A New Control Method for Hybrid Electric Vehicle Battery Cooling System

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Manuscript received 11 February, 2025; revised 25 April, 2025; accepted 1 May, 2025. Paper no. JEMT-2501-1538.

Hybrid electric vehicles (HEVs) hold significant importance in the automotive industry owing to their superior fuel efficiency, lower operating costs, reduced emissions, and enhanced performance. This article proposes a novel battery cooling system for HEVs designed to minimize the electrical power required for battery thermal management. The proposed control strategy is based on the battery's real-time temperature. First, the engine architecture of the HEV is outlined. Subsequently, mathematical models of key components—including the internal combustion engine, electric motor, battery, and driver—are developed, and their governing equations are derived. The HEV is then simulated in MATLAB to analyze the impact of vehicle speed on battery temperature and cooling system performance. A comparative study is conducted between the proposed and conventional cooling systems, evaluating battery temperature trends, cooling pump power consumption, and refrigerant power under speed variations based on the FTP-75 driving cycle. The results demonstrate that the proposed controller effectively maintains the battery temperature within the permissible range while reducing cooling power consumption by 30% and eliminating peak refrigerant power demands.

Keywords: *Hybrid electric vehicle, Battery temperature, Cooling system, Power consumption.*

http://dx.doi.org/10.22109/jemt.2025.499228.1538

Nomenclature

$fuel$	Fuel consumption
n_{eng}	Engine speed
T_{eng}	Engine output torque
T_{eng}^{cmd}	Engine torque command
τ	Time constant
P_{mot}	Power output of ICE
T_{mot}	ICE torque
n_{mot}	ICE speed
η_{mot}	Efficiency of the motor
T_{tar}	Target torque
T_{RL}	Air drag, rolling resistance and gradient resistance
T_{PI}	Controller torque
ρ	Air density
A	Frontal area
C_d	Aerodynamic drag coefficient
v_{tar}	Target speed
C_r	Rolling resistance coefficient
m	Mass
g	Gravitational acceleration
δ	Road gradient
r	Tire radius
v_{act}	Actual speed
k_p	Proportional gain
k_i	Integral gain

acc	Throttle pedal position
$T_{drive\_\max}$	Maximum driving torque
brk	Brake pedal position
$T_{brake\_\max}$	Maximum braking torque
V	Battery terminal voltage
V_{oc}	Battery open-circuit voltage
R_0	Battery internal resistance
I	Battery current
P_{batt}	Battery power
SOC	Battery state of charge
SOC_0	Battery initial state of charge
Q_{nom}	Full capacity of the battery
$\dot{m}_{Ideal}$	Pump ideal mass flow rate
β	Pump average fluid densities at thermal liquid ports
ω	Pump shaft angular velocity
D	Pump displacement parameter
γ	Pump controller weighting coefficient
$\Delta T_{Battery}$	Difference between the battery temperature and the reference temperature
$\omega_{\min}^{Pump}$	Pump minimum speed after relay activation

1. Introduction

Extensive research in advanced automotive technologies is driven by the urgent need to reduce greenhouse gas emissions, the dependence on fossil fuels, and air pollution caused by traditional internal combustion engine vehicles [1]. Hybrid Electric Vehicles (HEV) are increasingly developing for their ability to reduce fuel consumption and emissions [2]. As the fastest-responding dispatchable power source on electric grids, battery energy storage plays a critical role in enhancing grid and system stability [3, 4]. Electric vehicles (EVs) are a crucial technology, enabled by advanced batteries. EV batteries, primarily lithium-ion (Li-ion), play a pivotal role in the performance, cost, and market adoption of electric vehicles. Other battery technologies include solid-state batteries, lithium-sulfur (Li-S), and sodium-ion batteries [5-8].

Li-ion batteries degrade over time with repeated charge and discharge cycles, leading to reduced range and efficiency. Factors such as temperature, discharge depth, and charge rate significantly affect the degradation. Advanced BMSs are crucial for monitoring the battery health in real-time and optimizing charging patterns [9].

The performance of EV batteries is influenced by charging methods. Fast charge technologies have garnered significant attention due to the need to reduce charging times for electric vehicles. Traditional lithium-ion batteries suffer from reduced lifespan and performance degradation caused by increased internal heat and stress during rapid charge-discharge cycles.

Researchers have explored various strategies to enhance fast-charging performance without significantly compromising battery lifespan. These strategies include optimizing charging protocols, improving thermal management systems, and developing new materials with better tolerance for fast charging [10].

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 is being conducted to address these challenges and ensure the long-term success of electric vehicles. As advancements in battery performance continue, the future of electric vehicles looks promising, with the potential for longer driving ranges, faster charging times, and reduced environmental impacts [11].

