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Intelligent Refrigerant-Based Battery Thermal Management System for EV: A Brief Review

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ABSTRACT

Electric vehicles powered by renewable sources offer promising solutions to address greenhouse gas emissions and environmental pollution. In this context, lithium-ion batteries have emerged as the preferred energy source due to their impressive energy density and durability. However, it's important to note that battery performance is notably influenced by temperature. This is where battery thermal management systems (BTMS) step in. These systems play a crucial role in maintaining the optimal temperature range for battery packs, impacting both their performance and overall safety. The focus of this research is to overcome the limitations of the existing evaporative BTMS, particularly in the realm of electric vehicles. The study involves simulations exploring air cooling, liquid cooling, and phase change refrigerant-based cooling systems individually, all aimed at ensuring battery sustainability under various operational conditions while adhering to the recommended battery temperature of 40ºC or lower. Moreover, an experimental investigation into an evaporative BTMS demonstrates its potential to maintain the desired temperature. On the other hand, the battery management system BMS plays a pivotal role in identifying any defective cells within the battery. This monitoring is essential to detect any variations in cell voltage, temperature, and state of charge. The AI system easily identifies if there is any problem with the cells and warns the EV users about faulty cells. This paper presents an intelligent evaporative battery thermal management system for EVs. It may prolong the battery life; provide security and safety of the battery, and save energy, especially by decreasing the frequency of recharging the battery.

Keywords:

Electric vehicle; cooling system; thermal management system

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1. Introduction

An electric vehicle (EV) comes with a 25kWh battery pack, necessitating major adjustments in DC link voltage to fulfill power demands. Lithium-ion batteries, essential for optimal performance and capacity must be operated within -20°C to 60°C, but they are only efficient within a range of 20°C to 40°C [1-3]. Degradation can occur rapidly at temperatures above 40ºC, affecting performance, capacity, and lifespan. Due to attributes like energy density, absence of memory effect, and longevity, lithium-ion batteries are common in electric and hybrid vehicles [2,4]. However, the rising demands of EV performance pose significant challenges to battery safety. Recent years have seen widespread use of the heat pipe cooling method in battery modules, enabling LiFePO4 batteries to maintain a temperature under 50°C with a heat generation rate of

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less than 30 W [6,7]. A temperature exceeding 30-40°C may cause thermal runaway, leading to potential fire hazards. The development of the AI CAN BUS system for battery thermal management systems (BTMS) has attracted attention from electric vehicle manufacturers. Parameters like the maximum temperature and temperature gradient are vital in assessing the BTMS's heat dissipation performance [7]. Internal cooling of a lithium-ion battery using electrolyte (refrigerant) as coolant can be considered the best cooling system, however, air-cooling systems are sometimes impractical due to stressful conditions, high ambient temperatures, and high charge/discharge rates [9]. Some HEV battery packs, such as those in the Toyota Prius and Honda Insight, still use air cooling. Thermal cooling in batteries ensures extended life and efficiency by managing heat produced from the chemical reactions during power discharge. Micro channel heat sinks are effective for increasing heat removal, but keeping battery cells below 35°C remains a challenge [10]. Current popular methods in EV applications include air cooling, liquid cooling, and fin cooling [11]. Liquid cooling is considered promising but has drawbacks in terms of cost, space utilization, complexity, and potential leakage. A series of stacks embedded with liquid cooling systems are developed to maintain average temperature and uniformity, but they increase pumping power [12]. The performance of EVs and HEVs heavily depends on battery performance, which in turn is influenced by its operating temperature. Thermal management is vital due to high power demands and aggressive charge/discharge profiles [13]. A battery-cooling thermal management system is designed to maintain desirable temperature ranges, prevent exceeding temperature limits, and control temperature variations. Optimization requires delivering an ideal average temperature with uniform distribution [13]. Cooling is essential for lithium-ion batteries to prevent early aging and ensure the desired lifespan. Heat generation during rapid cycles can significantly raise battery temperature, making heat control crucial. Studies have shown that Li-ion battery capacity drops significantly under low temperatures, with a decrease of 17-22% at -20°C. The internal impedance increases as temperature drops, and heat discharging starts between 40°C-72°C and more than 5 times at 80°C-119°C [14]. Research indicates that Li-ion battery capacity falls drastically under low temperatures, while temperatures above 40ºC reduce battery life [15].

