

Research Paper

Innovative Pickup Car Cooling System Based on Thermoelectric Coupled with Heat Pipe Sink

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Abstract

Pickup cars are one of the most important means of transportation in the distribution of goods and logistics. However, many customers choose pickup cars without air conditioning because they are less expensive and more energy-efficient, resulting in lower operating costs. Car air conditioning systems generally utilize vapor compression systems, which consume a significant amount of energy. Additionally, some studies on thermoelectric cooling face challenges due to incompatible and difficult-to-install designs within vehicle cabins. To address this issue, this research was conducted on developing an innovative compact air conditioning (AC) system for the cabin of a pickup car. This system utilizes thermoelectric cooling (TEC) combined with a heat pipe sink. This cooling system features a practical and installation-friendly design compared to previous work, which can be integrated into existing pickup models without significant modifications. It is designed as a cooling box that generates and circulates cold air within the cabin. In this testing, the cooling box comprises six-unit thermoelectric cooling, where each unit varies using one-stage TEC modules and two-stage TEC modules. A 175-watt and 200-watt heat was applied and varied in the cabin to simulate the cooling load, and the air outlet duct's velocity also varied at 2 m/s and 3 m/s. The results showed that the thermoelectric cooling systems can significantly reduce cabin temperature increases, lowering the rise by 11.0 °C for a single-stage TEC system and by 10.8 °C for a double-stage TEC system compared to the cabin without a cooling system. The highest COP value of 1.4 was obtained in the single-stage TEC cooling system at a velocity of 3 m/s. The results show the potential of an innovative thermoelectric cooling (TEC) system when combined with heat pipes, offering an alternative cooling solution for the cabin of a pickup car. This proposed cooling system can be adapted for vehicles that require compact and energy-efficient cooling solutions.

Keywords: Thermoelectric cooling (TEC); Heat pipe sink; Cabin pickup cars; Cooling system; Coefficient of Performance (COP)

1. Introduction

Pickup cars are one of the most important means of transportation in the distribution of goods and logistics. In operation, pickup cars often carry heavy loads and cover long distances,

which causes the driver's cabin to be hot, especially in tropical countries like Indonesia. Therefore, an air conditioning system (AC) becomes crucial to keep the driver and passengers comfortable during the trip. However, many



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pickups are not equipped with an air conditioning system. Manufacturers provide pickup car without air conditioning as an option for customers who do not need air conditioning. In Indonesia, some customers choose to pickup cars without AC because it's cheaper compared to picking up a car with AC, and also to reduce energy consumption and operating costs [1], [2]. However, driving a vehicle without air conditioning causes discomfort for the driver and passengers during the trip [3]. Efficient air conditioning systems are needed to help reduce fuel consumption and emission impacts in conventional and electric cars [4], [5], [6]. In vehicles, the most commonly used air conditioning system is the vapor compression refrigeration system type [7], [8], [9]. While this system offers stable performance, it consumes a significant amount of energy [10], [11], [12], [13]. Therefore, an alternative air conditioning system with low energy consumption and environmentally friendly is necessary.

Thermoelectric cooling, which operates with a direct current (DC) source and does not use harmful refrigerants, can serve as an alternative cooling system in a pickup car [14], [15]. Thermoelectric coolers (TECs) offer several advantages, including a solid-state nature, without moving parts, minimal maintenance requirements, and the ability to provide localized cooling [16], [17], [18]. Heat is transferred from one side to the other side of the thermoelectric cooler (TEC) module to produce cold air, based on the Peltier effect [19], [20]. Numerous studies have been conducted on utilizing thermoelectric cooling in automobile and building air conditioning systems. Kim *et al.* [21] developed a thermoelectric cooler for the rear seat's ceiling space by circulating cold air from the TEC directly to the head, thereby improving passenger comfort. The car space in this study is represented by an insulation chamber cooled by a TEC. Su *et al.* [22] and Wan *et al.* [23] conducted a study on using localized air conditioning systems with thermoelectric cooling in commercial vehicles. The results show that localized cooling around the driver reduces overall energy consumption while maintaining thermal comfort. Sukarno *et al.* [24] conducted a preliminary study to test the performance of a thermoelectric cooling-based air conditioning system on a prototype pickup car.

The cooling system varies using 2 and 4 TEC modules, whereas on the hot side, the module also varies using conventional heatsinks and heat pipe sinks. The highest COP value is 1.16 in the condition of 4 TEC and using a heat pipe sink. Sukarno *et al.* [11] also used a thermoelectric (TEC) as an air conditioner for parked car cabins. Tests were carried out on passenger cars parked in open areas. By using four thermoelectric coolers equipped with heatsinks, the cooling system can reduce the cabin temperature by 6.1 °C compared to not using a cooling system.

Thermoelectric cooling systems have been widely used in automobiles; however, the designs developed are not fixed, making installation in the vehicle's interior quite complex. Kim *et al.* [21] placed the TEC cooling system on the top or roof of the back row of the car, where the heat dissipation has not been designed separately. Sukarno *et al.* [24] used a TEC cooling system on the back of the passenger and driver seats in the car cabin. This requires modifications such as drilling holes to install the cold and hot sides of the TEC. Sukarno *et al.* [11] also placed the TEC cooling system onto the dashboard so that the heat dissipation side of the TEC requires a slightly open window as an exhaust channel. CFD simulation of local cooling systems for drivers and passengers by Su *et al.* [22] and Wan *et al.* [23] placed TEC units in several locations close to the driver and passenger. The simulation results show that local cooling using this TEC system effectively provides passenger comfort. However, these studies have not considered the heat dissipation design from the hot side of the thermoelectric cooler (TEC). As a result, there is a risk that exhaust heat could recirculate within the cabin. Moreover, creating additional holes in the car cabin, if necessary, can be quite challenging.