In electric vehicles with lithium-ion batteries, widespread commercial deployment faces challenges related to operational temperatures. These temperature variations can negatively affect battery performance, degradation, and safety, creating barriers to their efficient application in vehicles. To address these issues, the development of effective high-performance cooling techniques is crucial for mitigating the adverse effects of surface temperatures on battery cells [12, 13].

A two-level optimization strategy is proposed in [14] for speed and thermal management in connected and automated EVs. The global reference trajectory of speed and battery temperature is planned. In addition, speed following and temperature tracking based on model predictive control are discussed. The Gaussian process model is also considered in the model predictive control method to enhance the estimation accuracy.

In [15], a new battery self-heating mechanism during driving is presented to maintain battery temperature. This method is embedded within the heating mechanism of the motor driving system without modification of the existing driving circuitry. In this method, the battery voltage can be regulated to prevent out of limit conditions. Therefore, the safety of battery is ensured.

While previous studies have partially examined thermal management in electric vehicle (EV) battery systems, the specific effects of variable speed conditions on both battery temperature and cooling system power consumption remain insufficiently explored. This study provides a comprehensive analysis of how vehicle speed dynamics influence battery thermal behavior and corresponding cooling demands.

Key contributions of this work:

- Identifies a research gap in existing literature regarding the influence of vehicle speed variations on battery temperature and cooling power consumption in electric vehicles.
- Provides a comprehensive analysis of HEV powertrain components and their mechanisms (presented in Section 2).
- Proposes a novel control system for hybrid electric vehicle (HEV) battery cooling to minimize electrical power usage (detailed in Section 3).
- Validates findings through MATLAB simulations, analyzing battery behavior under dynamic speed conditions (Section 4).

Initially, in Section 2, the components and mechanisms of the electric vehicle powertrain are explained. Then in Section 3, the new control system is proposed. Finally, in Section 4, the behavior of the electric vehicle battery is analyzed through MATLAB-based simulations and software results.

2. Analysis of Electric Vehicle Powertrain Components

2.1. Working principles and mechanism of hybrid electric vehicles

HEVs use two energy sources. Most road-going HEVs have an internal combustion engine (ICE) and an electric motor (EM) [16].

Compared to conventional ICE vehicles, HEVs offer functions such as rapid stop-and-start, energy recovery during braking (regenerative braking) and torque boost. HEVs include three types: parallel, series, and series-parallel hybrid electric vehicles. In parallel hybrids, the ICE and EM can independently or simultaneously deliver torque to the drive wheels [17]. In series hybrids, the ICE does not directly provide torque to the wheels. Instead, it powers a generator that supplies electricity to the traction motor [18]. Since there is no direct mechanical connection between the engine and the drive wheels, a gearbox is unnecessary. This is advantageous in terms of packaging, because it requires less space for engine and generator connections. While series hybrids eliminate the need for a traditional gearbox, they suffer from energy conversion losses, making them less suitable for high-speed applications. A series-parallel hybrid electric vehicle is a type of hybrid vehicle that combines the features of both series and parallel hybrid systems [19, 20]. Figure 1 illustrates the powertrains of three hybrid vehicles (series, parallel, and series-parallel) for comparison. In this paper, the modeling of a series-parallel hybrid electric vehicle is presented and analyzed.

A series-parallel hybrid electric vehicle combines the operational advantages of both series and parallel hybrid architectures, enabling flexible power flow management for optimal efficiency. In this configuration, the ICE and electric motor(s) can either work independently or in tandem, connected through a planetary gear set or power-split device that allows torque coupling and speed decoupling. The ICE can directly drive the wheels (parallel mode) or act as a generator to charge the battery while the electric motor propels the vehicle (series mode), depending on driving conditions and energy demands. This dual functionality improves fuel economy by operating the ICE within its most efficient range via load-leveling and enables regenerative braking to recover kinetic energy. Key components include a high-voltage battery pack, one or more electric machines (often permanent magnet synchronous motors), and sophisticated energy management systems (EMS) that dynamically select the optimal power distribution strategy based on real-time inputs such as speed, acceleration, and state of charge. Series-parallel hybrid electric vehicles are particularly effective in urban and highway driving cycles, where their ability to switch between pure electric, hybrid, and engine-only modes reduces emissions and energy consumption compared to conventional or single-mode hybrid systems. Advanced variants may incorporate plug-in capabilities for extended electric-only range, further enhancing sustainability. The architecture's complexity necessitates precise control algorithms but offers superior performance and efficiency, making it a preferred choice for modern hybrid vehicles.

