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Cooling effect and heat index (HI) assessment on car cabin cooler powered by solar panel in parked car

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ABSTRACT

Damage to the car compartment, thermal discomfort, fuel wastage, health risks, and the death threat of passengers/pets in the cabin due to high temperatures in cars parked under the sun is an interesting discussion. Therefore, this research examines the characteristics of solar cells-based cabin cooler system on car parked under the sun. Four ST32M100W-FLP solar panels installed on the car roof are used to activate the existing evaporator blower with modified wiring lines. The blower is activated in two modes, i.e addition and without addition of external air at blower speed levels 1 ($\dot{m}$=0.0086 kg/s) and level 2 ($\dot{m}$=0.0114 kg/s). The results showed that the car cabin cooler able to reduce cabin temperature by 9.8 °C. In addition to temperature reduction, latent and sensible cooling effect, as well as heat index (HI) are also discussed in this paper. It was found that due to increased humidity, the release of sensible heat affects the car cabin cooling while parked under the sun from noon to afternoon. Finally, the car cabin cooler can reduce the heat index (HI) from danger and extreme danger categories to caution and extreme caution category.

1. Introduction

Vehicles parked under the sun during the day tend to experience the cabin temperature increasing due to trapped solar radiation, which damages the steering wheel, seats, dashboard, and other interior compartments [1–7]. According to Sugimura et al. [8], the child's seat in a vehicle parked in a parking lot has a maximum temperature of 65.5 °C. Meanwhile, at the equator, the temperature of vehicles parked in open areas can reach 68.7 °C [9]. Cars parked under the sun tend to have excess cabin which causes thermal discomfort, increases air conditioning (AC) load and fuel consumption [10–13]. Moreover, it produces toxic gases from interior materials' evaporation, thereby increasing health risks for passengers/pets in the cabin [14–18]. Many children were reported die from heatstroke and hyperthermia every year because they are left unattended in closed and parked cars over a prolonged period [19–23].

Previous studies have been carried out to regulate the cabin temperature of parked vehicles with numerous respective methods. For instance, a cabin cooling device consisting of a photovoltaic, axial fan, and the battery was simulated by Yan et al. on the Kymco UXV-500 small-size electric car [24]. Yan et al. claimed that the proposed device can release the heat load trapped in the cabin effectively. However, this study was carried out at a simulated scale with computational fluid dynamic (CFD) in a conditioned environment, therefore, the actual performance of the proposed device cannot be validated yet. The AC concept powered by photovoltaic was also

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proposed by Daut [25] using photovoltaic (PV) modules, a charge controller, and a battery to power the AC system. There were no simulations or trials reported in this research, therefore the performance of the proposed idea cannot be estimated.

Meanwhile, Sudhir [26] carried out a research on the solar panels used to drive a mini fan as cabin cooler. A fan was installed in the rear dashboard, which releases heat from the cabin into the environment. This study reported a temperature drop up to 10 °C, however, it was unable to compare cabin temperatures throughout the day. Therefore, the temperature ratio with and without refrigeration was unable to be further evaluated. The same result was also reported by Sudhir while using different media [27].

A cooling system with a peltier installed prototype car's roof was proposed by Abraham [28]. In this trial, the addition of thermoelectric powerd by photovoltaic was able to reduce the cabin temperature of a car parked under the sun. Unfortunately, this study did not display in-cabin temperature profile at the time of testing, hence its effectiveness is unable to compare. A portable solar cooling equipment trial was carried out by Pan et al. [29] by placing a foldable photovoltaic array on the parked car roof under the hot sun. The electrical energy generated is then stored in the supercapacitor and used to drive the mini cooler placed on the vehicle dashboard. This experiment produced a maximum output power of 2.181 W, while the simulation results showed that an average of 4.2 °C reduces the temperature inside the cabin. Even though the temperature drop was not as expected, it is interesting that wireless power transfer (WPT) was successfully used to transfer the electrical energy from photovoltaic without damaging the car parts to make wiring system. Another study reported the use of an integrated PV usage system on the electric vehicle roof to drive a fan to mitigate excess cabin temperature during parking [29]. The cabin temperature is monitored while vehicle is exposed to sunlight. This study reported a significant temperature decrease by adding fans to dissipate heat, however, the windshield opened by 1.3 cm, which is a risk to vehicle safety. Sagar [30] carried out a research to run a car cooling system with a small size PV (103 × 67 × 3.4 cm) used to drive an electric motor and expected to power the vapor compression AC compressor. However, this proposal is unconfirmed because the results were not reported clearly.

Another study examined a cabin cooling system by spraying compressed liquid air. This method was used to cool the cabin quickly as the car is run from open parking lot. However, it was unable to reduce the cabin temperature when parked under the sun for a prolonged period [6]. Meanwhile, an experiment to reduce a parked vehicle's temperature was successfully carried out by installing a fan on the 800 cc Perodoa Kancil car [9]. However, activating the fan with a battery is risky due to discharging the battery capacity if it is not continuously charged from free sources such as radiation energy with solar panels. Another method was proposed by Vishal et al. [18] to determine the use of electrochromic tints on the windshield, intake and exit vents, windows reduction, and their combination. The results showed a decrease temperature by 14 °C between 10.00 and 10.30 a.m. during summer. However, this study was carried out on a vehicle prototype that was downsized 5 times, therefore the practice in actual conditions was not validated. Meanwhile, other studies stated that the high temperature in the cabin has the potential to be converted into electrical energy via thermoelectricity [31]. However, unadequate heat energy can be reduced and converted to electrical energy by approximately 0.17 Watt and invisible to reduce the cabin temperature until it is in balance with the ambient temperature.