Despite its many advantages, TECs have limitations in temperature control range and low thermoelectric conversion efficiency. TEC cooling occurs by transferring heat from both ends, thereby causing heat accumulation on the hot side of the TEC [11], which can impact the service life and decrease the TEC's cooling capacity. To enhance the cooling efficiency of thermoelectric cooling modules (TEC), it is recommended to lower the hot side temperature [25], [26]. Typically, the hot side is equipped with a conventional heat sink [26]. Therefore, to further

improve cooling efficiency, an alternative heat exchanger with lower thermal resistance is needed.

Hu *et al.* [27] used a water-cooled heatsink for thermoelectric cooling in computer applications. Lin *et al.* [25] used a microchannel heat sink in thermoelectric cooling to enhance the thermal management of high-power LED lamps. Pakrouh *et al.* [28] used PCM as a medium to control the temperature on the hot side of the TEC in the liquid cooling system of the battery system. Using water-cooled, microchannel heat sinks and PCMs improves the heat dissipation capability of the TEC hot side, but they are more complex and complicated to install. On the other hand, this approach is effective in achieving low temperatures, but it often neglects the portability of the cooling device [29]. To enhance the efficiency of thermoelectric modules as cooling systems, alternatives to different cooling methods on the hot side are required [30]. Another technology widely used to control temperature, energy conservation, and heat recovery in many applications is heat pipes [31], [32], [33]. Heat pipes have a high thermal conductivity and have advantages, including passive cooling, no moving parts, and minimal maintenance needed [32]. Using heat pipes has also proven to result in better heat dissipation than conventional heat sinks and higher cooling capacity in TEC cooling systems [24].

The above studies show that thermoelectric cooling can reduce the air temperature in the car cabin. The simulation results also show that local cooling using the TEC system effectively provides passenger comfort. However, the existing design is still not fixed, where the TEC cooling unit is placed on the car cabin's dashboard, rear side, and roof. Research related to the utilization of TEC in the car cabin has also not considered the heat dissipation design from the hot side of the TEC, which could pose a risk of exhaust heat recirculation. Making interior holes in the roof or sides of the car cabin is difficult in car applications. In addition, installing conventional heatsinks, water-cooled, or PCM coolers on the hot side of the TEC is also quite complex. Therefore, this research proposed an innovative compact air conditioning system for pickup cabins based on thermoelectric cooling coupled with a heat pipe sink. This cooling system can be integrated into existing pickup models without

significant modifications. It offers one of the most practical and installation-friendly cooling system designs compared to previous works. The cooling system is designed like a conventional air conditioning system found in cars. It is placed in front of the car's hood and distributes cold air from the cooling unit into the car's cabin. On the hot side, the thermoelectric cooler (TEC) features a heat pipe heat sink that enhances heat dissipation and optimizes cooling capacity. Developing a thermoelectric cooling system equipped with heat pipe sinks in pickup trucks is essential for enhancing energy efficiency, reducing the operational costs associated with energy-intensive air conditioning systems, and improving passenger comfort.

2. Methodology

2.1. An Overview of the Cabin Car System

In a general car, the air conditioning system uses a compressor as one of the main components, driven by electricity, and requires large amounts of energy [34]. Fresh air or return air from inside the cabin is cooled by passing it through the evaporator coil and then flowing it into the car cabin [7]. This study seeks to develop an alternative cooling system for pickup vehicles using a thermoelectric cooling (TEC) system. In pickup vehicles without AC, manufacturers typically provide designated spaces for AC ducts and units to facilitate future installation. Accordingly, this research introduces a compact thermoelectric cooling box system that produces cold air and can be positioned within the available space in the vehicle. In this cooling system, return air from the cabin passes through the TEC cooling unit for re-cooling. The cold air is then redirected back into the cabin through the system's channels and grilles.

This research is a preliminary study to determine the performance of thermoelectric cooling systems, which was conducted on a laboratory scale. The test was conducted indoors, and an electric heater was operated to simulate a cooling load in the car cabin. The cooling load is calculated based on the car cabin's condition, including the heat generated by the cabin space when it is outside, the heat engine exposed to the sun, and the presence of two people. The cooling calculation obtained 196.3 watts on the scale of the test equipment. However, because the sun's heat

can vary based on the weather, the cooling load ranges between 175 watts and 200 watts during testing.

The car cabin prototype was designed to resemble the shape of an actual pickup car ([Figure 1](#)), but with a smaller size compared to the actual pickup car, measuring 1.0 m x 1.2 m x 0.60 m (length x width x height). It is made of galvanized plate material, with a layer of glass wool added as an insulator and partly transparent glass. The test was conducted indoors, and an electric heater was used to provide a cooling load in the car cabin.

Thermoelectric cooling systems are installed in the engine room, similar to a conventional air

conditioning system. This cooling system comprises an air inlet duct, a thermoelectric cooling channel, and an air outlet duct. The air inlet and outlet ducts are made through a 3D printing process using PLA material, while the thermoelectric cooling channel is made of acrylic material. The working principle of this thermoelectric cooling system is that air from inside the cabin first flows into the cooling duct and is cooled using a thermoelectric cooling system. Then, cold air exits through the air outlet duct and flows into the cabin of the pickup car. This system works repeatedly during the cooling process as shown in [Figure 2](#).