In a series-parallel hybrid electric vehicle, the internal combustion engine generates electricity via a generator in series mode. This electricity is either sent to the electric motor to drive the wheels or stored in the battery. In this configuration, the internal combustion engine does not directly power the wheels, and the electric motor handles all the power delivery. In parallel mode, the internal combustion engine and the electric motors drive the wheels. The two power sources work together, and depending on the situation (e.g., high acceleration, climbing hills), power can be supplied by either or both. In series-parallel mode, the vehicle can switch between series and parallel configurations or use a combination of both. For example, during low-speed city driving, the vehicle may operate in series mode, whereas at higher speeds on highways, it may switch to parallel mode for greater efficiency [21].

2.2. Series-Parallel Hybrid Electric Vehicle Model

In the modeling of the vehicle's internal combustion engine, the inputs include the engine speed, torque command, and fuel injection activation command. The outputs are the engine torque and fuel consumption rate [22].

The fuel consumption as a function of engine speed and torque is expressed in Equation (1):

$$fuel = f\,(n_{eng}, T_{eng}) \tag{1}$$

where T_{eng} is the engine output torque, n_{eng} is the engine speed, and $fuel$ is the fuel consumption rate of the engine. The engine output torque is regulated to stay within the engine's operational limits, modeled using a first-order transfer function as shown in Eq. (2) [23]:

$$T_{eng} = \frac{1}{\tau s + 1} T_{eng}^{cmd} \tag{2}$$

where T_{eng}^{cmd} is the engine torque command and τ is the time constant. Similar to the ICE, the electric motor is modeled based on the torque and efficiency maps. It operates in traction and generation modes, and its power output calculated as [22]:

$$P_{mot} = \begin{cases} \dfrac{T_{mot} \times n_{mot}}{9550 \times \eta_{mot}} & \text{Traction mode} \\[2ex] \dfrac{T_{mot} \times n_{mot}}{9550} \times \eta_{mot} & \text{Generation mode} \end{cases} \tag{3}$$

where T_{mot} is the torque, n_{mot} is the speed, and η_{mot} is the motor efficiency.

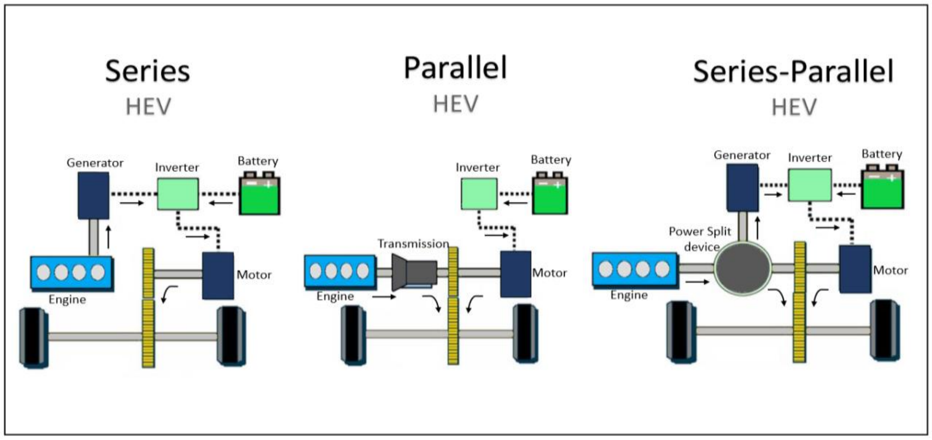


Fig. 1. Powertrain configurations of three series, parallel, and series-parallel hybrid vehicles

The driver model simulates the throttle and brake pedal positions based on the difference between the target speed (v_{tar}) and the actual speed (v_{act}). The target torque (T_{tar}) is calculated as:

$$T_{tar} = T_{RL} + T_{PI} \tag{4}$$

where T_{RL} accounts for air drag, rolling resistance, and gradient resistance, and is calculated using Equation (5) [22].

$$T_{RL} = (\frac{1}{2}\rho A C_d V_{tar}^2 + C_r mg\cos\delta + mg\cos\delta)r \tag{5}$$

where ρ is the air density, A is the frontal area, C_d is the aerodynamic drag coefficient, g is the gravitational acceleration, δ is the road gradient, C_r is the rolling resistance coefficient, m is the mass, and r is the tire radius.

T_{PI} is calculated using a proportional-integral (PI) controller. The controller torque T_{PI} is calculated using Equation (6) [22]:

$$T_{PI} = k_p(v_{tar} - v_{act}) + \int k_i(v_{tar} - v_{act})dt \tag{6}$$

where k_p is the proportional gain, and k_i is the integral gain.

