined by naming the face as inlet and outlet, and the zone type for the body of the car was determined by naming it is car body.



(a)



(b)

Fig. 9: (a) sketching of the car outline, (b) 3D model of the car with SPVS

The configuration for the flow analysis apparatus is established in the setup section of the FLUENT in order to begin the analysis. The simulation is configured to run as a transient simulation, and the models that will be used for this investigation are the energy model, which is used to govern the heat transfer in the vehicle, and the RNG k-epsilon model, which is the most common type of turbulence model and is used to simulate the flow development under turbulent flow conditions. Both of these models will be used to simulate the flow. The material selected for the fluid is air.

Table 3. summary of system parameters.

Parameters	Value
Element Size	0.2
Orthogonal Quality	0.77
Skewness	0.23
Total Number of Elements	686,842
Model	RNG K-Epsilon
Flow	Transient
Fluid	Air
Fan's Average Air in Flow	34.86 CFM
Fan's Average Air in Flow	0.82 m/s
Air Mass Flow Rate	0.02 kg/s
Time-Step	600
Number of Iterations Each Time-Step	10
Initial Temperature of Car After Parked	50 ºC / 323 K
Temperature of Ambient Air	32.4 ºC / 305.4 K

The simulation was done for two cases where the first case is with the most effective configuration has been established that consist of putting two inlets on the right side of the car and two outlets on the left side of the car. The second case is carried out with a single inlet, which was located on the right side of the window of the driver's seat of the vehicle. This is in accordance with the results of the real-time testing, which had only a single system attached due to financial and time constraints. The simulation for both cases was carried out for five and ten minutes.

4.4 Data Analysis Phase

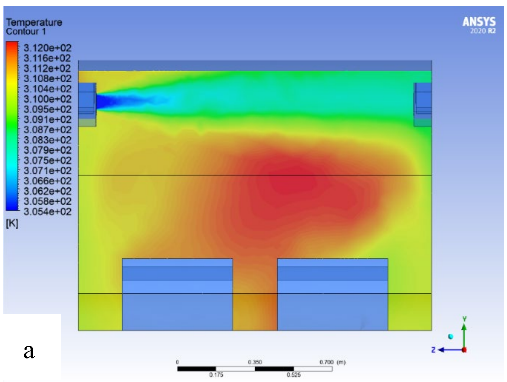
After the simulation of the heat transfer flow has been finished, the findings were analyzed, and data was obtained for each of the numerous situations. The comparison of the temperature distributions for each scenario will be used to do the analysis. The results of the analysis are seen in the result area of the ANSYS Workbench Project Schematic. The real-life testing was also done for 5 days in order to calculate the efficacy of the system and comparisons are made with the simulations.

5. Results and discussion

5.1 Simulation results

A. Case 1: 2 Inlets 2 Outlets

From Figure 10(a), the minimum temperature is 305.4 K located at the area near the inlets while the maximum temperature in the car is 312.3 K located mostly near the center to the left seat of the car. The average temperature of the car is around 308.85 K, with a temperature drop of 14.15 K from the initial condition of the car after 5 minutes. This demonstrates that the system is operating in the appropriate manner.



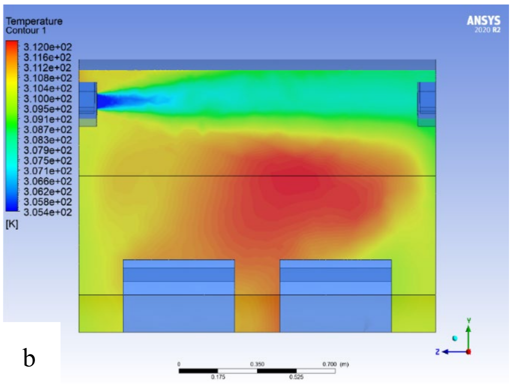


Fig. 10: Temperature contour at YZ plane for case 1 after (a) 5 minutes, (b) 10 minutes

From Figure 10(b), the highest recorded temperature was 307.88 K and the lowest was 305.4 K. The sum of these two figures results in an average outflow temperature of 306.64 K, or 33.49 ºC. The temperature has decreased by 16.36 ºC from the original condition, with an increase of 2.21 ºC occurring during the first five minutes after the system is turned on. The effectiveness of the system has been calculated based on the findings.

