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Evaluating the Effect of Electric Vehicle Driving Forces on Battery Cooling System

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ABSTRACT

The electric vehicle plays an important role in today's automotive industry. It has no fuel consumption, reduced emissions and improved performance. In this article, the effect of drive system of the electric vehicle on the battery of this vehicle is investigated. First, the engine structure of the hybrid vehicle is described. In the following, by modeling different parts of the hybrid vehicle such as combustion engine, electric motor, battery and pedal, equations and mathematical analysis is performed. Then, by implementing the electric vehicle in Matlab, the effect of the speed change parameter on the battery is analyzed by considering the automatic cruise control, and the battery charge changes are also checked by running the simulation. Also, the effect of the vehicle speed on the temperature of the battery and its cooling system is checked. The trend of battery temperature changes, cooling pump power and total cooling power consumption in the conditions of speed changes of the electric vehicle based on the ftp 75 pattern and also in the conditions of battery charging are calculated and shown. Results show that in the conditions of speed changes based on the ftp 75 pattern the battery temperature varies between 20 to 22 centigrade while during the battery charging it is higher than 24 centigrade. The cooling pump power is always above 0.6 Kw during battery charging while it is temporary exceeds 0.6 kW on the ftp 75 pattern. Total cooling power consumption during battery charging is always higher that ftp 75 pattern condition.

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Introduction

Studying and improving the performance of vehicles is one of the most important research fields. Improving the mechanical performance of vehicles which consumes fossil fuels has been one of the areas of study in this regard [1]. Extensive research into new automotive technologies is driven by the need to reduce greenhouse gas emissions, reliance on fossil fuels, and air pollution from traditional internal combustion engine vehicles [2; 3]. Electric vehicles (EVs) are a critical technology that enables this transition with the help of batteries [4]. EV batteries, mainly lithium-ion (Li-ion), play a key role in the performance, cost, and market acceptance of electric vehicles [5].

Electric vehicle batteries have several different chemistries. Lithium-ion batteries are the most widely used due to their energy density and performance characteristics.

Lithium-ion batteries dominate the electric vehicle market due to their high energy density, long cycle life, and relatively low discharge rate. The growing demand for lithium-ion batteries has driven research to reduce costs, improve energy density, and increase safety.

Lithium-ion batteries face challenges such as thermal stability and the risk of combustion under harsh conditions. To mitigate these risks, battery management systems have been developed that improve both the safety and lifespan of these batteries [6].

Solid-state batteries are a promising alternative to traditional Li-ion batteries due to their potential for higher energy density and greater safety. Unlike Li-ion batteries that use liquid electrolytes, solid-state batteries use solid electrolytes, which reduce the risk of leakage and fire. Research shows that solid-state batteries can provide energy densities up to 2 to 3 times higher than current lithium-ion batteries, allowing for longer driving ranges and faster charging times. However, the development of solid-state batteries faces significant challenges in materials and manufacturing. Issues such as the surface resistance between the solid electrolyte and electrodes must be overcome before large-scale commercial deployment [7].

Lithium-sulfur batteries are another potential alternative to lithium-ion batteries due to their high energy density and lower cost. The sulfur used in Li-S batteries is more accessible and has lower cost, making these batteries an attractive option for large-scale energy storages. Li-S batteries suffer from problems such as poor cycle life and the “shuttle effect,” in which dissolved polysulfides migrate between the cathode and anode, causing rapid capacity loss. Recent studies have focused on developing new materials to mitigate these issues, but significant challenges remain before commercial viability is achieved [8].

One of the critical challenges for EV batteries is their degradation over time. The performance of lithium-ion batteries degrades with repeated charge and discharge cycles, reducing the vehicle's range and efficiency. Several studies have identified factors such as temperature, depth of discharge, and charge rate as important factors in battery degradation. To extend battery life, researchers have focused on developing advanced battery management systems that monitor battery health in real time, optimize charging patterns, and prevent conditions that accelerate degradation [9].

In addition to battery chemistry, the performance of EV batteries is also affected by the infrastructure and charging methods. Fast charging technologies have attracted significant attention due to the need to reduce the charging time of electric vehicles. Traditional lithium-ion batteries suffer from reduced lifespan and performance degradation due to increased internal heat and stress generated during rapid charge-discharge cycles. Researchers have explored various strategies to improve fast charging performance without significantly reducing battery life. These strategies include optimizing charging protocols, improving thermal management systems, and developing new materials with better tolerance to fast charging [10].