The pedal position is calculated based on the ratio of the target torque to the torque capacity of the vehicle and is expressed by Equations (7) and (8), where *acc* is the throttle pedal position, *brk* is the brake pedal position, T_{drive_max} is the maximum driving torque, and T_{brake_max} is the maximum braking torque [22].

$$acc = \begin{cases} \dfrac{T_{tar}}{T_{drive\_\max}} & T_{tar} > 0 \\ 0 & T_{tar} \le 0 \end{cases} \tag{7}$$

$$brk = \begin{cases} \dfrac{T_{tar}}{T_{brake\_\max}} & T_{tar} \le 0 \\ 0 & T_{tar} > 0 \end{cases} \tag{8}$$

The battery is modeled using an ideal voltage source representing the open-circuit voltage V_{oc} and an internal resistance R_0. Terminal voltage V and power P_{batt} are computed using the following equations [24].

$$V = V_{oc} - R_0.I \tag{9}$$

$$P_{batt} = V.I \tag{10}$$

In hybrid electric vehicle P_{batt} depends on the total required power from or delivered power to the Combustion Engine and Electric Motor system.

The battery state of charge (*SOC*) is also determined as [22]:

$$SOC = SOC_0 - \frac{1}{Q_{nom}}\int_0^t I(t)dt \tag{11}$$

where SOC_0 is the initial state of charge, and Q_{nom} is the full capacity of the battery.

According to the heat generation mechanism, the heat generation in battery (*Q*) is defined by Equation (12). In this equation, the change in entropy caused by the electrochemical reaction is ignored.

$$Q = \int_0^t (I^2(t) \times R)dt \tag{12}$$

According to the above equations, it can be concluded that a series-parallel hybrid electric vehicle can be modeled as a system in which the required torque for driving forces is an input and the power delivered by the battery is the output. The battery power is divided into mechanical and thermal parts.

3. Proposed battery cooling system

This section presents the control mechanism of the battery cooling system in hybrid electric vehicles. The proposed method is based on determining the appropriate temperature for battery operation. The basic battery temperature control method is illustrated in Figure 2.

In this model, the battery packs are located on top of a cold plate consisting of cooling channels to direct the cooling liquid flow below the battery packs. The heat absorbed by the cooling liquid is transported to the Heating-Cooling Unit. The Heating-Cooling Unit consists of three branches that switch operating modes to cool and heat the battery. Heater represents an electrical equipment for fast heating of batteries under low-temperature conditions. The Radiator uses air-cooling and/or heating when the batteries are operated stably. The Refrigerant system is used to cool the overheated batteries. The refrigeration cycle is represented by the amount of heat flow extracted from the cooling liquid.

In conventional controllers, a fixed-speed pump is used to move the fluid, which leads to high power consumption by the pump. While in the proposed method, the pump speed is adjusted in proportion to the difference between the battery temperature and the desired temperature (T_set). The control diagram of the proposed method for determining the cooling pump speed is shown in Figure 3.

In the proposed method, the pump displacement is specified by the displacement parameter. Accordingly, the ideal mass flow rate is calculated by (13).

$$\dot{m}_{Ideal} = \beta\omega D \tag{13}$$

where β is the average of fluid densities at thermal liquid ports, ω is the shaft angular velocity, and D is the displacement parameter. ω is determined by (14).

$$\omega = (\gamma \times \Delta T_{Battery}) + \omega_{\min}^{Pump} \tag{14}$$

where γ is the weighting coefficient, $\Delta T_{Battery}$ is the difference between the battery temperature and the reference temperature and $\omega_{\min}^{Pump}$ is the minimum required pump operating speed after activating the coolant pump relay.

4. Results and Discussion

This section evaluates the proposed control mechanism for the HEV battery cooling system. The test system is implemented and analyzed using MATLAB/Simulink. The data sources for the HEV battery cooling test system, battery thermal data and temperature profiles come from measurements by thermocouples or infrared sensors embedded in the battery pack.

First, the impact of series-parallel hybrid electric vehicle speed on battery temperature and its cooling system is examined. The effect of vehicle speed on battery charge is also evaluated. In the following, the results of battery temperature control and the power required to cool the battery in the proposed method are presented and compared with those of the conventional method.