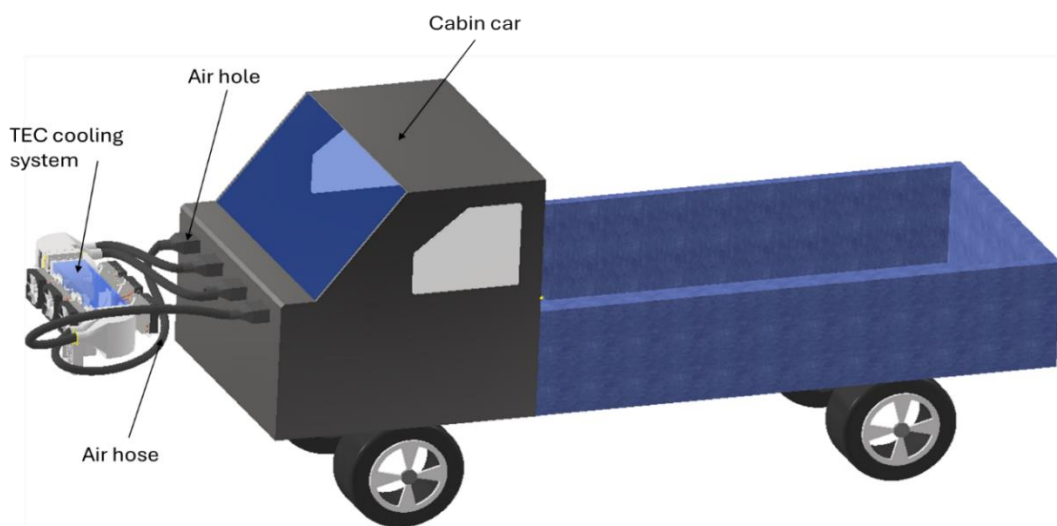


Figure 1. Pickup car and thermoelectric cooling system

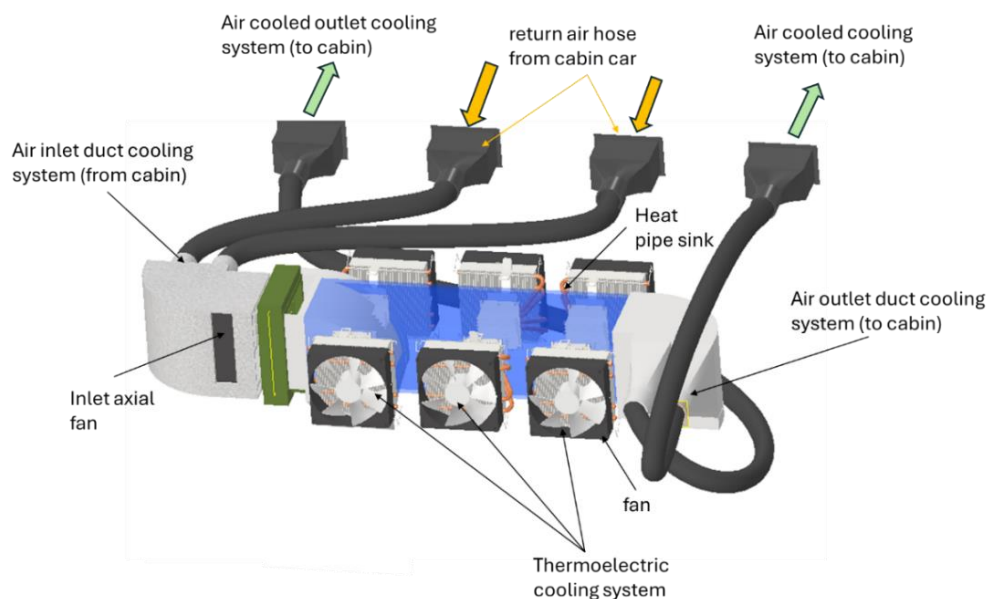


Figure 2. Cooling system components

Thermoelectric cooling systems are installed in the engine room, similar to a conventional air conditioning system. This cooling system comprises an air inlet duct, a thermoelectric cooling channel, and an air outlet duct. The air inlet and outlet ducts are made through a 3D printing process using PLA material, while the thermoelectric cooling channel is made of acrylic material. The working principle of this thermoelectric cooling system is that air from inside the cabin first flows into the cooling duct and is cooled using a thermoelectric cooling system. Then, cold air exits through the air outlet duct and flows into the cabin of the pickup car. This system works repeatedly during the cooling process.

The cooling system was tested by varying the thermoelectric cooling system configuration, air velocity, and cooling load. First, the testing is conducted to measure the car cabin temperature

and relative humidity without the use of a cooling system. Six thermoelectric cooling units are placed in the thermoelectric cooling channel, each consisting of a cold heat sink, a TEC module (TEC1-12706), heat pipe sinks on the hot side, and an axial fan. In this test, each unit utilizes either a single-stage TEC module or a two-stage TEC module arranged in parallel. Therefore, the TEC cooling system consists of 6 TEC modules when using a single-stage TEC configuration and 12 TEC modules when using a two-stage TEC configuration, as shown in **Figure 3**. To simulate the cooling load in the car cabin, this study varied by 175 watts and 200 watts using an electric heater, which was adjusted by the Voltage Regulator. The test schematic of this study is shown in **Figure 4**.

The cabin air temperature and ambient temperature were measured using Type-K thermocouples connected to a thermometer logger, which was connected to a laptop.