DSTATCOM is usually employed in distribution systems to address power quality issues. It plays a crucial role in maintaining the voltage across the Point of Common Coupling (PCC) [7]. It is used to solve voltage sags, surges, and to mitigate current-based power quality issues [9]. It is made up of three major components: a voltage source converter (VSC), a coupling reactor, and a controller [10]. Its performance relies heavily on its controller [11].

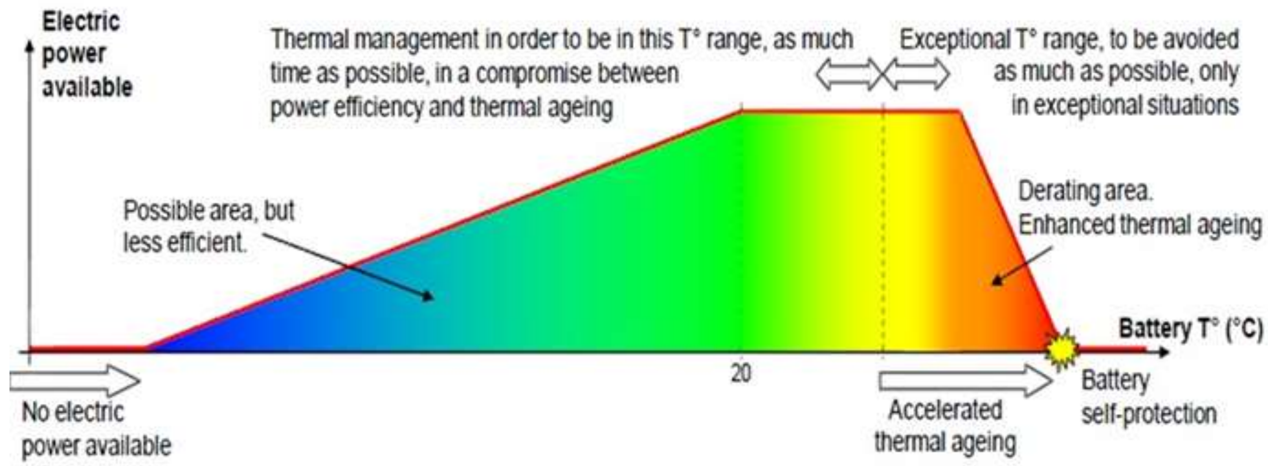


Fig. 1. Temperature range, regarding available performances, efficiency, and thermal ageing [16]

Optimal performance and thermal aging for an EV's LiFePO4 battery pack should occur within a 20°C-40°C range. Battery cell capacity decreases significantly at temperatures below 15°C, while above 40°C affects performance to a lesser extent [5,17]. Low temperatures increase electrolyte density and disrupt ion transitions between electrodes. High temperatures, above 40°C, are more dangerous due to the risk of Thermal Runaway (TRA), causing irreparable damage and safety concerns for vehicle occupants [8]. Figure 1 illustrates the performances, efficiency, and thermal aging of Li-ion batteries [16].

2. Mathematical Model

When a battery cell generates heat, it's then transferred to the surface and eventually dispersed into the surroundings through the process of convection heat transfer. Large molecules' movements create a temperature gradient, contributing to heat transfer. Battery cell heat generation causes heat transfer to the surface area, causing removal or dissipation to surrounding areas as shown in Figure 2.