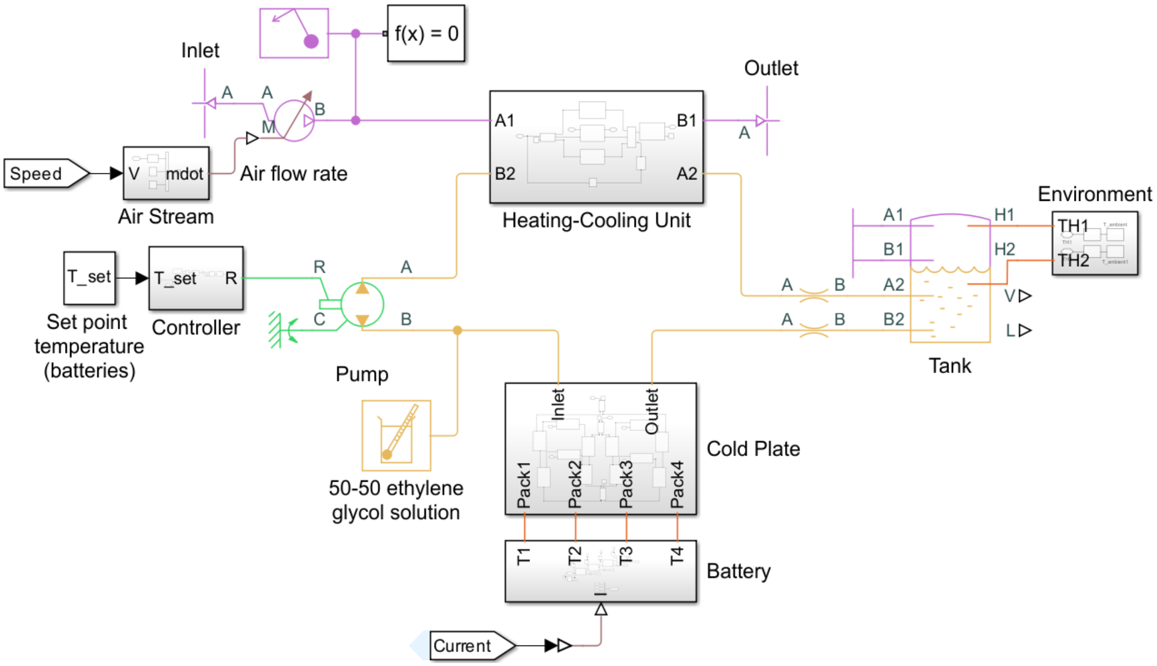


Fig. 2. Control diagram of hybrid electric vehicle battery cooling system

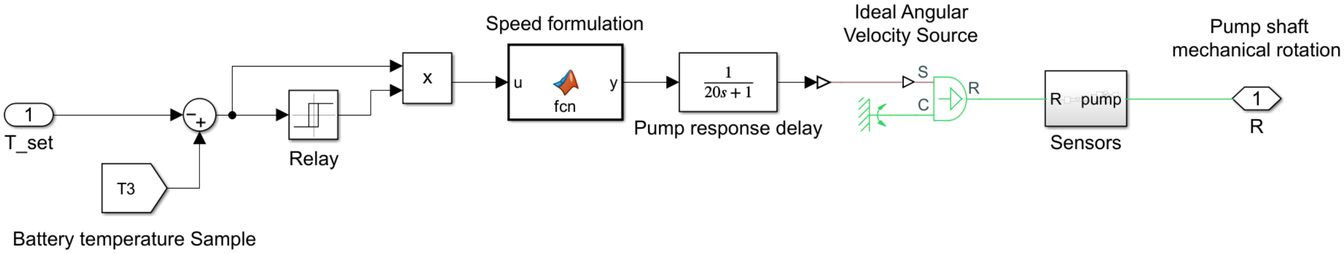


Fig. 3. The proposed battery cooling control method

4.1. Evaluating the Impact of vehicle speed on Battery Charge

Evaluating the impact of vehicle speed on Battery Charge can be examined using Adaptive Cruise Control (ACC). ACC is an advanced driver assistance system that automatically adjusts the vehicle's speed to maintain a safe distance from the car ahead [25]. In many modern systems, the ACC can bring the car to a complete stop in heavy traffic and resume driving once the traffic begins to move again. The changes in cruise control are illustrated in Figure 4. The effect of these changes on vehicle speed is shown in Figure 5. Moreover, the impact of cruise control variations on the battery charge is shown in Figure 6.