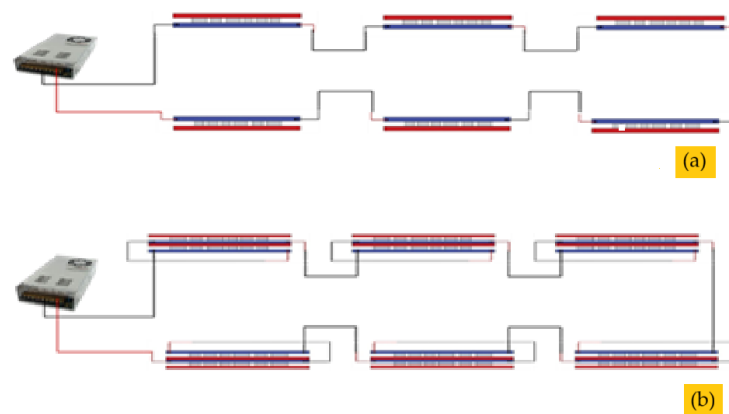


Figure 3. Thermoelectric arrangement: (a) Single-stage TEC module; (b) Two-stage TEC modules which are arranged in parallel thermal and a series of electrical arrangements [7]

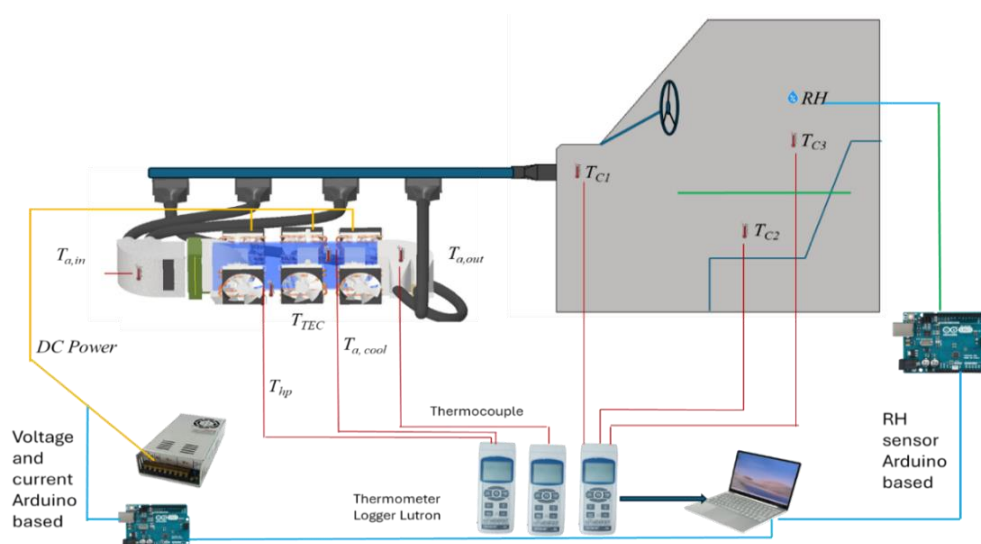


Figure 4. Experimental setup

Lutron TM-947SD. The Lutron AM-4204 sensor with an accuracy of ± 0.1 m/s, was used to measure air outlet velocities from the cooling channel. The calibrated Arduino humidity sensor is used to record changes in relative humidity (RH) within the cabin space. The calibrated Arduino Current and voltage sensors are used to measure the power the cooling system uses during the testing.

2.2. The Performance of Thermoelectric Cooling

The performance of the thermoelectric cooling system with variations in the arrangement of TEC modules, changes in velocities, and differences in cooling load can be determined using the Coefficient of Performance (COP), as in Eq. (1) and Eq. (2) [24], [35], [36], [37]. The coefficient of performance (COP) on thermoelectrics is the cooling capacity divided by the electrical input power used to operate the TEC module and fan.

$$COP_{TEC} = \frac{\text{Cooling Capacity}}{\text{Electrical input power}} \quad (1)$$

$$COP_{TEC} = \frac{\dot{q}_c}{P_{tot}} \quad (2)$$

The thermoelectric cooling capacity ($\dot{Q}_c$) and total energy consumption (P_m) can be determined by Eq. (3) and Eq. (4), respectively.

$$\dot{q}_c = \dot{m}_a c_{pa} (T_{a,in} - T_{a,out}) \quad (3)$$

$$P_m = I_m V_m \quad (4)$$

where $\dot{m}_a$ is the air mass flow rate in the cooling channel, c_{pa} is the air-specific heat, $T_{a,in}$ is the air temperature entering and $T_{a,out}$ is the air temperature leaving the cooling system, I_m expresses the electric current, and the voltage used to operate the cooling system is represented by V_m .

3. Results and Discussion

3.1. Profile Temperature and Relative Humidity

Testing was initially conducted on the pickup car cabin without a cooling system and continued with the thermoelectric cooling system. Data collection is carried out for 1 hour for each variation. The air velocity varied by 2 m/s and 3 m/s, and two variations of cooling load, 175 watts and 200 watts.