To reduce excess temperature in a car, Lahimer [32] conducted an experiment by attaching a solar chimney to part of the vehicle roof by perforating it for air circulation. This study reported a significant reduction in temperature; however, it was aesthetically less acceptable with the presence of solar chimneys. In other study, the phase change material (PCM) addition to the truck cabin was reported to reduce temperature [33]. However, this simulation study has not been accompanied by an experimental research to determine the performance of the proposed PCM. Recently, an effort to keep the cool cabin temperature when parked under sun was carried out by installing a PCM, and the result showed a decrease temperature from 55 °C to 36 °C [10]. However, the awkwardness of this study that the cabin volume and air mass were not accountable, therefore the total heat released during the test was not further analyzed.

In author's previous study, a series of solar panels were installed to the car roof to drive fans in the cabin [34]. A mini cooler was attached to the dashboard and successfully reduced temperature by 34%. Recently, Purnomo et al. [35] researched a solar panel for cooling cabin on the Bajaj Qute, which produced positive results. However, the addition of a mini cooler in the dashboard reduced the aesthetics and frequent water spilled from the reservoir in the mini cooler.

Based on discussed literatures, analyzes related to the mitigation of car cabin temperature with devices powered by solar cells that report the amount of energy released during the car's exposure to the sun are very limited. In fact, as reported by Horak [36], there is no ventilation and/or AC works in parked vehicles. Heat from sunlight propagates through the car windows and other cabin walls causing the accumulation of heat energy in the cabin. High cabin temperatures can threaten children left in vehicles and cause an average death rate of 37 children per year in the US. In addition, high temperatures in the cabin can damage temperature-sensitive items, such as medicine in an ambulance. Releasing heat energy in the cabin can indeed be done by opening the car window, but it is risky for thievery and contamination of dirty air or the entry of insects into the cabin. Therefore, a smart solution is needed to release heat energy in the cabin without opening the windows to reduce the risk of damage to components and items in the cabin and reduce the risk of thievery.

The majority of studies report only cooling effect from sensible heat, including by Kolhe [37], while cabin air contains water with heat vaporization is about 2,260 kJ/kg [38], which is quite important to consider. Previous studies did not address the effect of cabin temperature and humidity on health risks by comparing it with the heat index (HI). In fact, the thermal comfort felt by humans is not only influenced by temperature but also air humidity and it is closely related to stress levels [39–41]. So, it is important to consider the heat index which combines temperature with humidity into a new indicator in vehicle cabin thermal engineering. Therefore, this article reports the experimental results on a cabin cooling system powered by a solar cell that not only addresses temperature reduction but also discusses the amount of cooling effect and heat index. In this study, to circulate air in the cabin, we do not add an electric fan as reported by previous researchers [5,9,27,29] but we use the existing blower evaporator. Two test scenarios, with and without the addition of outside air are reported at level 1 and level 2 blower speeds.

2. Method

2.1. Experiment set up

Two 1.8-L Nissan Grand Livina cars, with and without a car cabin cooler, are placed in an area exposed to direct sunlight as presented in Fig. 1 with temperature, pressure, and humidity measuring instruments which are presented in Fig. 2. The two cars were selected based on similar colors. The test was carried out in the parking area Universitas Muhammadiyah Magelang (link location), where sunlight is available from morning to the afternoon. To estimate the air volume in the cabin, we use AutoCAD which considers the shape of the car's interior compartment, as presented in Fig. 3. It was found that the air volume space in the cabin is 3.473 m^3.

In the car equipped with a cabin cooler, four solar cells (ST32M100W-FLP) are assembled in parallel and installed on the roof with a double-tape adhesive that allows the solar cell array to adhere to the car roof shape (see Fig. 1). The output cable from the solar cell is extended into the cabin through the front door rubber seal. The electricity generated is supplied to the battery through a Solar Charge Controller Regulator (SCCR) to drive the HVAC knop at levels 1 and 2, as shown in Fig. 4. In this study, although there are 4 speed levels of evaporator blower available, we only use level 1 and 2 because the power from the solar cell is not sufficient to operate the evaporator blower at levels 3 and 4. The measured air flowrate ($\dot{m}$) by LM-8010 air flow meter is 0.0086 kg/s and 0.0114 kg/s at level 1 and level 2, respectively. In this circuit, a Voltmeter and Ammeter are also installed to monitor the solar cell's voltage and current generated. Each car has 3 thermocouples, which are hung at the front, center, and rear of the cabin and used to measure the cabin temperature. Then, a thermocouple is installed in the evaporator blower outlet in car A and another is installed outside the car to measure the ambient temperature. All thermocouples are connected to the Multi-Channel Temperature Controller (TM4-N2RB), with the data transmitted to DAQ Master software through the Serial Communication Converter Module (SCM-US48I).

Furthermore, to monitor the cabin pressure, each car is installed with a pressure sensor (PSAN D1CA-RC1/8) connected to the SCM-US48I via a temperature control module (TK-4S). Finally, a humidity sensor (THD-R-C) is installed inside and outside each car to measure cabin and ambient humidity. Three THD-R-Cs are also connected to the SCM-US48I via the K–4S, with the experimental set-up shown in Fig. 2. The test carried out with and without the addition of external air, through the HVAC knob setting on the car dashboard.