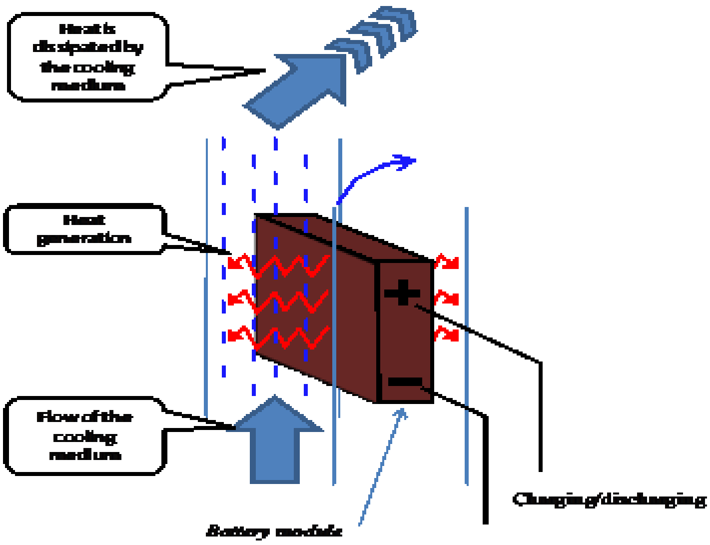


Fig. 2. Diagram of heat generation and dissipation

Total heat rate Qgen generated inside a battery cell due to electrochemical reactions Qelec, polarization resistance Qpolar, and Joule's effects Qjoule can be expressed as follows:

$$Q_{gen} = |I| \cdot \sum_i \frac{-T_{batt}\Delta S_i}{n_i F} + \sum_i I\eta_i + I^2 R \tag{1}$$

Here's the breakdown: *I* stand for the current flow, F is the Faraday constant (which is 9.64122×104 C/mol), and $T_{batt(initial)}$) represents the battery's starting temperature. The ΔSi refers to the change in entropy associated with the electrochemical reaction '*i*'. η_i represents the number of electrons involved in this reaction, and it also considers the total over-potential, accounting for the kinetic aspects and mass transport linked to the electrochemical reaction '*i*'. Lastly, *R* corresponds to the total ohmic series electrical resistance that occurs within the battery. The above overall energy equation used to calculate the average module temperature T_{batt} over time can then be written as:

$$T_{batt(final)} = T_{batt(initial)} + \frac{\Delta t}{mc_p}\left[\left(|I| \cdot \sum_i \frac{-T_{batt(initial)}\Delta S_i}{n_i F} + \sum_i I\eta_i + I^2 R\right)\right] \quad (2)$$

In this study, ΔT , Q_{gen} and Q_{out} are the variable parameters that represent the element of the system being modeled. While $T_{batt(initial)}$ and mc_p are the constant parameters or factors that qualify the variables. Eq 2 can be written as:

$$T_{batt(final)} = T_{batt(initial)} + \frac{\Delta t}{mc_p}\left[\left(|I| \cdot \sum_i \frac{-T_{batt(initial)}\Delta S_i}{n_i F} + \sum_i I\eta_i + I^2 R\right) - h_m A_s\left(T_{batt(iinitial)} - T_\infty\right)\right] \quad (3)$$

In other words, Eq 3, can be defined as:

$$T_{batt(final)} = T_{batt(initial)} + \frac{\Delta t}{mc_p}\left(Q_{gen} - Q_{out}\right) \quad (4)$$

Two important elements of the mathematical model are variable parameters and constant parameters. In this study, ΔT , Q_{gen} and Q_{out} are the variable parameters that represent the element of the system being modeled. While $T_{batt(initial)}$ and mc_p are the constant parameters or factors that qualify the variables.

3. Performance of Cooling System

3.1 Performance of Cooling System: Theoretically

Figure 3 demonstrates battery temperature profiles without cooling, based on discharge current range from 50 A to 350 A. The initial temperature is 30ºC. Low discharge current rates are suitable, but high discharge currents may explode. Effective thermal management systems (BTMS) are essential for high-discharge currents.