3.1.1. Without cooling system

Figure 5 shows the air temperature and relative humidity profiles in the car cabin without a cooling system, with a 175-watt cooling load, and an air velocity of 2 m/s. At the beginning of the measurement, the air temperature in the cabin was 31.0 °C and the relative humidity was 67.2%. As the cooling load of 175 W was applied, the air temperature increased, and the relative humidity decreased rapidly from 0 to 1000 s. After 1000 s, the increase in air temperature slowed and began to stabilize at 2500 s. The same thing happened to the relative humidity; after 1000 s, the decrease was slower. Figure 5 illustrates that as air temperature increases, humidity decreases. In thermoelectric cooling, there is no change in moisture content, where the change in air humidity results from an increase in temperature, which causes an increase in the vapor saturation pressure. Under the condition that the partial pressure of water vapor remains constant, while the vapor saturation pressure increases, the relative humidity becomes lower [38]. In the car cabin without a cooling system, with a 175-watt cooling load and an air velocity of 2 m/s, the air temperature increased from 30.5 °C to 50.6 °C, and the relative humidity decreased from 67.2% to 33.5%. A car cabin without a cooling system, and when the windshield is closed, the air temperature rises by 20.1 °C, and the humidity drops by 43.7 %.

Figure 6 shows a comparison of the air temperature profile inside the cabin without a cooling system at cooling loads of 175 W and 200 W, and at air velocities out of the cooling box of 2 m/s and 3 m/s. As the cabin's cooling load

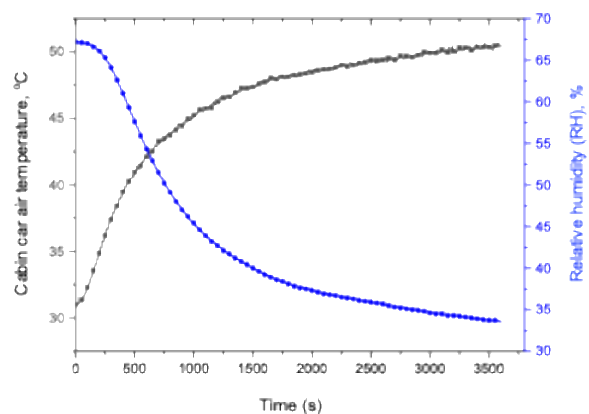


Figure 5. Cabin car air temperature and humidity profiles without a cooling system at 175 watts, 2 m/s

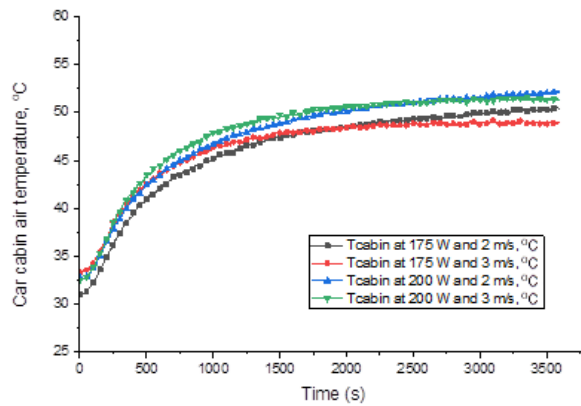


Figure 6. Air temperature in the cabin car without a cooling system

increases, its temperature rises. The cabin with a cooling load of 200 W has a higher cabin temperature than the one with a cooling load of 175 W. With the same cooling load, the air temperature in the cabin becomes lower as the velocity increases. This indicates that as the velocity increases, the heat transfer from the heat source to the air passing through becomes maximized, resulting in a lower indoor air temperature. In the cabin without a cooling system, after 1 hour of testing, the highest temperature was 52.3 °C, in the condition of 200 W heat load and 2 m/s velocity, and the lowest temperature was 49.1 °C in the condition of 175 W heat load and 3 m/s velocity. The average temperature in the measurement condition of 175 W and 200 W cooling loads, with velocities of 2 m/s and 3 m/s, without a cooling system, at the highest temperature is 50.9 °C.

A comparison of the relative humidity (RH) profile of the air at cooling loads of 175 W and 200 W, and at air velocities out of the cooling system of 2 m/s and 3 m/s in the cabin without a cooling system is shown in **Figure 7**. As the cabin's cooling load increases, its temperature rises, and the relative humidity decreases. With the same cooling load, as the velocity increases, the relative humidity of the air inside the cabin becomes higher. This shows that the change in air humidity is inversely proportional to the change in air temperature in the cabin; as the air temperature increases, the air humidity decreases. This is due to the rise in temperature in a closed space without an increase in water vapor in the air, resulting in a decrease in the relative humidity level in the cabin space as the temperature rises. In the cabin without a cooling system, after 1 hour

of testing, the lowest relative humidity was 26.9%, with a cooling load of 200 W and a velocity of 2 m/s.

3.1.2. Single-stage TEC cooling system

Figure 8 shows the air temperature profile inside the cabin utilizing the single-stage TEC cooling system. From 0 to 1500 seconds, the cabin temperature continues to rise, and after 1500 seconds, the air temperature begins to approach a steady state. The air temperature in the cabin with cooling loads of 175 W and 200 W is not significantly different. In the cabin using the Single-stage TEC cooling system, after 1 hour of testing, the highest air temperatures in the 175 W cooling load conditions with velocities of 2 m/s and 3 m/s are 40.6 °C and 40.8 °C, respectively. The highest air temperature in the cabin using the single-stage TEC cooling system, under conditions of a 200 W cooling load with velocities of 2 m/s and 3 m/s, is 41.2 °C and 40.9 °C, respectively. The air temperature measurement