With the increasing demand for electric vehicles, attention has also been focused on the sustainability of battery materials and the environmental impact of battery disposal. EV battery recycling technologies are being developed with the aim of recovering valuable materials such as lithium, cobalt, and nickel. Advances in battery recycling technologies are critical to ensuring the sustainability of electric vehicles, reducing the demand for raw materials, and minimizing environmental impacts. Additionally, second-life applications, in which used EV batteries are used for stationary energy storage, are being explored as a way to extend the lifecycle of EV batteries and reduce waste. In addition, recycling and second-life applications of EV batteries are being explored as strategies to reduce the environmental impacts and costs associated with battery disposal [11].

EV batteries are essential for the advancement of electric vehicles and the transition to a sustainable transportation system. While lithium-ion batteries currently dominate the market, significant challenges remain regarding battery degradation, cost, and sustainability. Research into new battery chemistries, improved battery management systems, and recycling technologies are critical to overcoming these challenges and ensuring the long-term success of electric vehicles. With continued advances in battery technology, the future of electric vehicles looks promising, with the potential for longer driving ranges, faster charging times, and reduced environmental impacts [12].

In electric vehicles with lithium-ion batteries, their widespread commercial deployment has been hampered by challenges related to operating temperatures. These temperature variations can negatively impact battery performance, degradation, and safety, creating barriers to their efficient application in vehicles. To address these issues, the development of effective and efficient cooling techniques to reduce the adverse effects of surface temperature on battery cells is crucial [13].

In [14] recent research on liquid-cooling systems for lithium-ion batteries is reviewed. It focuses on battery pack design, liquid-cooling system classifications and coolant performance. The paper also examines how temperature affects battery performance and provides a systematic review of direct and indirect liquid-cooling methods.

Liquid-cooling battery thermal management systems are a leading solution for electric vehicles due to their superior heat transfer compared to air-cooling. In [15] the background of liquid-cooling battery thermal management systems is discussed, then focuses on recent research in design improvements and optimization. Key approaches discussed include coolant channels, heat transfer jackets, cold plates, coolants, refrigeration cooling, heat pipes, and hybrid liquid systems.

In [16] a review is presented which focuses on battery cooling strategies, particularly direct liquid cooling, addressing a gap in research that has primarily focused on phase change material cooling. It summarizes advancements in battery thermal management system thermal characteristics, challenges, and future directions, including experimental, simulation, and modeling work. The study also covers optimization and control for safe and efficient battery operation, aligning with environmental, social, and governance principles and sustainable development goals by promoting energy efficiency and reducing emissions. Ultimately, this review aims to guide the development of more practical and effective battery thermal management system solutions.

In this paper, the effect of vehicle speed on battery temperature and its cooling system is investigated. The effect of vehicle charging is also studied. First, the components and mechanism of electric vehicle propulsion are described, and then the speed control method in electric vehicles is discussed. Finally, the behavior of electric vehicle batteries is analyzed by presenting software results and simulating the electric vehicle system in Matlab.

Analysis of components and operating mechanisms of electric vehicle propulsion systems

A hybrid electric vehicle (HEV) is a vehicle that uses two energy sources for propulsion, one of which is electric energy. Most hybrid-powered road vehicles use an internal combustion engine in conjunction with an electric machine (EM) [17]. Compared to a conventional vehicle powered by an internal combustion engine, a hybrid electric vehicle is capable of performing the following functions:

- Quick stop and start
- Energy recovery during braking (regenerative braking)
- Torque boost.

Series-parallel hybrid powertrain

In a parallel hybrid powertrain, both the internal combustion engine and the electric motor can deliver torque to the drive wheels either sequentially or simultaneously [18]. In series hybrids, the internal combustion engine does not provide torque directly to the drive wheels. Instead, the engine powers an electric generator that supplies electrical energy to the traction electric motor [19].

A series-parallel hybrid electric vehicle is a type of hybrid vehicle that combines the features of both series and parallel hybrid systems [20]. A series-parallel hybrid electric vehicle has a powertrain that allows the vehicle to operate in different modes depending on driving conditions and the state of charge of the battery.

In series mode, the internal combustion engine is used to generate electricity through a generator. This electricity is either sent to the electric motor to drive the wheels or stored in the battery. In this configuration, the combustion engine does not directly power the wheels. The electric motor does all the power transfer.

In parallel mode, both the internal combustion engine and the electric motor can drive the vehicle's wheels. The combustion engine and electric motor work together, and power can be provided by either or both, depending on the situation (e.g., high acceleration, climbing hills, etc.).

In series-parallel mode, the vehicle can switch between series and parallel configurations, or use a combination of both. For example, when driving in a city at low speeds, it may use series mode, while when driving on the highway, it may switch to parallel mode for better efficiency [21].