In this study, 5 tests were carried out from 8 a.m. to 4 p.m. GMT+7 (480 min) with the configuration as shown in Table 1. The temperature, pressure, and humidity data were recorded every minute by DAQ-Master.

2.2. System performance calculation

System performance is calculated in two parameters to determine the temperature reduction effectiveness and estimate the total cooling effect by adding a car cabin cooler. Firstly, there is air circulation in the cabin, to calculate the temperature reduction effectiveness, with the data from three thermocouples installed in each car to determine the averaged T_A and T_B, which represent the temperature of car A (with cabin cooler) and B (without car cabin cooler), respectively. The temperature reduction effectiveness with a car cabin cooler is calculated by Equation (1). Where, $\in$ is the effectiveness of the car cabin cooler T_A, T_B, and T_{en} are the average cabin temperature of car A, car B, and ambient temperature in Celsius, respectively.

Fig. 1. The test vehicle placement: (a) with a car cabin cooler and (b) without a car cabin cooler.

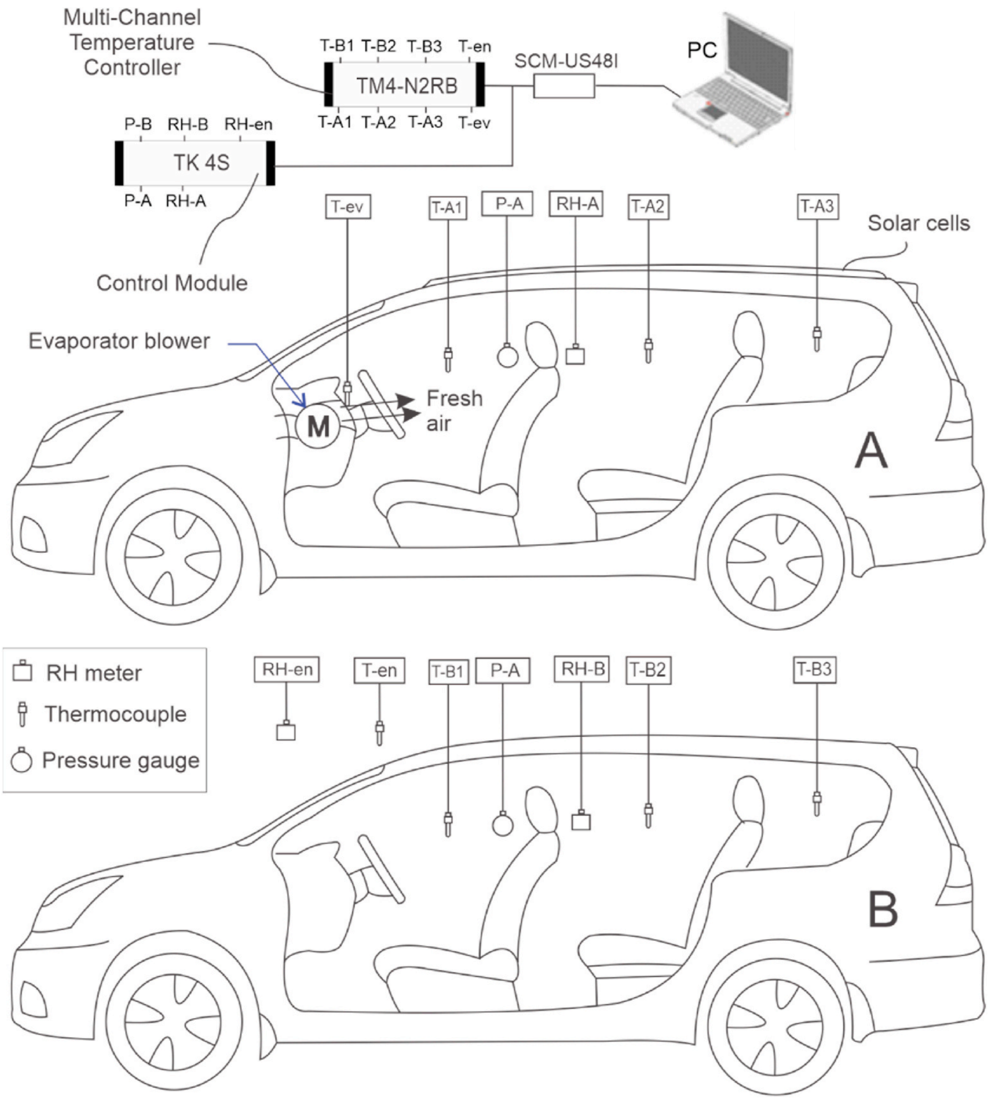

Fig. 2. Experiment setup: (A) with a car cabin cooler and (B) without a car cabin cooler.

$$\in = \frac{(T_B - T_A)}{(T_B - T_{en})} \; x \; 100\% \tag{1}$$

Secondly, the total cooling effect, Q_c (kJ) by each test configuration is calculated from the heat load on the car installed by the cabin cooler, Q_B (kJ) minus those on the car without the cabin cooler, Q_A (kJ), by the formulation presented in Equation (2). While Q_A and Q_B are the total of sensible heat and latent heat.

$$Q_c = (Q_B - Q_A) \tag{2}$$

The ideal gas equation is used to obtain the air mass in the cabin changes, which is calculated by Equation (3). Where m is the air mass in the cabin, P is the pressure (Pa), V is the cabin volume (m^3), M is molecular weight (kg/kmol, air is 28.97 kg/kmol), R is the air constant (8.314 kJ/kmol°C), and T is the temperature (°C).