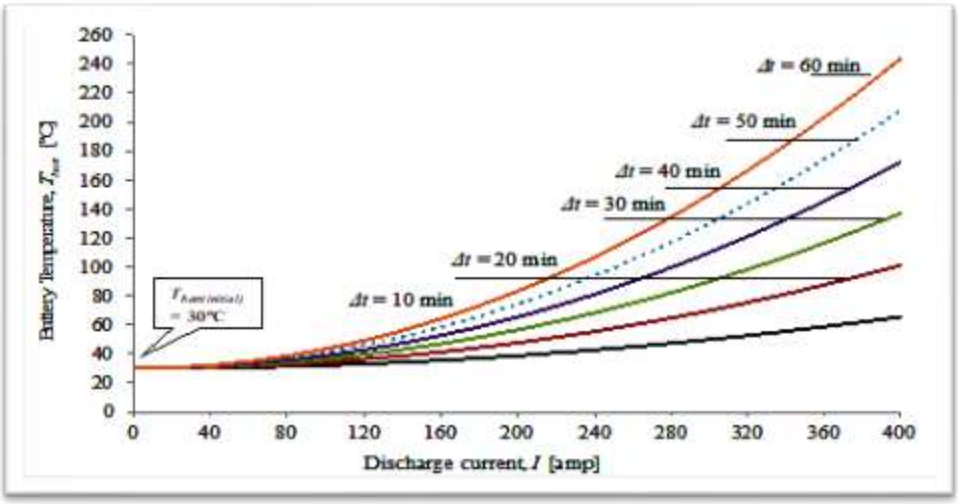
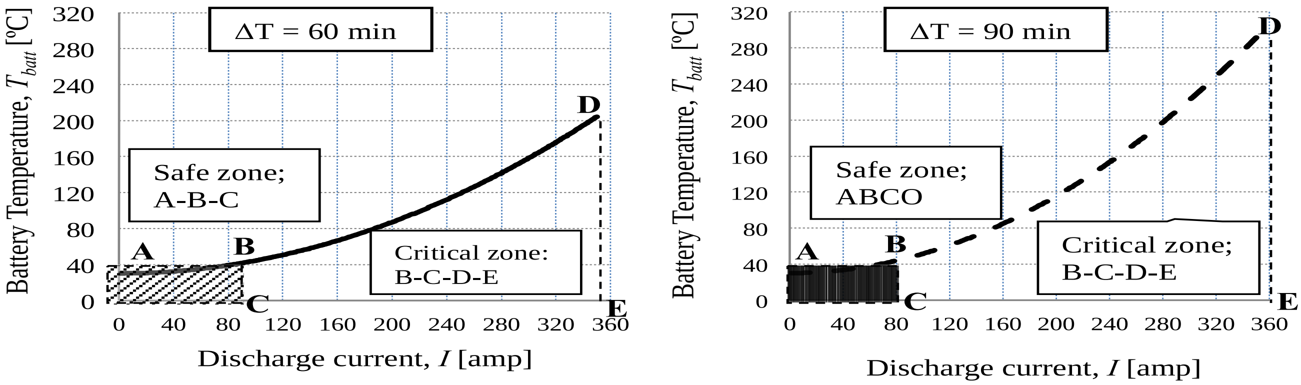


Fig. 3. Battery temperature rises with an increase in discharge current

Figure 4 shows that a vehicle's safe zone requires a maximum discharge current of 90 A for 60 minutes, while the critical zone requires a higher discharge current of 80 A for 90 minutes. A 30 minute difference in operating time results in a 12% reduction in the recommended maximum discharge current. Thermal management is crucial for battery pack completion at high discharge rates, as it prevents the battery from reaching its desired temperature.