Key advantages of a series-parallel hybrid electric vehicle include:

- Fuel efficiency: The vehicle can operate in the most efficient mode depending on the driving conditions, saving fuel.

- Emission reduction: More electrical energy is used, which reduces dependence on the combustion engine and thus reduces greenhouse gas emissions.
- Flexibility: The ability to switch between series and parallel modes provides greater flexibility and allows the vehicle to adapt to different driving conditions.

A series hybrid vehicle is converted to a series-parallel hybrid vehicle by adding a mechanical connection (clutch) between the two electric motors. Compared to a series hybrid, a series-parallel hybrid has the advantage of lower generator power because the excess engine power can be directly transmitted to the drive wheels. The disadvantage is that by adding a mechanical connection (clutch), we lose flexibility in terms of packaging.

In terms of propulsion functions, a series-parallel hybrid has the following capabilities:

- Engine stop-start
- Energy recovery
- Torque boost
- Charging at standstill

Compared to a parallel hybrid, a series-parallel hybrid uses two electric machines, performing the same tasks. For these reasons, the series-parallel architecture of the propulsion with a clutch connection between the two electric machines is not widely used by automakers.

Hybrid electric vehicle modeling

In this section, the modeling of a hybrid electric vehicle is performed. In the modeling of a vehicle combustion engine, the inputs are engine speed, engine torque command, and fuel injection activation command. The outputs are engine torque and fuel consumption rate [22]. The fuel consumption rate is obtained as a function of engine speed and torque as equation (1).

$$EFC = f(ES, EOT) \tag{1}$$

Where, ES is the engine speed, EOT is the engine output torque, and EFC is the engine fuel consumption.

The torque curve ensures that the output torque does not exceed the engine limits. A first-order transfer function is used to represent the engine torque output response ($ETOR$). This function is expressed by equation (2).

$$ETOR = \frac{1}{\tau + 1} MTC \tag{2}$$

Where MTC is the motor torque command and τ is the time constant.

The electric motor modeling approach is similar to that of the combustion engine, which is based on torque and efficiency maps. The model inputs are the motor torque command and motor speed; the outputs are the motor torque and electric power. A motor can operate in traction mode and power generation mode. The motor power (MP) in the two modes is expressed by equation (3).

$$MP = \begin{cases} \dfrac{T \times n}{9550 \times \eta} & \text{Traction mode} \\ \dfrac{T \times n}{9550} \times \eta & \text{Generation mode} \end{cases} \tag{3}$$

Where T is the torque, n is the speed, and η is the efficiency of the motor.

The battery model consists of an ideal voltage source to provide the open circuit voltage (V_{OC}) and the internal resistance (R_O). According to Kirchhoff's law, the terminal voltage of the battery is a function of the current and is expressed by equation (4).

$$V_{Battery} = V_{OC} - (R_O \times I_{Battery}) \tag{4}$$

Battery power is calculated as equation (5):

$$P_{Battery} = V_{Battery} \times I_{Battery} \tag{5}$$

State of charge (SOC) for battery is defined as the percentage of the battery's remaining capacity to its full capacity. SOC determines how much energy is left in the battery compared to its maximum capacity. SOC is important for battery management. Knowing the SOC is important for both EV users and the battery itself. It helps electric vehicle driver to know how much further can drive. Also, SOC helps avoid overcharging and completely draining a battery. Because they shorten its lifespan. SOC can be calculated by equation (6).

$$SOC = SOC_0 - \frac{1}{Q_{Full}} \int_0^t I_{Battery}(t)\, dt \tag{6}$$

Where SOC_0 is the initial capacity and Q_{Full} is the full battery capacity.

The driver model controls the accelerator pedal position and the brake pedal position according to the actual vehicle speed and the target vehicle speed, so that the vehicle follows the desired speed path. The process of calculating the pedal position in the form of the target torque (T_{Target}), which is equal to the sum of the road load torque T_{RL} and the controller torque $T_{Control}$, is calculated by equation (7).

$$T_{Target} = T_{RL} + T_{Control} \tag{7}$$

The road load moment is the sum of air resistance, rolling resistance, and slope resistance and is calculated by equation (8).

$$T_{RL} = (\frac{1}{2} \times \rho \times A \times C_{AR} \times v_{Target}^2 + C_{TRR} \times m.g.\cos\delta + m.g.\cos\delta) \times r \tag{8}$$

Where, v_{Target} is the target speed, ρ is the air density, A is the headwind surface area, C_{AR} is the air resistance coefficient, g is the acceleration of gravity, δ is the road slope, C_{TRR} is the tire rolling resistance coefficient, m is the mass and r is the tire radius.