$$m = \frac{PVM}{RT} \tag{3}$$

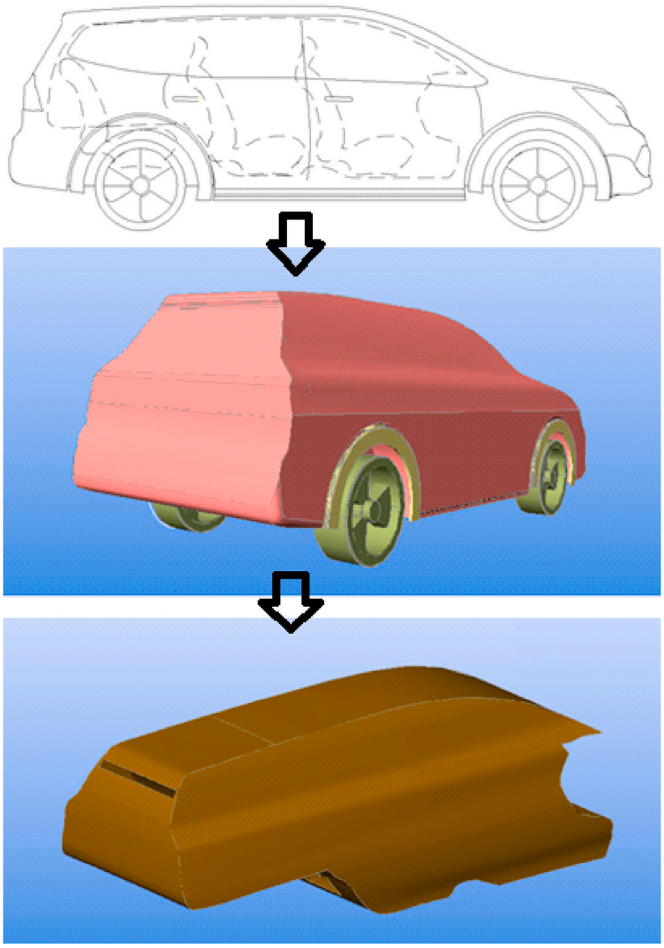

Fig. 3. In-cabin air volume sketch.

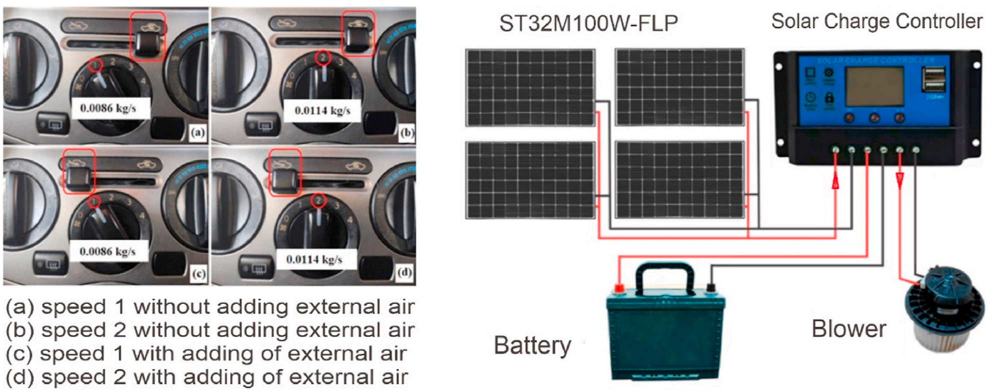

Fig. 4. HVAC knop (left) and the main components of the car cabin cooler (right).

3. Results and discussion

3.1. Test results for cabin temperature and humidity before the car cabin cooler activation

The pressure was assumed to be 1 bar absolute during the test, thereby indicating insignificant change for cars A and B (between 0.00 and 0.001 bar gauge). Prior activating the cabin cooler in car A, temperature and humidity tests were carried out on both cars to

Table 1
Test configuration.

Test	Description
Test 1	A comparative test of temperature and humidity without treatment to ensure that both cars have the same thermal load when parked under direct sunlight.
Test 2	A comparative test of cabin temperature at blower speed level 1 without additional air from the environment.
Test 3	A comparative test of cabin temperature at blower speed level 2 without additional air from the environment.
Test 4	A comparative test of cabin temperature at blower speed level 1 with additional air from the environment.
Test 5	A comparative test of cabin temperature at blower speed level 2 with additional air from the environment.

ensure they have similar values when exposed to direct sunlight. The test was carried out from 08.00 to 16.00 GMT+7, which represents the daytime conditions in Indonesia. Furthermore, these test results indicated that both cars have almost the same cabin temperature and humidity profiles as shown in Fig. 5. In this test, only the middle cabin temperature is used, where T_{A2}, T_{B2}, and T_{en} are represented by a solid line curve with red, green, and blue, colors, respectively as shown in Fig. 5a. Meanwhile, the humidity in car A (RH_A), car B (RH_B), and ambient air humidity (RH_{en}) are shown by the black, red, and green dot line curves, as shown in Fig. 5b.