B. Case 2: 1 Inlet

From Figure 11, the minimum temperature was found out to be 305.4 K located closely to the ventilation system and the maximum temperature was 322.13 K which is mostly all of the area in the interior car except for the top area of the driver's seat. The average temperature of the car is 313.77 K which decreases about 9.23 K from the initial temperature of the car. This illustrates that the temperature inside the car may be lowered by one unit of the ventilation system, albeit by 4.92 ºC less than in Case 1.

The results of the experiment showed that after 10 minutes of operation, the minimum temperature is 305.4 K and the highest temperature is 322.04 K. These findings are depicted in the Fig. The difference between this scenario and Case 1 is that the temperature distribution is more equally distributed throughout the car, which demonstrates that there is turbulent air flow within the car. The calculated average temperature is 313.72 K, which is not substantially different from the temperature 5 minutes earlier. As a result, it is possible to draw the conclusion that Case 2 has a temperature drop of 9.28 degrees Celsius when compared to the initial temperature of the hot car.

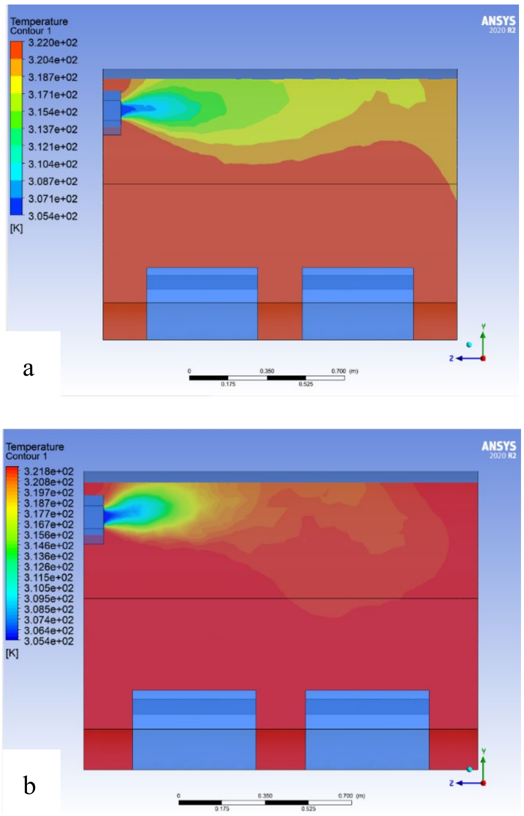


Fig. 11: Temperature contour at YZ plane for case 2 after (a) 5 minutes, (b) 10 minutes

C. Summary of Simulation Results

Calculated and reported in Table 4 and Table 5 is the overall effectiveness of the ventilation system, which was determined by applying Equations (1) and (2) to the data that was collected.

Table 4. Summary of heat transfer of the simulation results after 5 minutes.

Case	**Initial Temperature (K)**	**Maximum Temperature (K)**	**Minimum Temperature (K)**
1	323	312.3	305.4
2	323	322.13	305.4
Case	Average Temperature (K)	Temperature Transfer Efficiency for Heat Loss, μ_v	Max Velocity (m/s)
1	308.85	80.4%	0.701
2	313.77	52.44%	0.2

Table 5. Summary of heat transfer of the simulation results after 10 minutes.