The controller torque is calculated by equation (9).

$$T_{Control} = k_p \times (v_{Target} - v_{Actual}) + \int k_i \times (v_{Target} - v_{Actual})\, dt \tag{9}$$

Where v_{Actual} is the actual speed, k_p is the proportional gain, and k_i is the integral gain.

The pedal position is calculated by the ratio of the target torque to the vehicle torque capacity and is expressed by equations (10) and (11), where APP is the accelerator pedal position, BPP is the brake pedal position, $T_{\max}^{Drive}$ is the maximum driving torque, and $T_{\max}^{Brake}$ is the maximum braking torque.

$$APP = \begin{cases} \dfrac{T_{Target}}{T_{\max}^{Drive}} & T_{Target} > 0 \\ 0 & T_{Target} \le 0 \end{cases} \tag{10}$$

$$BPP = \begin{cases} \dfrac{T_{Target}}{T_{\max}^{Brake}} & T_{Target} \le 0 \\ 0 & T_{Target} > 0 \end{cases} \tag{11}$$

According to equations (1) to (11), it can be concluded that series-parallel hybrid electric vehicle is modeled as a system in which the required torque for driving forces is derived from the motors. The electric motor power is supplied by the battery. The battery power is divided to two mechanical and thermal parts. The goal of this study is to analyze the thermal part in different operation condition of the hybrid electric vehicle.

Results and discussion

In this section, the effect of vehicle speed on battery temperature and its cooling system is examined. Also, the effect of vehicle charging on vehicle speed is evaluated. For this purpose, a hybrid vehicle has been implemented and simulated in Matlab software.

Evaluating the impact of automatic cruise control on battery charging

Adaptive cruise control (ACC), is an advanced driver assistance system that automatically adjusts the vehicle's speed to maintain a safe distance from the vehicle in front [23]. Unlike traditional cruise control where the driver sets a fixed speed, ACC uses radar, cameras, or lidar sensors to monitor traffic conditions and adjusts the vehicle's speed based on the distance and speed of the vehicle in front. If a slower vehicle is detected in the same lane, ACC slows the vehicle down and returns to the preset speed when the lane is clear. Drivers can set a preferred distance from the vehicle in front, usually measured in seconds or meters. In many modern systems, ACC can bring the vehicle to a complete stop in heavy traffic and resume driving when traffic starts moving again. In this section, the impact of adaptive cruise control on battery charging in a hybrid vehicle is evaluated. The cruise control variations are shown in Figure 1. The effect of these changes on the vehicle's speed can be seen in Figure 2.

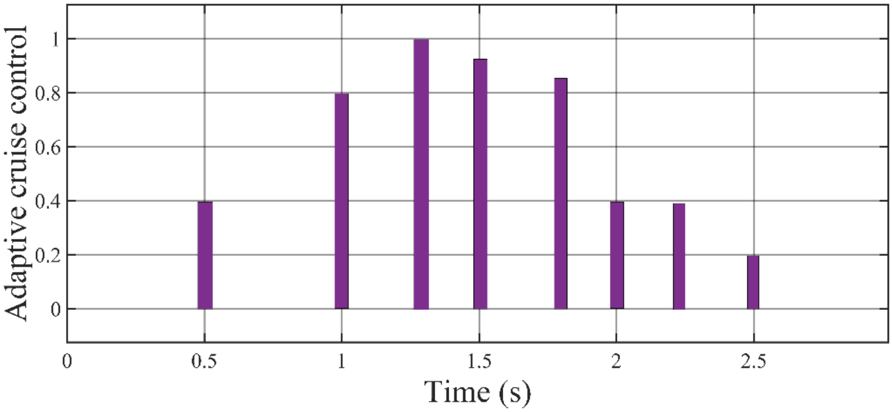

Figure 1. Cruise control pattern of EV

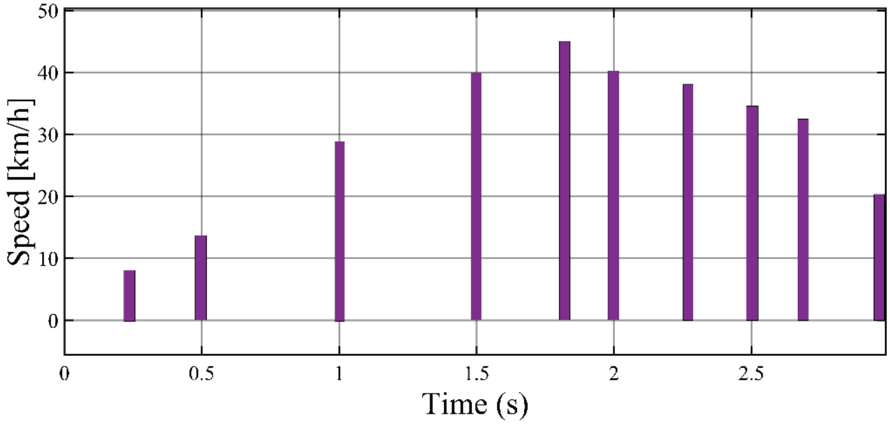

Figure 2. The effect of cruise control on EV speed

The effect of cruise control on battery SOC is seen in Figure 3.