3.2. In-cabin temperature assessment

The car cabin cooler application without additional external air was tested twice, with the evaporator blower speed at levels 1 and 2, as shown in Fig. 6a and Fig. 6b. Each test configuration showed that the cabin temperature fluctuated based on the trend of ambient temperature. However, the difference is that ambient temperature changes sharper while the other is smoother. The test results confirm that the cabin temperature in car A is relatively uniform, characterized by the blower exit temperature trend, which is like the average cabin temperature, where the green curve always coincides with the red curve. At the end of the ambient temperature curve at level 2 blower speed, there is a drastic decrease in temperature, which gradually increased due to the presence of rainfall during the test. This test results differ from those of other previous studies [5,27], which created a trendline plot, while this study attached real-time data taken every minute. This study reports that the maximum temperature reduction achieved is 5.8 °C for both levels of blower speed without the addition of external air.

The test with the addition of external air showed better results. The test was carried out twice, with the evaporator blower speed at levels 1 and 2. The cabin temperature profile at blower speed levels 1 and 2 are shown in Fig. 6c and d. Similar to the test without a car cabin cooler, the temperature profile in the cabin follows the ambient temperature trend. The difference is the lower blower's exit air temperature than the cabin room's average temperature in car A because ambient air is added to the cabin. This study reports that the maximum temperature reduction that can be achieved is 9.8 °C for both levels of blower speed with the addition of external air. This result shows a better finding from previous one which only lowered the temperature to 4.2 °C [29].

Then, we use two logic role to calculate the effectiveness of using a car cabin cooler:

1. When the temperature in the cabin with the car cabin cooler (T_A) is equal to the ambient temperature (T_{en}), the effectiveness is 100%, and
2. When the cabin temperature with a car cabin cooler (T_A) is equal to the cabin temperature without a car cabin cooler (T_B), the effectiveness is 0%.

This study found that the temperature in cabin A cannot reach the ambient temperature as it is exposed to direct sunlight. This study shows that a car cabin cooler without external air addition produces average effectiveness of 30% and 20% for blower speed

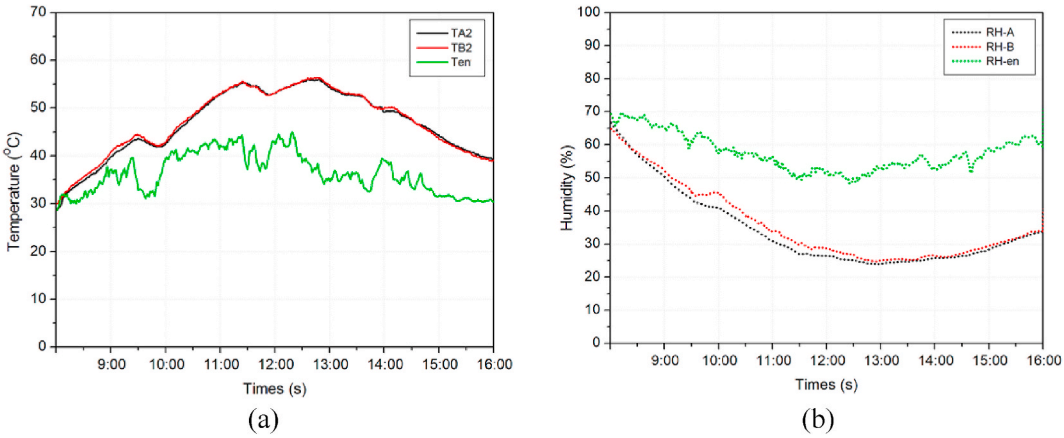

Fig. 5. In-cabin temperature (a) and humidity (b) profiles before treatment.