Case	**Initial Temperature (K)**	**Maximum Temperature (K)**	**Minimum Temperature (K)**
1	323	307.88	305.4
2	323	322.04	305.4
Case	Average Temperature	Temperature Transfer	Max Velocity

	(K)	Efficiency for Heat Loss, μ_v	(m/s)
1	306.64	92.95%	0.701
2	313.72	52.73%	0.2

Analyzing the provided tables reveals a substantial disparity between Case 1 and Case 2 in terms of efficiency, attributed to the distinct configurations of inlets and outlets. Notably, Case 1 emerged as the favored and optimal arrangement. While a significant divergence exists between these two cases, it is imperative to underscore that both instances underscore the ventilation system's remarkable potential to curtail the interior temperature of the vehicle.

5.2 Experimental results

The experimental testing spanned a duration of seven days, aimed at comprehensively assessing the product's practicality and effectiveness in its core objective of reducing the interior temperature of the car. The used car in tests was Proton GEN•2. Tests were conducted within a sunlit car park, the research transpired precisely at noon – a time when the sun reaches its zenith, providing a stringent scenario[39]. Ambient air temperature and the vehicle's internal temperature were meticulously measured using a RH temperature meter. Additionally, the temperature transfer efficiency for heat loss was calculated in order to compare the results of the real-world testing with the theoretical results obtained from simulations. The monsoon season was in effect in Malaysia at the time of the study, which explains why the ambient air and initial inside car temperatures are varying. The summary of the results is shown in Table 6, which lists the measurements for the seven-day tests. The measurements revealed a decrease in the vehicle's internal temperature ranging from 9.05 degrees Celsius (day four) to 11.63 degrees Celsius (day five). This fluctuation in the rate of temperature decline can be attributed to climatic conditions such as humidity, wind speed, and the movement of shadows.

Table 6. Summary of experimental results

Day	Ambient Air Temp. (K)	Initial Temp. (K)	Average Temp. (K)	Temp. Transfer Efficiency for Heat Loss, μ_v	Temp Drop (K)
1	305.15	321.25	311.25	62.11 %	10
2	302.35	319.92	308.47	65.17 %	11.45
3	303.46	320.66	309.88	62.66 %	10.78
4	310.75	325.75	316.7	60.35 %	9.05
5	301.93	319.55	307.92	66.02%	11.63
6	308.16	324.78	314.97	59.02 %	9.81
7	310	325.03	315.93	60.57 %	9.10

Fig. 12: (a) measured ambient air temperature, (b) measuring initial Car's interior temperature and (c) measuring average Car's interior temperature

5.3 Comparison of simulation and experimental results

A simulation was meticulously executed mirroring the conditions of the initial day of real-world testing. All pertinent parameters from that particular day were faithfully integrated into the simulation framework. This strategic approach was adopted to facilitate a comprehensive examination of the distinctions between the simulation outcomes and the actual results obtained from real-world experimentation. The simulation results are visually represented in Fig. 13, while a detailed comparative analysis between the simulated and real-life data is presented in Table 7.

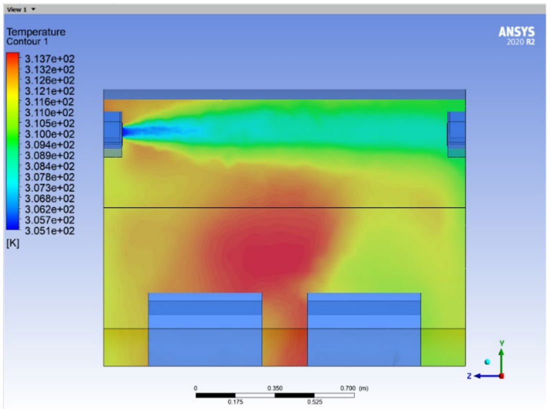


Fig. 13: Temperature contour at YZ plane for day 1

Table 7. Comparison of simulation and experimental results.

Results	**Ambient Air Temp. (K)**	**Initial Temp. (K)**	**Average Temp. (K)**	**Temp Transfer Efficiency for Heat Loss, μ_v**	**Temp Drop (K)**
Simulation	305.15	321.15	309.4	73.44 %	11.75
Real-Life Testing	305.15	321.25	311.25	62.11 %	10

Based on the findings, a discernible deviation of 11.33% was observed between the simulation conducted using CFD Ansys Software and the results obtained from the practical experimental testing. This variance can potentially be attributed to the dynamic weather conditions experienced during the testing phase, wherein fluctuations in the surrounding air temperature around the car might have occurred, possibly differing from the conditions simulated.