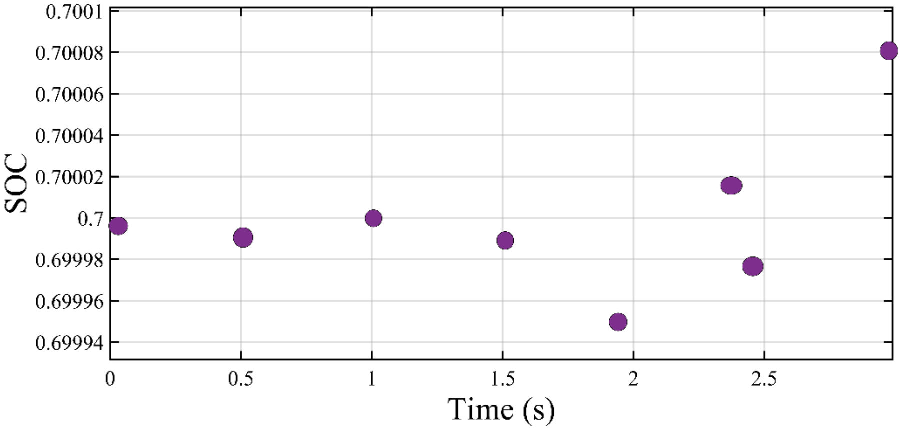

Figure 3. The impact of cruise control on battery SOC

As can be seen in Figures 1 to 3, the vehicle speed is subject to changes in cruise control and follow a similar trend. Conversely, the charging of the hybrid vehicle battery follows the opposite trend of changes in cruise control. In other words, when the vehicle is directed to increase speed, the battery charge decreases and when the vehicle is directed to decrease speed, the battery charge increases.

In order to analyze the effect of vehicle speed on the output power of the vehicle generator and electric current consumed by the vehicle, simulation results in Figures 4 and 5 are shown.

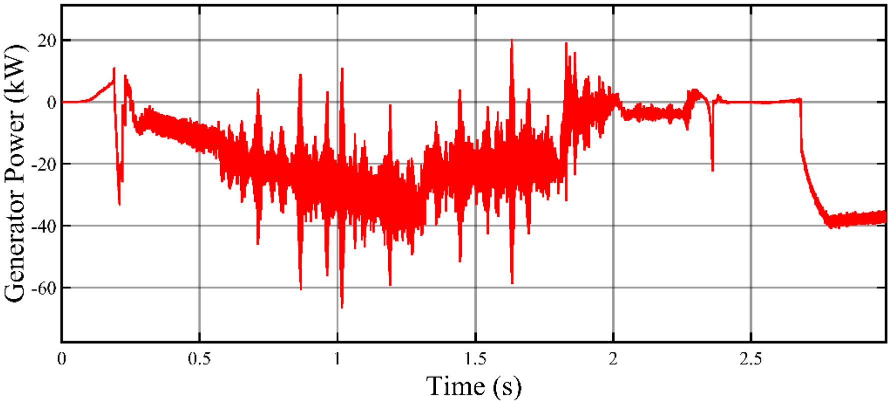

Figure 4. The impact of cruise control on the output power of the vehicle generator

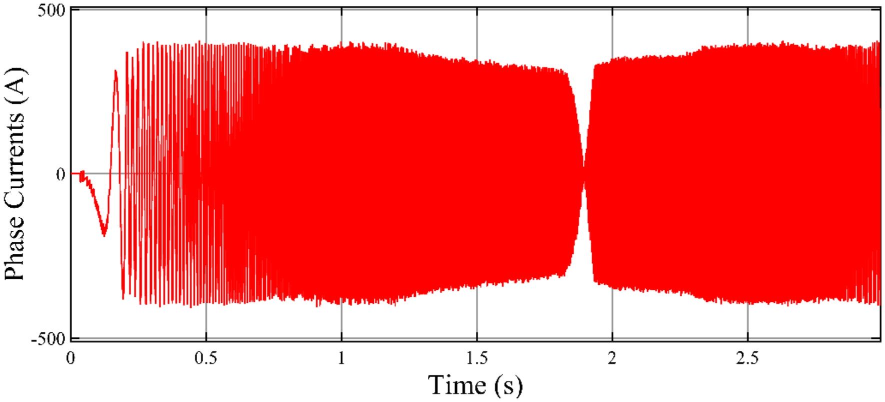

Figure 5. The impact of cruise control on electric current consumed by the electric vehicle