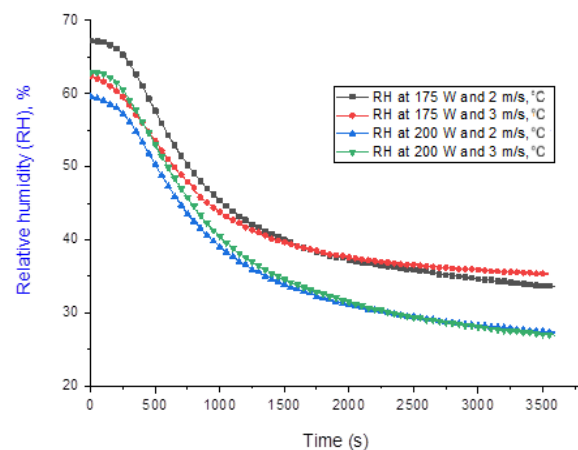


Figure 7. Relative humidity in the cabin car without a cooling system

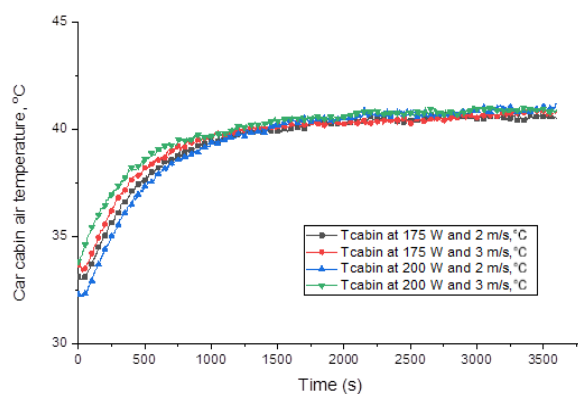


Figure 8. Air temperature in the cabin car with a single-stage TEC cooling system

results show that the 200 W cooling load produces a higher cabin air temperature than the 175 W heat load. However, changes in air velocity of 2 m/s and 3 m/s do not show significant differences and are nearly identical. On average, the highest air temperature in the cabin after using the Single-stage TEC cooling system is 40.9 °C, in conditions of an average ambient temperature of 32.4 °C. This indicates that using the single-stage TEC cooling system can reduce the cabin temperature by 10.0 °C compared to using the cooling system without it.

The relative humidity (RH) profile of the air inside the cabin using the Single-stage TEC cooling system is shown in Figure 9. After the 1-hour test, the lowest relative humidity was observed in the 175 W heat load condition with velocities of 2 m/s and 3 m/s, at 46.0% and 45.9%, respectively. The lowest relative humidity in the 200 W heat load condition, with velocities of 2 m/s and 3 m/s, was 46.6% and 45.5%, respectively. On average, the highest relative humidity of air using a Single-stage TEC cooling system is 46.0%, indicating that the relative humidity remains within the limits of passenger comfort standards. This shows that using the single-stage TEC cooling system can keep the room humidity within the comfort limits of passengers. Using the Single-stage TEC cooling system can increase the relative humidity of the air by 15.2% compared to not using the cooling system by 30.8%.

3.1.3. Two-stage TEC Cooling System

In the Two-stage TEC cooling system, from 0 to 1500 seconds, the cabin temperature continues to rise rapidly. After 1500 seconds, the air temperature in the cabin starts to approach a steady state, as shown in Figure 10. The air temperature in the cabin with 175 W and 200 W cooling loads is not very different. In the cabin equipped with a two-stage TEC cooling system, testing conducted over one hour reveals the following air temperature results under varying cooling loads. The highest average air temperatures in the cabin with a 175 W cooling load were 39.1 °C at a velocity of 2 m/s and 38.4 °C at a velocity of 3 m/s. When the cooling load increased to 200 W, the air temperature inside the cabin also increased to 40.4 °C, at both 2 m/s and 3 m/s. The air temperature measurement results show that the 200 W cooling load produces a

higher cabin air temperature than the 175 W cooling load. However, changes in air velocity of 2 m/s and 3 m/s do not show significant differences and are nearly identical. On average, the highest air temperature in the cabin after using the two-stage TEC cooling system is 39.6 °C, in conditions of an average ambient temperature of 30.9 °C.

Using the Two-stage TEC cooling system, the lowest relative humidity is achieved in the 175 W heat load condition with velocities of 2 m/s and 3 m/s, at 48.8% and 48.6%, respectively. While the lowest relative humidity in the 200 W heat load condition, with velocities of 2 m/s and 3 m/s, is 45.7% and 45.8%, respectively, as shown in Figure 11. On average, the highest relative humidity of air using a single-stage TEC cooling system is 47.2%, indicating that the relative humidity remains within the limits of passenger comfort standards. This shows that the Two-stage TEC cooling system can also keep the room humidity within the passengers' comfort limit.