As it can be seen in figure 5, the vehicle speed variations are a function of the changes in cruise control and follow a similar trend. Conversely, figure 6 shows that the hybrid vehicle's battery charge follows the opposite trend of the cruise control changes. The observed battery charge fluctuations during speed changes reflect fundamental energy conversion principles in hybrid electric vehicles:

a. Acceleration Phase (Charge Depletion):

- Before the 2-second mark (Figure 6), commanded acceleration triggers:
    - Immediate torque demand from the electric motor
    - Power draw from the battery (discharge) to supplement engine output

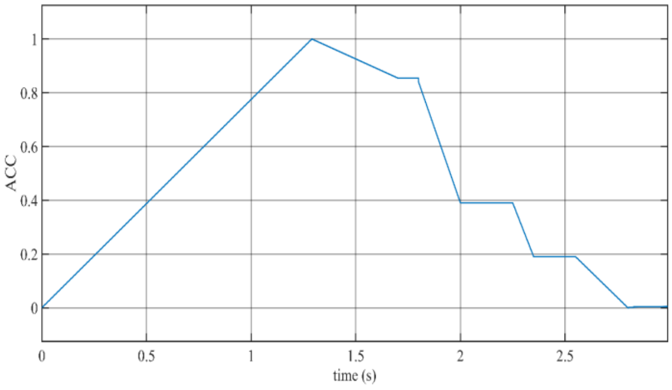


Fig. 4. Cruise control variations

- Batteries exhibit State-of-Charge (SOC) reduction proportional to current draw.

b. Deceleration Phase (Charge Recovery):

- After the 2-second mark (Figure 6), speed reduction activates:
    - Regenerative braking converting kinetic energy to electrical energy
    - Generator mode operation of the electric motor
- *Energy Recovery Mechanism*: The motor becomes a

generator, with back-EMF charging the battery.

c. Control System Interaction:
  - The Energy Management System (EMS) prioritizes discharge during acceleration to maintain driveline power continuity.

The inverse relationship between speed commands and SOC follows from the characteristic of charge-sustaining HEV operation, where the battery acts as an energy buffer rather than primary source. The exact SOC swing magnitude depends on specific drive conditions.

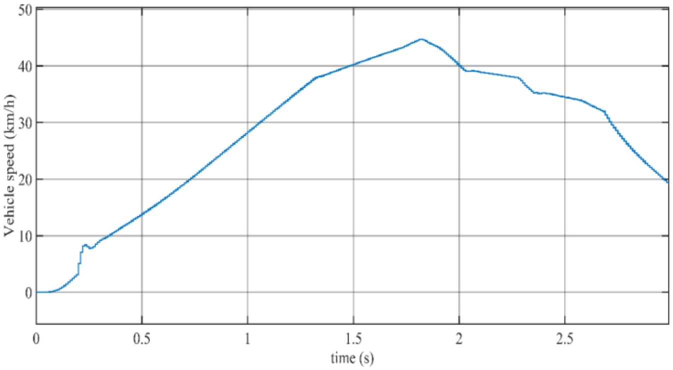


Fig. 5. Impact of cruise control variations on vehicle speed

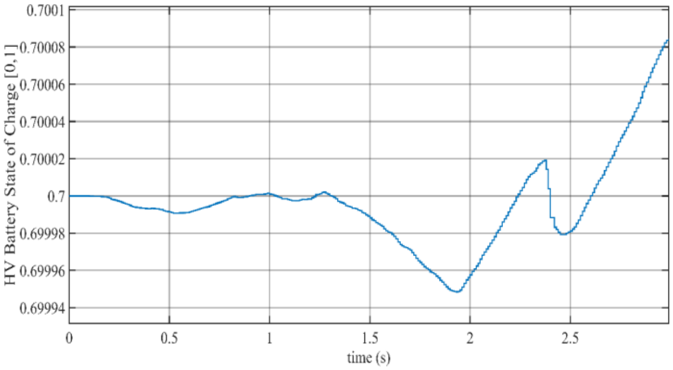


Fig. 6. Impact of cruise control variations on battery charge

4.2. Evaluating the Impact of Speed on Battery Behavior

To examine the impact of vehicle speed on battery temperature and its cooling system, the battery and cooling system assembly was simulated in MATLAB software using the FTP-75 drive cycle (Figure 7). The FTP-75, developed by the U.S. Environmental Protection Agency (EPA), represented a standard urban driving pattern for evaluating emissions and fuel economy in passenger vehicles [26].

First, the system was simulated using conventional fixed-speed cooling pump control. The results (Figures 8a, 9a and 10a) revealed three distinct thermal phases:

a. During the cold start phase (0-505 sec), the battery temperature peaked initially but decreased as the cooling system activated, followed by system deactivation.

b. In steady-state (506-1372 sec) and hot idle (1373-1995 sec) phases, passive thermal behavior dominated as temperatures gradually increased without cooling intervention.

c. The warm start phase (1995-2500 sec) exhibited sudden temperature spikes that triggered cooling system reactivation. As the cooling pump is activated and the cooling power increases, the battery temperature decreases. At the end of this period, the cooling pump is turned off, and the cooling power becomes zero.