Figures 4 and 5 show that at high speeds, the frequency of power and current is higher than low speeds. It means that the power and current will have high oscillations at high speeds. Also, the amplitude of current consumed by the electric vehicle is reduced by increasing the vehicle speed.

Evaluating the impact of vehicle speed on battery

In order to investigate the effect of vehicle speed on the temperature of the battery and its cooling system, the battery assembly and its cooling system were simulated in Matlab software [24].

In the following, the speed changes of the hybrid vehicle are applied based on the ftp 75 pattern [25]. The FTP 75 pattern is used for ratings of vehicles, standardized testing and real simulation. The FTP 75 attempts to simulate usual urban driving conditions such as accelerations and decelerations and frequent stops. This helps to provide a more realistic assessment of vehicle. This pattern is shown in Figure 6.

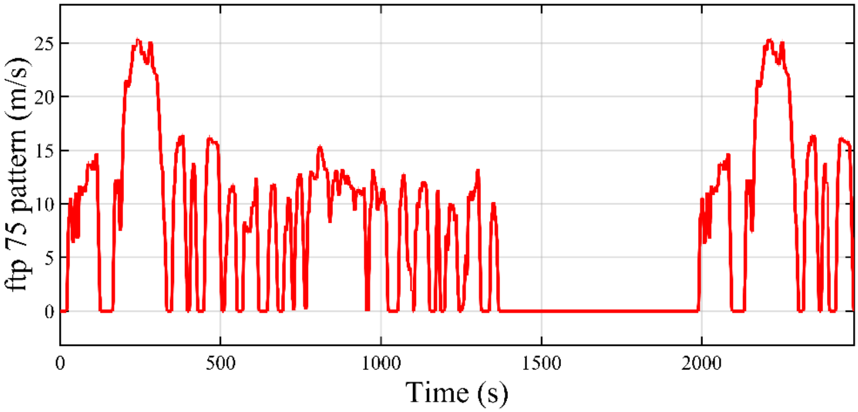

Figure 6. FTP 75 pattern for EV speed tests [25]

The trend of changes in battery temperature is shown in figure 7 for the battery.

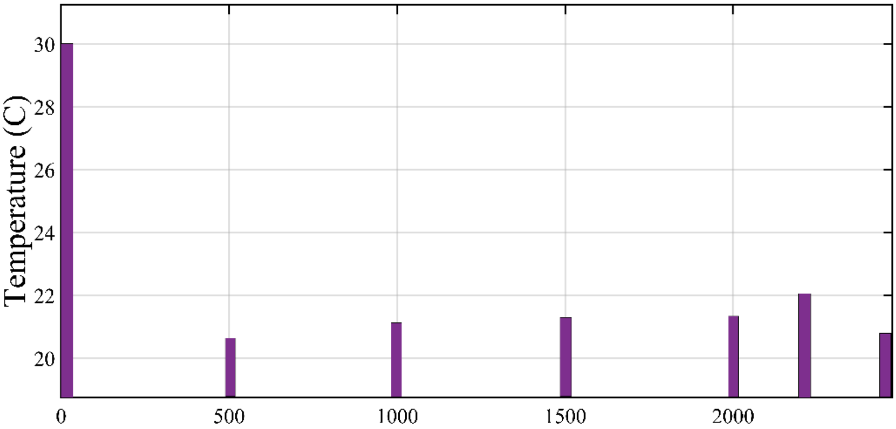

Figure 7. The trend of battery temperature due to changes in EV speed

Cooling pump power consumption, and total cooling power consumption is shown in figures 8 and 9, respectively.