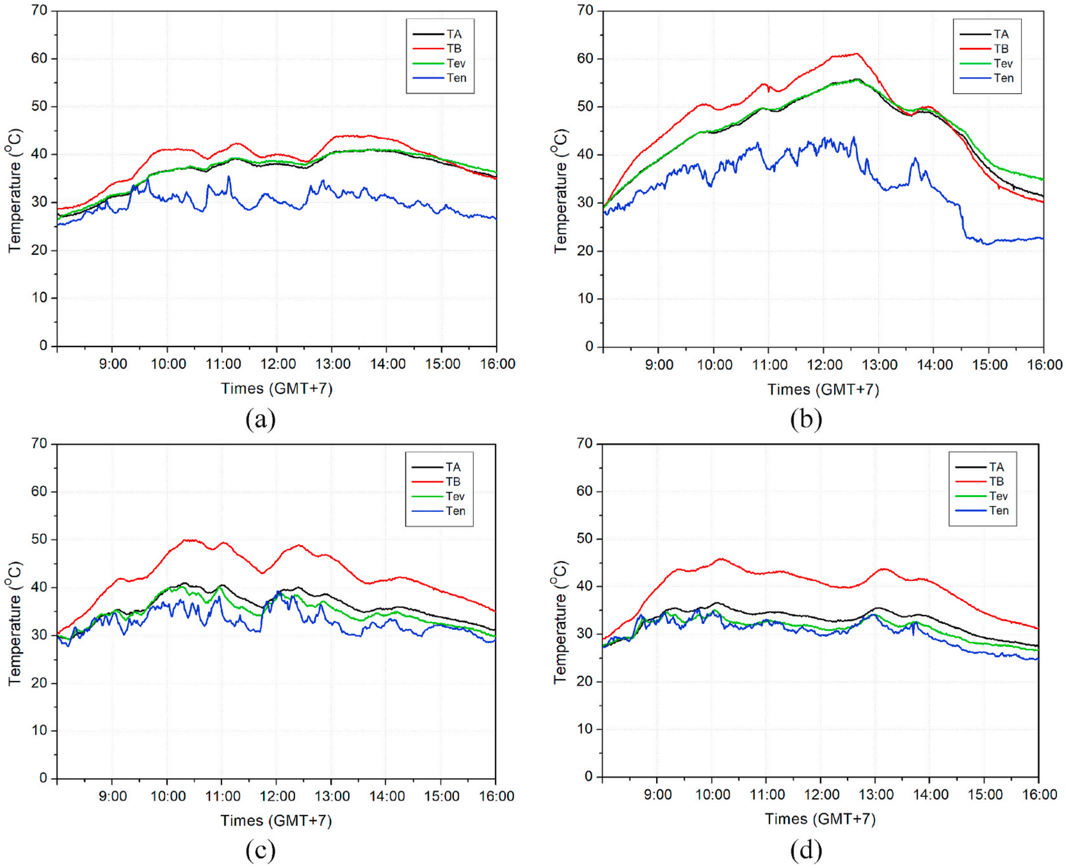

Fig. 6. In-cabin temperature profiles (T_A, T_B), exit blower temperature (T_{ev}), and ambient temperature (T_{en}): (a) without car cabin cooler at blower speed level 1, (b) without car cabin cooler at blower speed level 2, (c) with car cabin cooler at blower speed level 1, and (d) with car cabin cooler at blower speed level 2.

levels 1 and 2, respectively. Better effectiveness was obtained by external air addition, average of 71% and 80% for levels 1 and 2 blower speeds, respectively.

3.3. Cooling effect (Q) assessment

Four tests with car cabin cooler intervention were carried out in this study, that the removal and additional of heat due to evaporation/condensation is taken into account, with the latent heat of vaporization of water is about 2,260 kJ/kg [38]. Fig. 7 shows the test results of four cabin conditions, with and without cabin cooler with two blower speed levels, respectively. Fig. 7a and b represent the use of car cooling without additional air from the environment. Then, Fig. 7c and d represent the use of car cooling with additional air from the environment through the ducting system of original AC system. In-cabin warming increases in the morning when the sun is getting hotter, and this trend is reported by several researchers discussed in this article. However, we found different conditions between 1 p.m. and 4 p.m., with latent heat effects considered in this analysis, where, ambient temperature decreases gradually as the sunlight intensity decreases, and the environmental humidity increases. In-cabin temperature difference between car A and car B is getting narrower but the humidity difference is getting wider, as shown in Fig. 8.

An interesting finding of this study is the phenomenon of increasing latent heat evaporation in the cabin with the addition of air from the environment as shown in Fig. 7c and d. Towards the afternoon, the intensity of sunlight decreases and the humidity of the air environment increases. In a cabin equipped with a car cooler, the addition of air from the environment increases the humidity in the cabin, which means there is more moisture in the cabin. Heat transfer will continue until the temperature equilibrium is reached. The blower circulates air in-cabin, resulting in a lower pressure velocity which aids the evaporation process and results in a greater overall cooling effect. The cooling effect is greater in car A than in car B, although the temperature drop in car B is sharper than in car A, both at blower speed level 1 and level 2, as confirmed in Fig. 8.

3.4. Heat index (HI) assessment

Air temperature and humidity not only affect thermal comfort but also affect health [42–44]. Temperatures that are above the