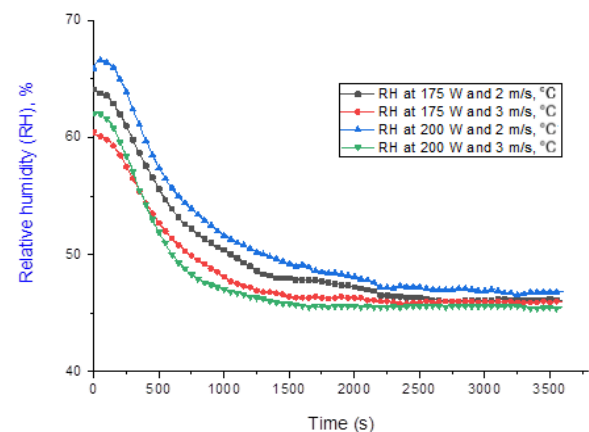


Figure 9. Relative humidity in the cabin car without a cooling system

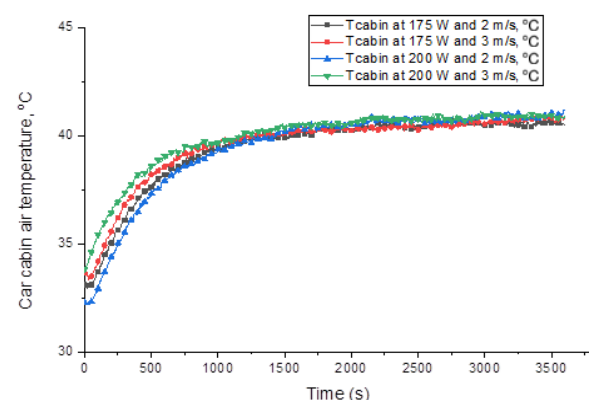


Figure 10. Air temperature in the cabin car with a two-stage TEC cooling system

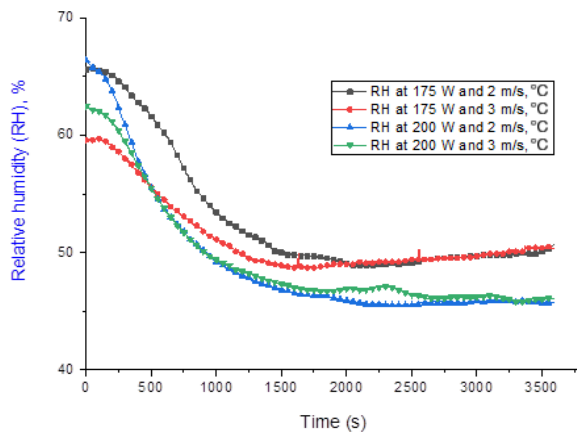


Figure 11. Relative humidity in the cabin car with a two-stage TEC cooling system

3.2. Cooling System Power Consumption and Coefficient of Performance

Table 1 shows the electrical power, cooling capacity, and COP of each pickup truck cabin cooling system configuration. The two-stage TEC cooling system, arranged in electrical series, consumes less energy than the one-stage TEC cooling system. This is because thermal load sharing occurs in the two-stage modules TEC, so each module only needs to transfer half of the amount of heat that one TEC must transfer [7]. While in single-module TECs, there is no thermal sharing, so the module must handle the entire thermal load alone, which requires more power to cool the load.

The electrical energy required increases as the cabin's cooling load and air velocity increase. The highest power consumption occurs in the Single-stage TEC configuration with a cooling load of 200 watts at 3 m/s, averaging 42.4 watts. The two-stage TEC configuration with a cooling load of 175 watts at 2 m/s uses the lowest average power consumption of 28.9 watts. The electrical energy required increases as cooling and air velocity increase on the cabin side.

The increase in cooling capacity is influenced by the velocity of air flowing into the cabin; the higher the speed, the greater the cooling capacity [39]. The use of a thermoelectric cooling system in the cabin of a pickup car shows a significant decrease in temperature. When testing the cabin air temperature without a cooling system at heat loads of 175 W and 200 W, and at velocities of 2 m/s and 3 m/s, the cabin temperature increased by 19.5 °C above the ambient temperature. Meanwhile, when using a single-stage TEC

cooling system, the increase was only 8.5 °C, indicating that the use of a cooling system can reduce the increase in cabin temperature by 11.0 °C. With a double-stage TEC cooling system, the temperature rose by 8.7 °C, indicating that this system can lower the cabin temperature increase by 10.8 °C compared to having no air conditioning. It suggests that a cooling system with a single-stage TEC configuration performs better than a two-stage TEC, as evidenced by a higher COP value and a lower cabin air temperature. The use of a single-stage TEC delivers greater electrical power than the two-stage TEC module configuration, resulting in a higher cooling capacity for the single-TEC module. This is in line with the research of Ahmed *et al.* [40] that the cooling capacity increases as the electrical power on the module increases. A comparison of the air temperature inside the cabin of a pickup car without a cooling system and with a cooling system is shown in **Table 2**.

The results show that the use of thermoelectric cooling can lower the air temperature inside the cabin compared to when air conditioning is not used. The cabin temperature has not yet reached the standard for room comfort; however, the use of an alternative thermoelectric-based cooling system has been proven to function effectively in reducing the room temperature. The temperature reduction reaches 10-11 °C, and the low power consumption of around 37 W is undoubtedly an advantage of using this thermoelectric system.

With its benefits of not using refrigerants that are hazardous to the environment and having zero carbon emissions [18], [41], [42], thermoelectric holds promise for future applications. **Table 2** also shows that, by using the cooling system, the relative humidity of the air inside the cabin ranges from 45.7% to 48.8%. This shows that utilizing a thermoelectric cooling system can also keep the room humidity within the passengers' comfort limit.

An economic analysis is often performed to determine the feasibility of a product or system developed [42], [43]. Overall, the designs of the single-stage TEC and two-stage TEC cooling systems are almost identical, with the only difference being the number of TEC modules used. The cost components of the developed thermoelectric cooling system include the cooling box components, which consist of 3D-printed

Table 1. Power consumption and COP comparison

Configuration	Power consumption (watts)	Cooling capacity	COP
Single-stage TEC with a cooling load	175 watts at 2 m/s	37	38.33
	200 watts at 2 m/s	38.2	40.16
	175 watts at 3 m/s	41.8	57.50
	200 watts at 3 m/s	42.4	60.23
Two-stage TEC with a cooling load	175 watts at 2 m/s	28.9	31.03
	200 watts at 2 m/s	34.4	31.03
	175 watts at 3 m/s	36.9	43.81
	200 watts at 3 m/s	37.6	46.54