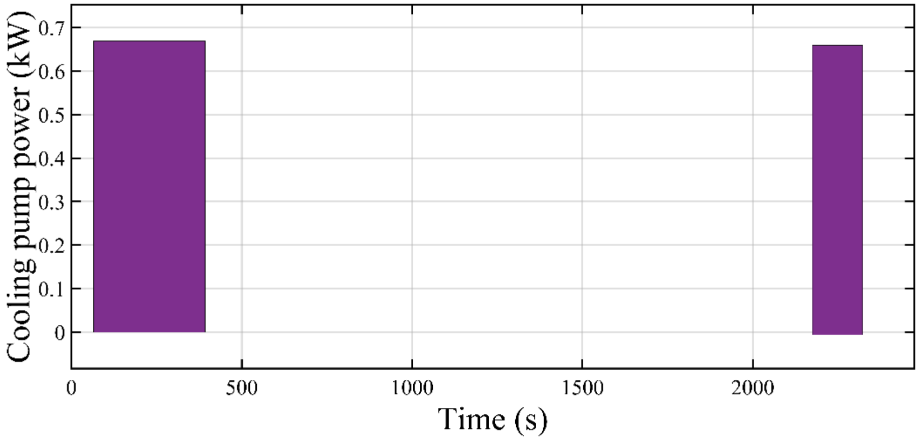

Figure 8. Trend of changes in cooling pump power due to changes in EV speed

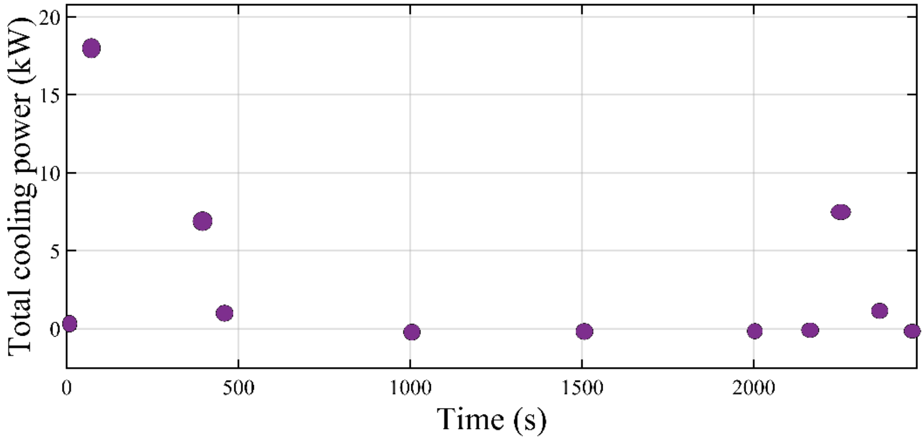

Figure 9. Trend of changes in total cooling power consumption due to changes in EV speed

The analysis of Figures 7 to 9 shows the following results:

- In the time interval 0 to 505 seconds, which is the cold start time of the vehicle, the battery temperature is initially at the highest level. As the cooling pump is activated and the cooling power increases, the battery temperature decreases. At the end of this interval, the cooling pump is turned off and the cooling power is zero.
- In the time interval 506 to 1372 seconds, which is the vehicle stability phase, and also the time interval 1373 to 1995 seconds, which is the hot engine phase in the off state, the battery temperature increases quite gently. Hence, the cooling pump is turned off and the cooling power is zero.

- In the time interval 1995 to 2500 seconds, which is the hot start time of the vehicle, the battery temperature increases suddenly. As the cooling pump is activated and the cooling power increases, the battery temperature decreases. At the end of this interval, the cooling pump is turned off and the cooling power is zero.

The behavior of the battery during charging time is also analyzed, and the trend of changes in battery temperature, cooling pump power, and total cooling power consumption are shown in Figures 10 to 12, respectively.