(a) (b)

Fig. 4. Comparison of battery temperature rises at various discharge currents for (a) 60 minutes and (b) 90 minutes of operating time

The battery temperature in an electric vehicle (EV) increases with increasing discharge current, causing it to rise over 60°C. To control this, a BTMS was developed to control the temperature range of 20°C – 40°C. A simulation study was conducted to select the most effective cooling system for the EV. The simulation assumed an operating time of 90 minutes, a vehicle traction torque of 280 Nm, and a heat transfer coefficient of 40 W/m2K for air cooling, 200 W/m2K for liquid cooling, and 500 W/m2K for evaporative cooling.

The temperature profiles of a battery pack are analyzed using forced air cooling with a heat transfer coefficient of 40 W/m2K. When cold air is blown into the battery pack the temperature increases until it reaches a steady state condition. When discharge current is drawn between 50 A and 350 A, the peak temperature is 31°C – 37°C, which is within the desired range. However, above 200A or high discharge rates, the temperature increases above the desired operating temperature. The performance of the battery drops significantly above 60°C. Figure 5 shows the temperature profiles of the battery pack as a function of operating time when discharge current 50 A – 350 A.

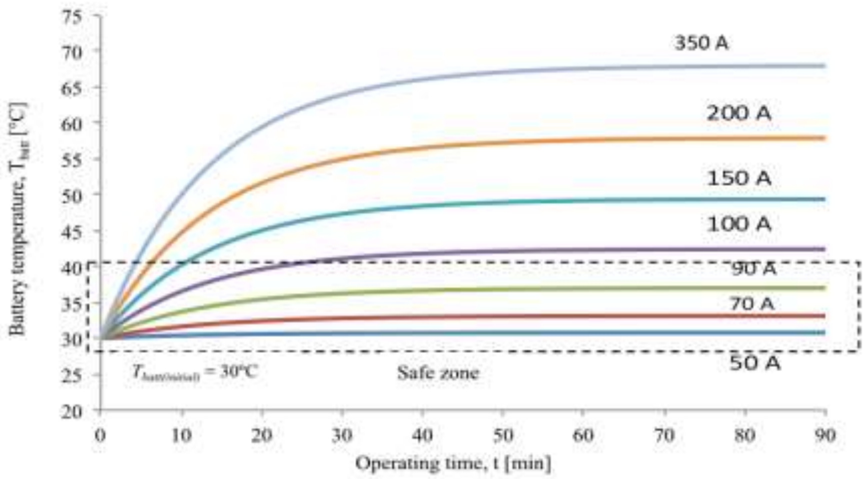


Fig.5. Temperature profiles of the battery pack using air cooling

Liquid cooling, with a heat transfer coefficient of 200 W/m2K, can maintain battery temperature within the desired range of 20°C – 40°C. Water cooling has a higher heat transfer coefficient than air, allowing high heat removal and minimizing non-uniform temperature distribution. However, these results only apply if the cooling operation is continuous throughout the vehicle driving. Continuous electrical energy is required for cooling components, which adds extra workload to the battery. Additionally, liquid cooling systems face leaking problems, which can cause electric short-circuits and potentially lead to a car fire. Fig 6 shows that at 50 A – 150 A of discharge current drawn from the battery.