Using the air conditioner in a car that has been heated by the sun while parked can take a large amount of energy. This is because the system must exert more effort to cool the car's interior, which can demand a great deal of energy. To add more disclosure, the actual fuel consumption will depend on more factors such as the size and type of vehicle, the efficiency of the air conditioning system, and the length of time the air conditioning system is running as[40] pointed out.

Here we can attribute the fact that air conditioning systems in cars can increase fuel consumption by up to 20%, as mentioned[41]. Consequently, many diesel vehicles lose a significant portion of their performance because the air conditioning system contributes to increased engine load, leading to increased fuel consumption. Excessive consumption of the car's air conditioner to cool a car parked in the sun for a long period of time often leads to increased fuel consumption.

Don't forget that your car's air conditioning system can use less energy if you take certain steps when cooling your car. This means that reducing the number of hours the air conditioner runs or keeping it at the lowest possible level helps reduce fuel consumption. The solar ventilation technology project for cars will help reduce fuel consumption, and less use of the air conditioner on high settings will help cool the car after heating.

5.4. Comparison with literature

In Figure 14, the results of several similar recent studies from the literature are compared with the current study. It must be emphasized that this comparison may be somewhat unfair due to the difference in the ventilation techniques used and the real weather conditions in which the studies were conducted. But such a comparison gives a kind of validation for the work whether it is within the range of temperature differences or outside it. The comparison shows that the technique used in the current study achieved the highest temperature difference, although most of them were close in the range of 5.8 to 5.10°C. As for the current study, the temperature difference was around 11.63°C. Ref.[42] examined a ventilation system consisting of a fan to draw in fresh air and expel hot air. It operates on solar energy with the use of a rechargeable battery to operate the ventilation device during cloudy days or the presence of shadows. Ref.[43] also installed a solar air-cooling system that used solar panels to generate electricity, which charged a 12-volt battery, which in turn provided the required power for the cooling unit consisting of a Peltier convection cooler and fan motor. As for Ref.[44], it used ventilation based on a photovoltaic panel installed on the roof of an electric car to manage/ventilate the cabin temperature. Ref.[45] adopted a mobile ventilation system powered by photovoltaic panels. Ref.[46] studied the possibility of using a solar-powered ventilation system based on the Internet of Things. Ref.[47] conducted practical experiments on a car equipped with a solar-powered ventilation system parked in the sun. Ref.[48] tried using solar panels to operate a blower in a car's HVAC system to automatically bring fresh air into the car's cabin by controlling some electrical means.

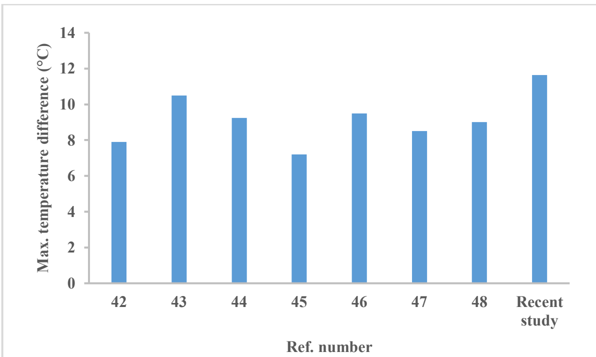


Fig. 14: Comparison of the resulted maximum temperatures differences between the current study and other from literature

5.5 Limitations of the Study

While the study demonstrates promising results for the solar ventilation system, several potential limitations should be acknowledged:

1. Variability of Solar Power Availability:
   - Inconsistent Solar Exposure: Some of the aspects of the solar ventilation system are shown below: The efficiency of working depended on constant and intensive sunlight. During the periods in which there is cloudy sky, intense rainfall, or during the winter time when the day is short, depending on the locations, the availability of solar power will be considerably less, thus the system.
   - Seasonal Variations: Therefore, because of the oscillations occurring with the change in seasons, the rate of power generation could go up and down greatly. For instance, the system may work well when there is so much sunshine as during summer while it may not work well during winter.
2. Performance Under Different Weather Conditions:
   - Adverse Weather Conditions: Adverse environmental conditions including very wet weather state, thunderstorm or dust storms affects the system. These conditions may lead to a decline in the generation and use of solar power besides compromising on the life and efficiency of the components.
   - Temperature and Humidity Fluctuations: Another factor that was considered is that the performance of this system depends on the degree of temperature and humidity of the environment. Increase of humidity results in the change of heat dissipation rate when using convection-based heat dissipation systems, whereas extreme temperatures influence the efficiency of the solar panels as well as the entire system.
3. Real-World Application vs. Simulations:
   - Discrepancies Between Simulations and Real-Life Testing: In the study the authors reported a changeover in thermal conductivity as observed in the simulation experiments and the actual experiments. Can also be attributed to the fact that definitely, more field testing is needed to prove the predominantly favorable results, to assess the effectiveness of the proposed system in recreating preconditions as close to real-life environment as possible.

6. Conclusion

This study has paved the way for the prospective integration of solar ventilation systems into Malaysian automobiles. The design's simplicity and user-friendly layout make it readily adaptable to a diverse range of vehicles. The procurement of components required for constructing the ventilation system from the Malaysian market is also notably convenient. Considering the remarkable functionality it delivers, the cost associated with the system remains reasonably justified.

The outcomes of the simulations conducted unequivocally demonstrate the solar ventilation system's ability to effectively counteract the elevated interior temperatures encountered when vehicles are parked under the scorching sun for extended periods. Beyond creating a highly comfortable environment for drivers upon entry, the system plays a pivotal role in environmental conservation by curtailing fuel consumption. This reduction is attributed to the diminished need for using the engine to cool the vehicle, a demand that's mitigated by the implementation of the ventilation system. In essence, this technology holds the potential to trigger a revolutionary shift within Malaysia's automotive sector. Summarily, the key conclusions derived from this study are as follows:

The most optimal configuration involves incorporating two inlets and two outlets, thus forming a quartet of solar ventilation systems.

The highest efficiency attained under optimal conditions stands at an impressive 92.95%.

Efficiency calculations under the same parameters for the simulation on day 1 yield 73.44%, whereas real-life testing yields 62.11%.

A discernible 11.33% variation in temperature transfer efficiency for heat loss is observed between simulation and real-world testing, primarily attributed to the influence of weather factors on heat transfer dynamics.

Air temperature plays a pivotal role in heat transfer through its impact on convection and conduction mechanisms.

Air humidity exerts a consequential influence on heat transmission, altering the efficacy of convection-based heat dissipation due to its impact on air's ability to circulate.

Upon concluding this developmental research, several recommendations emerge to amplify the solar-powered ventilation system's performance, providing potential avenues for future research endeavors informed by this study:

Enhancing the system's solar panels to maximize effectiveness, even to the extent of eliminating the need for a rechargeable battery.

Refining the system's geometrical dimensions and weight to enhance user-friendliness.

Addressing the system's holistic efficacy by considering the interplay of its various components.

Recognizing the potential for further optimization through improved solar panel efficiency and enhanced geometric design.

Taking into account the system's overall functionality, considering both individual components and their integrated performance.

In future work, more attention should be paid to this design to allow new and different types and sizes of compounds to be integrated into the system. This system can be enhanced to include small sedans, SUVs, trucks and bus types. This design can also be tried on hybrid and electric cars since they have rear electric motors.

Declaration of interest statement

"We the authors declare no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript".

Conflict of Interests

"The authors declare that there is no conflict of interests regarding the publication of this brief note".

Data Availability

"The research data is available upon request. To request the data, contact the first author of the article".

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