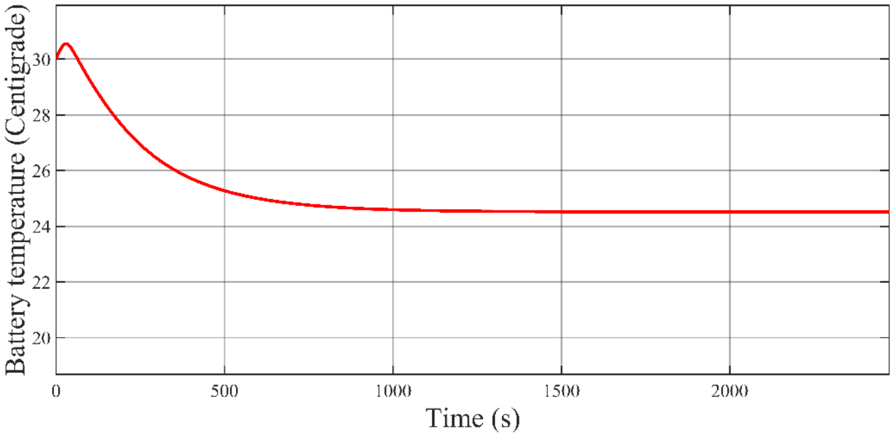

Figure 10. The trend of battery temperature changes during battery charging

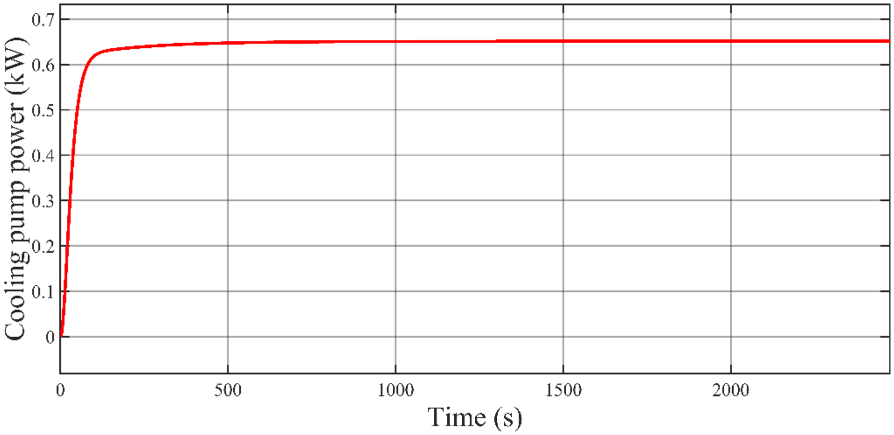

Figure 11. Trend of changes in cooling pump power during battery charging

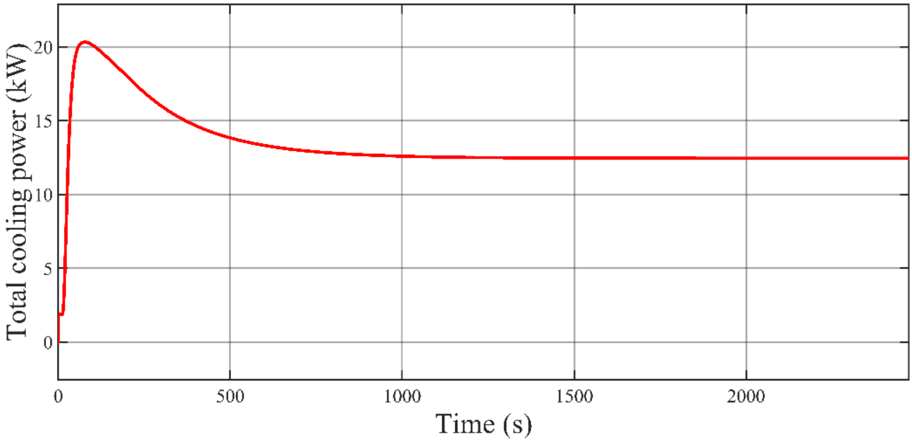

Figure 12. Trend of changes in total cooling power consumption during battery charging

Examination and analysis of Figures 10 to 12 show that during battery charging, the battery temperature is initially high and then increases slightly. For this reason, the battery cooling system is activated and the power of the cooling pump and the cooling power consumption increase. Then, after the battery temperature decreases, the cooling power also decreases, while the cooling pump continues to operate at a constant power until the end of the charging time.

Conclusion

In this article, the effect of the vehicle's propulsion system on the behavior of the hybrid vehicle battery was examined. First, the structure of the hybrid vehicle's propulsion system was described. Then, by modeling the various parts of the hybrid vehicle, such as the combustion engine, electric motor, battery, and driver pedal, the equations and mathematical relationships governing them were expressed. Then, by implementing the hybrid vehicle in Matlab software and running the simulation, the effect of the speed change parameter on the battery was analyzed first by considering the automatic cruise control. It was shown that the changes in the vehicle's speed are a function of the changes in the cruise control and follow a similar trend. Also, when the vehicle is driven to increase the speed, the battery charge decreases, and when the vehicle is driven to decrease the speed, the battery charge increases. Next, in order to investigate the effect of vehicle speed on battery temperature and its cooling system, this set was implemented in Matlab software and the trend of battery temperature changes, cooling pump power, and total cooling power consumption were calculated and shown under conditions of hybrid vehicle speed changes based on the ftp 75 model and also under battery charging conditions. Comparing the battery charging condition and ftp 75 pattern show that in the conditions of speed changes based on the ftp 75 pattern, the battery temperature is between 20 to 22 centigrade while during the battery charging condition it is higher than 24 centigrade. During battery charging, the cooling pump power is always above 0.6 Kw while on the ftp 75 pattern it is temporary exceeds 0.6 kW. Also cooling power consumption during battery charging is always higher that ftp 75 pattern condition.

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