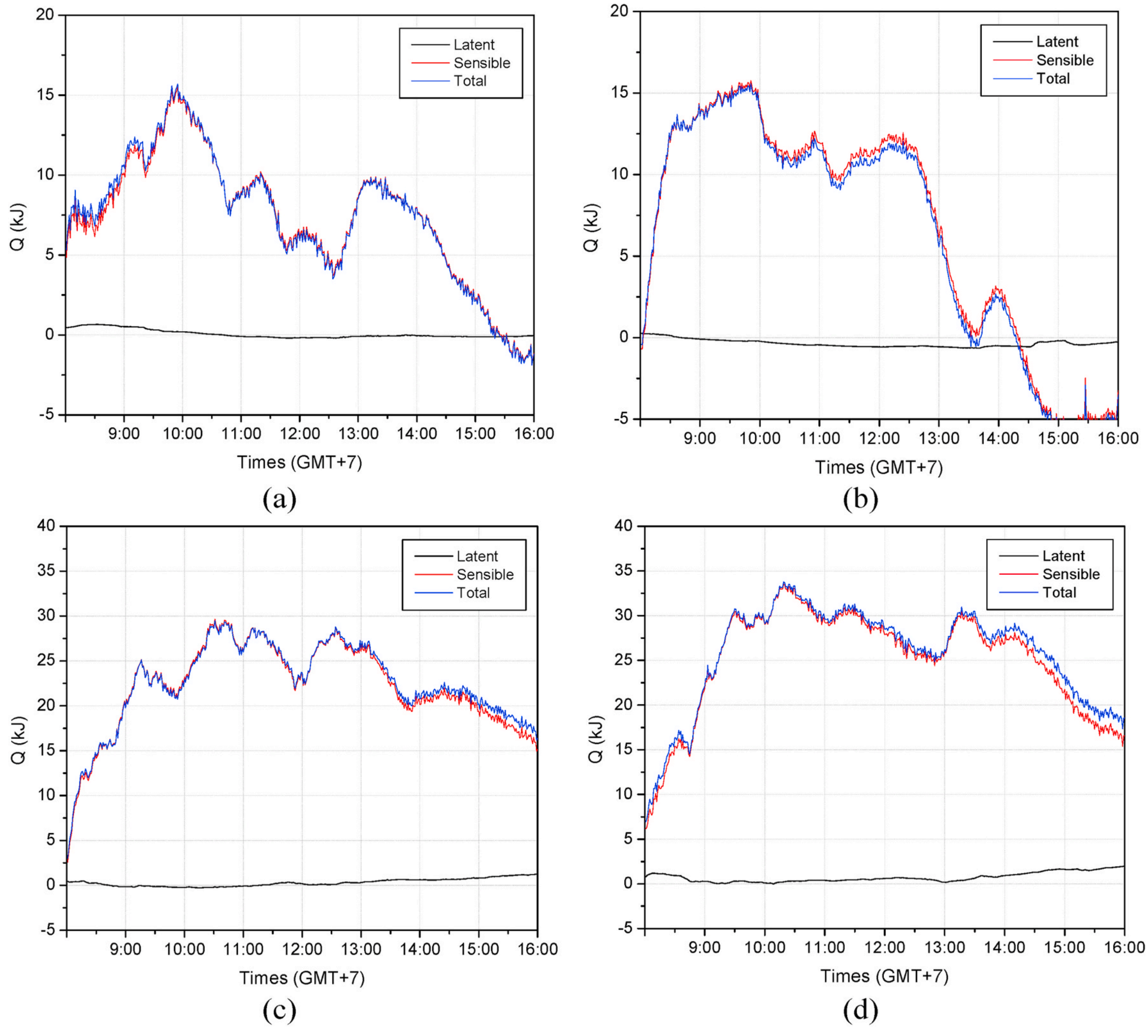

Fig. 7. Thermodynamics trend in-cabin: (a) without excess air of $\dot{m} = 0.0086$ kg/s circulated; (b) without excess air of $\dot{m} = 0.0114$ kg/s; (c) with excess air of $\dot{m} = 0.0086$ kg/s; and (d) with excess air of $\dot{m} = 0.0114$ kg/s.

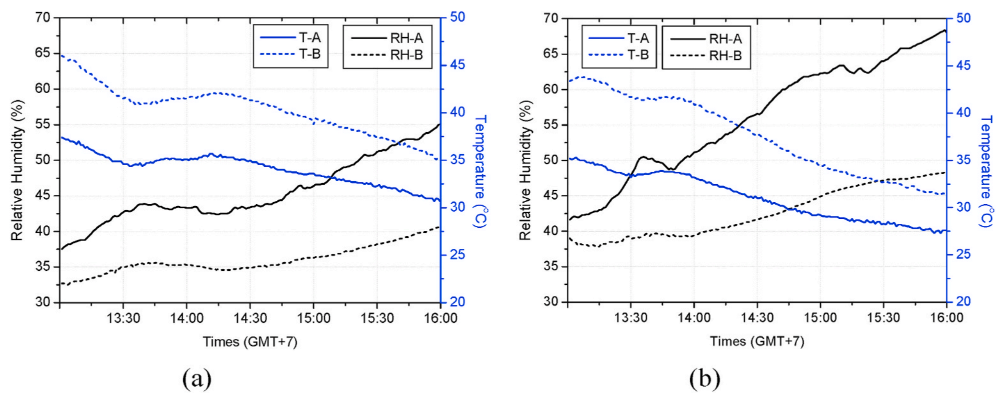

Fig. 8. Temperature and humidity trend in-cabin at 13:00 to 16:00 GMT+7: (a) with excess air of $\dot{m} = 0.0086$ kg/s; and (b) with excess air of $\dot{m} = 0.0114$ kg/s.

thermal comfort standard may not feel hot if the relative humidity is low, on the contrary, temperatures that are at the thermal comfort standard may feel uncomfortable if the humidity is high [45,46]. Therefore, this research also discusses adding a cabin cooler to the heat index/apparent temperature, a standard measure for assessing temperature related health risks. There are many formulas for calculating HI, as reported by Anderson [47], but in this study we use the generalized HI formula which is also used by Stapleton [48] as presented in Equation (4).

$$HI = c_1 + c_2T + c_3R + c_4TR + c_5T^2 + c_6R^2 + c_7T^2R + c_8TR^2 + c_9T^2R^2 \tag{4}$$

In this formula, HI = heat index in degrees Fahrenheit, T = Temperature in °F, and R = Relative humidity (%). Then, the constants $c_1$to c_9 are given as follows:

$$\begin{aligned}
c_1 &= -42.379 \\
c_2 &= -2.04901523 \\
c_3 &= -10.14333127 \\
c_4 &= -0.22475541 \\
c_5 &= -6.83783 \times 10^{-3} \\
c_6 &= -5.481717 \times 10^{-2} \\
c_7 &= -1.22874 \times 10^{-3} \\
c_8 &= 8.5282 \times 10^{-4} \\
c_9 &= -1.99 \times 10^{-6}
\end{aligned}$$

Temperature and humidity data from 8 a.m. to 4 p.m. are recorded, then, the results are compared with a heat index chart to assess their effectiveness. As a standard, possible heat disorders were obtained from NWS-US, as presented in Fig. 9a, which was also used by several researchers in ASEAN countries [48,49]. The results of the heat index measurements are presented in Fig. 9b. In general, the condition in car A (with a car cooler) is in the caution and extreme caution category and the condition in car B (without a car cooler) is in the danger and extreme danger categories. This indicates that the use of a car cooler is quite effective in reducing health risks in vehicles parked in hot weather.