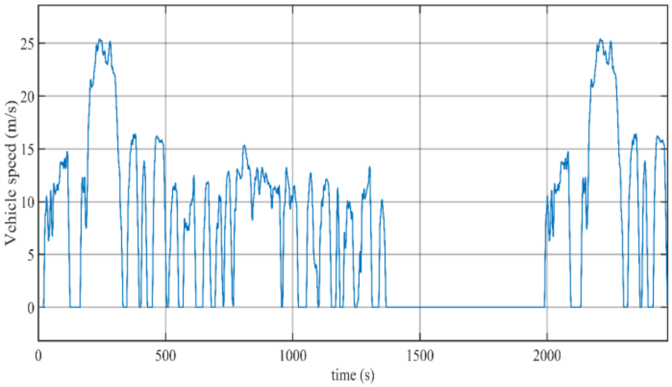
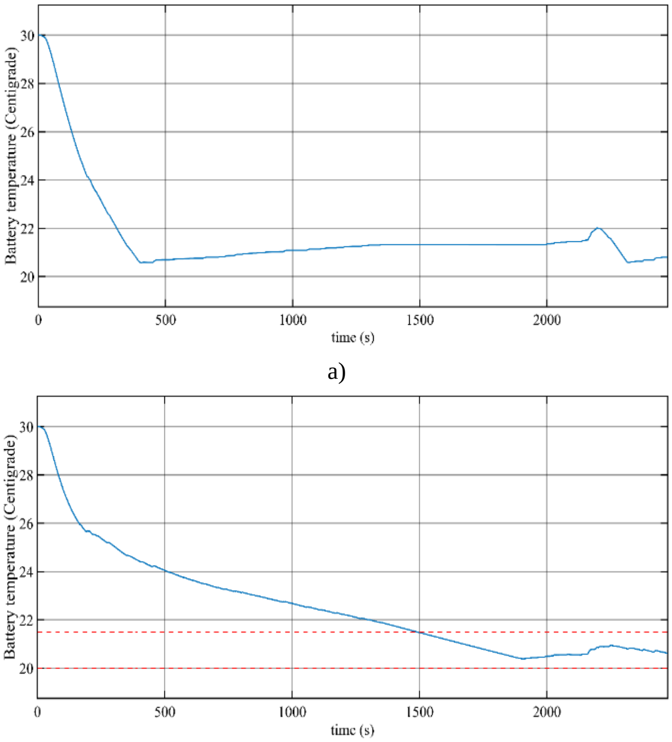


Fig. 7. FTP-75 pattern for vehicle speed variations



a)

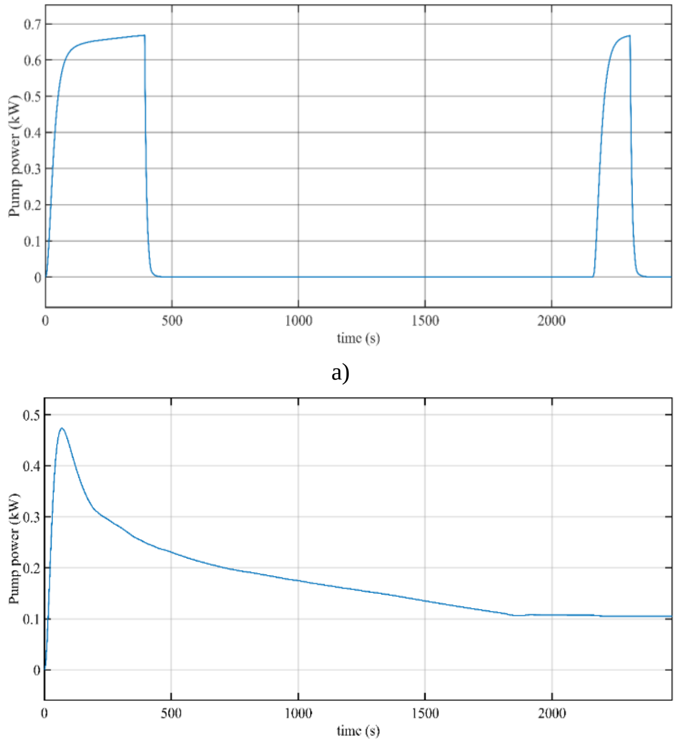
b)

Fig. 8. Battery temperature variation trends due to vehicle speed changes: a) Conventional method and b) Proposed method

Figure 8b shows the changes in battery temperature under FTP-75 drive cycle. As it can be seen, after the cold start of the vehicle at the beginning, where the battery temperature is at its highest level, when the proposed controller is activated, the battery temperature starts to decrease and falls within the allowable temperature range.