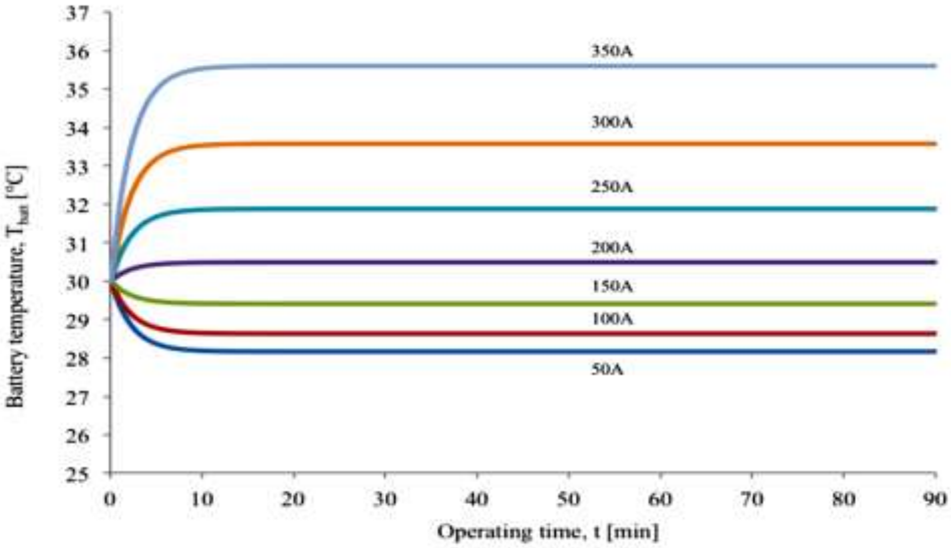


Fig. 6. Temperature profiles of battery modules using liquid (water) cooling

The simulation simulated the effect of a higher heat transfer coefficient on battery module temperature profiles using evaporating cooling. The refrigerant used was 500 W/m2K, achieving a smaller mass heat flux and flow rate. The results showed that evaporative cooling effectively controlled battery temperature within the 20°C – 40°C range. Figure 7 demonstrate the temperature profiles of the battery pack as a function of operating time at different discharge current range from 100A – 350A.

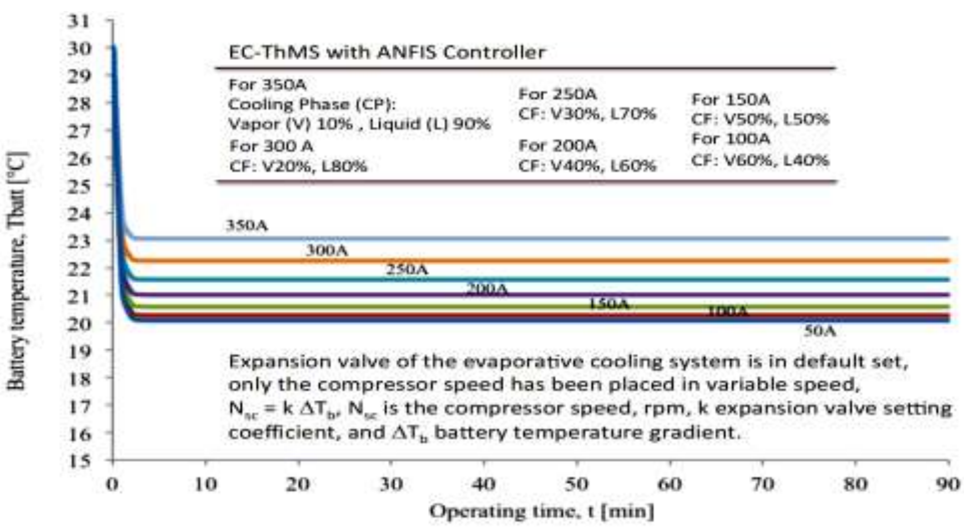


Fig. 7. Temperature profiles of battery modules using evaporative cooling

3.2 Performance of Cooling System: Experimentally

The Electric vehicle operation on the Sepang circuit (SF1) without a cooling system has been simulated and the result presented. The developed EC-BTMS with a fuzzy intelligent controller has been installed on the Proton Saga EV. Its performance has been investigated experimentally on the actual road and Sepang International Circuit (SIC). Figure 8 represents the A 8.6 KWh battery with EBTMS in EV for testing and validation during the experiment.

Fig. 8. Evaporative battery thermal management system

The parameters of the experiments were based on three different running modes. Table 1 simulated battery heat generation in discharge current and speed.