Table 2. Comparison of air temperature and air RH inside the car cabin

Cooling System in the Cabin car		Ambient temperature (°C)	Cabin temperature (°C)	ΔT cabin air compared with ambient (°C)	RH (%)
Without cooling system with cooling load	175 watts at 2 m/s	30.5	50.6	20.1	33.5
	200 watts at 2 m/s	31.6	52.3	20.7	27.3
	175 watts at 3 m/s	31.9	49.1	17.2	35.4
	200 watts at 3 m/s	31.5	51.5	20.0	26.9
Single-stage TEC with cooling load	175 watts at 2 m/s	32.8	40.6	7.8	46.0
	200 watts at 2 m/s	32.0	41.2	9.2	46.6
	175 watts at 3 m/s	32.7	40.8	8.1	45.9
	200 watts at 3 m/s	31.9	40.9	9.0	45.5
Two-stage TEC with cooling load	175 watts at 2 m/s	31.5	39.1	7.6	48.8
	200 watts at 2 m/s	31.3	40.4	9.1	45.7
	175 watts at 3 m/s	30.8	38.4	7.6	48.6
	200 watts at 3 m/s	30.0	40.4	10.4	45.8

filaments and acrylic, as well as the costs of the fan, heat pipe sink, and TEC modules. The Single-stage TEC cooling system utilizes six modules, while the two-stage TEC cooling system employs a total of 12 modules. According to the cost calculations, the investment cost for the single-stage TEC cooling system is IDR 1,110,000, while the two-stage TEC cooling system is IDR 1,320,000. In terms of cooling system performance, at a speed of 3 m/s, the single-stage cooling system produces a COP of 1.4, while the two-stage TEC cooling system produces a COP of 1.2. From these two configurations, it is evident that despite the lower investment, the single-stage cooling system configuration produces a higher COP. Therefore, the single-stage cooling system configuration can be recommended for future applications of thermoelectric cooling systems.

In most pickup trucks, even if it isn't equipped with air conditioning, manufacturers typically provide a space or hole for installing an air conditioning unit. This cooling system features a compact design, making it easy to install in existing vehicle cabins. While it performs well, the

investment cost is relatively high compared to the average cooling capacity it offers, which is around 60 watts. Therefore, further development is urgently needed so that this cooling system can be applied to pickup car cabins. Integrating thermoelectric cooling systems with other cooling systems, such as evaporative or conventional cooling, could be an alternative for producing large cooling capacities while also conserving energy. However, studies of this cooling system are still limited to the laboratory scale, where car prototypes are built at 1/8 of the actual car volumes, and the heat load inside the cabin is replaced with heat from an electric heater within a calculated range. Therefore, further research is needed to determine the cooling system's performance under real-world and extreme environmental conditions, so that the results of this study can be applied on a larger scale in real-world environments.

3.3. Uncertainty Analysis

Calibration was performed on several measuring instruments used in this study. The

temperature error measured using a Type K thermocouple and a thermometer Logger associated with $(T_{a,in} - T_{a,out})$ was ± 0.1 °C. The calibrated electric current sensor has an error of ± 0.02 A, the electric voltage sensor has an error of ± 0.02 V, and the air velocity has an accuracy of ± 0.1 m/s. With the assumption that air density (ρ) and specific heat (C_p) are constant [7], [44], the maximum uncertainty of the cooling capacity ($S_{\dot{Q}_c}/\dot{Q}_c$) is $\pm 7.7\%$ and the maximum uncertainty of the Coefficient of performance (S_{COP}/COP) is $\pm 7.8\%$.

4. Conclusion

This study demonstrates the potential of an innovative thermoelectric cooling (TEC) system, coupled with heat pipe sinks, as an alternative cooling system for the cabin of a pickup car. At an ambient temperature of 30-32 °C, the average air temperature inside the car cabin reaches 50.9 °C when the vehicle is not equipped with an air conditioning system, 40.9 °C with a single-stage TEC cooling system, and 39.6 °C with a double-stage TEC cooling system. When a car is parked, the cabin temperature can rise by 19.5 °C above the ambient temperature. In contrast, in a single-stage thermoelectric cooling (TEC) system, the temperature increase is only 8.5 °C, and with a double-stage TEC cooling system, the increase is also 8.7 °C. These results demonstrate that thermoelectric cooling systems can significantly reduce cabin temperature increases, lowering the rise by 11.0 °C for a single-stage TEC system and by 10.8 °C for a double-stage TEC system compared to one without AC. The highest COP of the Single-Stage and double-stage TEC was 1.4 and 1.2, respectively, and was obtained at a velocity of 3 m/s. This indicates that a cooling system with a single-stage TEC configuration performs better than a two-stage TEC, as evidenced by a higher COP value. In addition, the investment cost of a single-stage system is lower than that of a double-stage TEC system, making single-stage systems a more suitable choice for future thermoelectric cooling system applications. The relative humidity of the air inside the cabin ranges from 45.7% to 48.8% when the thermoelectric cooling system is used. It shows that utilizing a thermoelectric cooling system can also keep the room humidity within the passengers' comfort limit. The design of this

cooling system offers one of the most practical solutions for vehicles that require a compact, energy-efficient, and easy-to-install system compared to previous works. However, this study is still at the laboratory scale, where a car prototype was smaller than an actual car. Therefore, testing cars in real-world environments, along with further development to enhance cooling performance and capacity, can be conducted. Future studies can be performed by combining thermoelectric systems with other cooling systems, such as evaporative or conventional systems, to enhance TEC module performance and develop more effective heat exchangers for releasing heat from the hot side of the TEC.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Competing interests

The authors declare no competing interest.

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