Figure 9b shows the cooling pump power in the proposed method. As can be seen in this figure, compared to Figure 9a, the power consumption was reduced by 30%, and the second peak power consumption (in the period of 2200 seconds to 2400 seconds) has been eliminated.

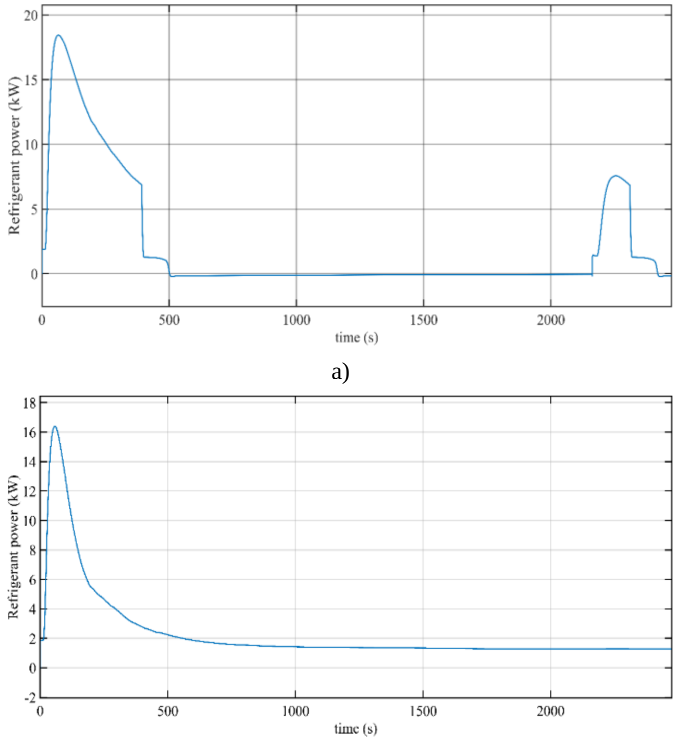
In addition, a comparison of Figures 10a and 10b shows that in the proposed method, the power required for cooling is reduced, and the second peak of cooling power (in the period of 2200 seconds to 2400 seconds) has been eliminated.



a)

b)

Fig. 9. Cooling pump power consumption trends due to vehicle speed changes: a) Conventional method and b) Proposed method



a)

b)

Fig. 10. Cooling power variation trends due to vehicle speed changes: a) Conventional method and b) Proposed method

The proposed adaptive control method demonstrated significant improvements:

- Maintained battery temperature within optimal range throughout all drive phases (Figure 8b)
- Reduced cooling pump power consumption by 30% compared to conventional methods (Figure 9b)
- Eliminated secondary power peaks (2200-2400 sec period) in both pump operation and refrigerant demand (Figures 9b and 10b)

Key Findings:

1. Vehicle acceleration phases (cold/warm starts) produced the most severe thermal challenges
2. Conventional systems wasted energy by maintaining fixed cooling during non-critical periods
3. The temperature-responsive control achieved better stability with lower energy expenditure

Implementation Challenges:

- The control algorithm required precise calibration of temperature thresholds to avoid overshooting
- System responsiveness depended on sensor accuracy and sampling frequency
- Real-world conditions (e.g., ambient temperature variations) were not fully accounted for in the simulation

Study Limitations:

1. The analysis considered only one standardized drive cycle (FTP-75)
2. Battery aging effects on thermal behavior were not modeled
3. The simulation assumed ideal sensor performance and instantaneous actuator response

These results validated the proposed method's effectiveness for reducing energy use in HEV thermal management systems while highlighting areas needing further investigation for practical deployment. The approach showed particular promise for urban driving conditions characterized by frequent stops and acceleration events.

5. Conclusions

This paper evaluated the impact of HEV speed variations on battery cooling system performance through comprehensive modeling and simulation. The study first established the hybrid powertrain architecture, developing mathematical models for all key components including the internal combustion engine, electric motor, battery system, and driver behavior to characterize the relationships between driving dynamics and battery thermal response. MATLAB simulations revealed significant speed-dependent effects on both battery temperature and cooling power consumption, highlighting the need for optimized thermal management. A novel instantaneous temperature-based control strategy was proposed and evaluated against conventional methods using the FTP-75 driving cycle. Comparative analysis demonstrated the proposed system's superior performance, achieving a 30% reduction in cooling power consumption while eliminating peak refrigerant power demands and consistently maintaining battery temperatures within the optimal operational range. These results validate the effectiveness of temperature-responsive control for enhancing HEV battery cooling efficiency under real-world driving conditions.

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