Table 1
Estimation of required vehicle input and output during PGMC 2012

Running mode	Speed, v [km/h]	Operating time, t	Discharge current, Id [A]	Heat generation, Q gen [W]
Quarter mile (402m) acceleration	100< V<120	25 sec	130< I <135	200<Q<400
Shortest time and maximum speed in two laps (11.4 km)	80< V < 120	20 min	130< I <270	500<Q<1600
Farthest distance	50 < V < 60	90 min	65< I < 90	50 <Q<200

3.2.1 Performance comparison

The performance of the electric coaster battery thermal management system EC-BTMS was tested against two other electric vehicles that utilize an air-cooling battery thermal management system: AC-BTMS 1 and AC-BTMS 2. The AC-BTMS 1 system had 8 fans in its battery pack, while AC-BTMS 2 featured 12 fans. For both these systems, cool air from the surroundings is drawn and directed towards the battery modules. Throughout the vehicles' operation, all fans in these systems remain active, blowing air across the battery surfaces. Table 2 reveals that the EV with EC-BTMS saves 17.69% more energy than the one with AC-BTMS 1 and 23% more than the EV with AC-BTMS 2. This efficiency is attributed to the EC-BTMS's capability to maintain the battery pack temperature consistently between 20 and 40°C.

Table 2
Performance of EC-BTMS over the AC-BTMS

Type of BCTMS	Quarter mile acceleration [sec]	The shortest time in to 11.5km [min]	Max velocity (within the shortest time in 11.6KM [Km/h]	Traveling distance for V out [Km]	Comparison of energy saving with EC-BTMS [%]
EV with EC-BTMS	22	17:15	119	68.62	-
EV with AC-BTMS 1	51	26:51:00	119	59.94	17.69
EV with AC-BTMS 2	25	26:19:00	91	57.75	23

3.2.2 Performance interpretation

One of the main successes of the IIUM winning the overall championship in the PROTON GREEN MOBILITY CHALLENGES (PGMC) 2012 was because of the effectiveness of the battery cooling system using the evaporative cooling method. The energy efficiency of the developed Electric Coaster battery thermal management system EC-BTMS was benchmarked against two other EVs employing the air-cooling battery thermal management system (AC-BTMS 1 and AC-BTMS 2). This is due to the potential of the EC-BTMS, which can keep the battery pack's temperature within the range of 20°C and 40°C. Data from Table 3 reveals that the EV equipped with EC-BTMS managed the battery temperature 25% more effectively than the EV with AC-BTMS 1 and 29.2% more than the EV with AC-BTMS 2 during quarter-mile acceleration. Additionally, it showed 21.12% greater efficiency than the EV with AC-BTMS 1 and 25.35% more than the EV with AC-BTMS 2 for maximum distance, which helped the EVs with EC-BTMS to cover a notably longer distance than the other two EVs.

Table 3
Performance analysis of EC-BTMS over two others AC-BTMS (II)

Testing mode	Recorded the highest battery temperature of each type of BCTMS [ºC]			Performance of EC-BTMS over tested EVs [%]	
	EC-BTMS	AC-BTMS 1	AC-BTMS 2	AC-BTMS 1	AC-BTMS 2
Quarter mile acceleration	36	45	46.5	25	29.2
Shortest time in two laps	47	56.5	57	20.21	21.275
Farthest distance	35.5	43	44.5	21.12	25.35

4. Conclusions

A comprehensive review of the thermal management system in terms of battery sustainability shows that an evaporative battery thermal management system (EBTMS) is preferable for an electric vehicle due to its ability to quickly dissipate heat compared to air and liquid cooling systems. However, the operation of EBTMS without intelligent technology is not safe and secure for the batteries' cell's inconsistent discharge and temperature spike. Furthermore, the review shows that intelligent EBTMS has a potential impact on the battery life span by reducing the charging frequency, controlling battery temperature in the range of 20-40ºC, and maintaining consistence cell discharge even in high EV acceleration. This study could be useful for industries, R&D, and graduate students to research optimizing the design of an electric vehicle BTMS.

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