Finally, Fig. 10 shows the average power generated by the solar cell during the test, compared to the blower power. This is used to confirm that the installed solar cell power can supply voltage to the blower without draining the vehicle's battery capacity. On the average, the solar cell series can produce 89 Watt of power at a maximum value of 162 Watt. Furthermore, with a blower power between 59 and 63 Watts, the solar cell's output power could activate the blower without draining the battery capacity. However, when the sunlight decreases, the solar cell circuit's power reduces below the power needed by the blower. Therefore, when this condition occurs, the cut-off mechanism works to deactivate the blower. Previous studies showed that when the cooling system takes energy from the battery [9], the average solar cell's output power exceeds the power required by the blower. Therefore, the data is also used to charge the battery to activate other electronic components suitable for car parking conditions.

4. Conclusion

This research found a practical solution to mitigate the cabin temperature of vehicles parked under direct sunlight. The research showed that the utilization of solar cell series, solar charge controllers, and existing blowers for air conditioning reduces the cabin temperature by 9.8 °C at an effective percentage of 80%. Several tests were carried out to determine the new insights provided by the unconditioned environment in-car cabin's cooling performance parked in sunny, cloudy, and even rainy conditions. We found that from noon to afternoon (1 p.m.–4 p.m.), there was an increasing in latent cooling effect due to an increasing in air humidity from a

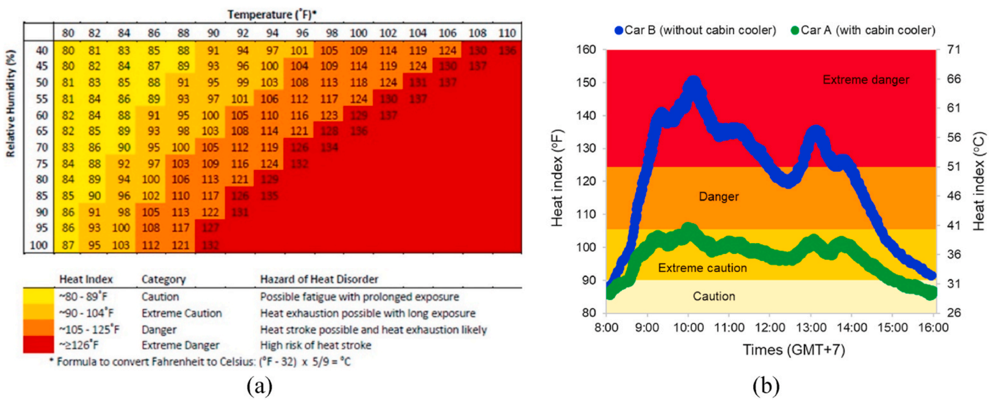

Fig. 9. (a) NWS heat index and (b) Heat index plot of in-cabin temperature car A (green marked) and car B (blue marked). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

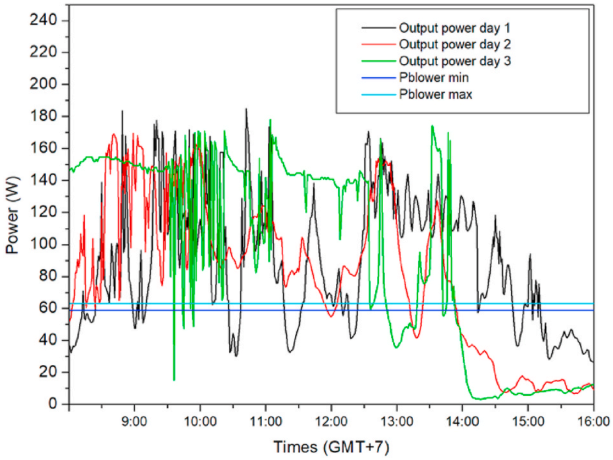

Fig. 10. Solar cell output power plot against the blower power.

decreasing in ambient temperature. From the heat index (HI) evaluation, the car cabin cooler can reduce health risks from danger and extreme danger to caution and extreme caution categories, based on NWS standards. On a wider scale and for commercial purposes, solar cells can be shaped in accordance with a car's roof (built-in) or other vehicle components that allow direct sun exposure such as the dashboard and hood.

Although this car cabin cooler prototype is generally able to reduce health risks from the danger and extreme danger categories to the caution and extreme caution category, this work has not been able to achieve the target in the caution category in all daily weather ranges during the research. Therefore, for future work, its effectiveness can still be improved, for example by combining air circulation from an electric blower with a mini cooler equipped with a water reservoir to increase the absorption of heat for evaporation, so that the temperature can be lowered.

Author contribution statement

Heat release and heat index (HI) assessment on car cabin cooler powered by solar panel on parked car. I declare.

- that we made a significant contribution to the above manuscript regarding the preparation and execution of research and development the manuscript;
- that we took responsibility for data analysis, interpretation, and discussion of results; and
- that we read and approved the final manuscript.

Muji setiyo. Conceptualization; Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Writing - Original Draft; and Writing - Review & Editing. Budi Waluyo. Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; and Writing - Original Draft. Noto Widodo. Performed the experiments; Supervision; and Project administration. Muhammad Latifur Rochman. Designed the experiments; and Data collecting. Suroto Munahar. Conceived and designed the experiments; and Sketching and calculating in-cabin volume, visualization, Siska Desy Fatmaryanti. Data validation; Writing - Original Draft; and Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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