Experimental investigation of batteries thermal management system using water cooling and thermoelectric cooling techniques

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Article Info

ABSTRACT

The booming electric vehicle industry seeks fast charging solutions to address the safety risks posed by high-power charging, including thermal runaway and other safety issues. This study investigates the impact of combining liquid with thermoelectric cooling on battery thermal management. A series of experiments were conducted using various thermal batteries, liquid flow rates and batteries temperature thermoelectric. The experimental results compared air cooling (AC), water cooling (WC) and thermoelectric cooling (TEC) with different water flow (WF) rate in system and revealed that TEC with WF at 4.0 l/min was the best cooling system. This system can decrease the temperature by about 41-52% from the maximum temperature at discharge rates of 1.0, 1.5, 2.0, 2.5, and 3.0 °C. However, TEC with WF 1.0 and 2.0 l/min can effectively lower the temperature and reduce energy consumption compared to other cooling systems, while still maintaining the battery temperature within appropriate ranges.

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1. INTRODUCTION

Global energy trends need push using renewable options instead of fossil fuels [1]–[3]. Environmental effects speed up this change, expecting a rise in renewable electricity [4]. Renewable applications such as electronics, vehicles, and buildings are increasing [5]. Electric and hybrid technologies are gaining global attention as eco-friendly alternatives to traditional cars. Therefore, energy storage from renewables, particularly batteries, is crucial [6], [7]. To address these issues, efficient energy storage solutions are of optimum importance, and lithium-ion (Li-ion) batteries currently dominate the market due to their high energy density.

Lithium ion (Li-ion) batteries have the largest share of the market, accounting for about 45.3% of the cost an electric vehicle (EV) [8], [9]. Li-on batteries offer numerous advantages, including high power density, high energy density, small size, low self-discharge, and long lifespan [10]–[12]. However, overheating during operation is a significant issue for Li-ion batteries, particularly in the context of electric

vehicle (EV) applications [13]–[15]. Maintaining a suitable operating temperature range poses a challenge for battery thermal management systems (BTMS) for Li-ion batteries [16]. BTMS is required for maintain the battery temperature between 20 °C and 40 °C [17], [18]. Therefore, effective BTMS are essential to maintain optimal operating temperatures and ensure extended battery life and performance.

BTMS refer to the technologies and strategies used to regulate and control the temperature of batteries in various applications, such as electric vehicles (EVs), hybrid vehicles, renewable energy storage systems, and portable electronics. BTMS technology is categorized into five main types: i) air cooling (AC), ii) liquid cooling (LC), iii) heat pipe cooling (HPC), iv) phase change material (PCM), and v) thermoelectric cooling (TEC), often combined in various configurations [19], [20]. In related research, in their study, Xu and He [21] introduced a dual U-shaped duct for forced air cooling during a 1C discharge test. The findings demonstrated a notable cooling effect, reducing the maximum temperature by 3.29 °C. Park and Jung [22], a comparison was made between the power consumption of air cooling and liquid cooling types in BTMS. The outcomes indicated significantly higher power usage for air cooling compared to liquid cooling. Karimi *et al.* [23] studied natural convection, forced convection, and liquid-based BTMS scenarios. Tuning inlet coolant temperature improved liquid-based BTMS by about 11.5% (23 °C to 30 °C) at 100 ml per minute flow rate. Behi *et al.* [24] introduced liquid cooling (LC) and liquid cooling with heat pipe (LCHP) BTMS designs for high-current discharges of Li-ion batteries. The findings highlighted improved performance of LC and LCHP compared to natural air-cooling, resulting in temperature reductions of 29.9% and 32.6% respectively within the battery module. Chen *et al.* [25] explored PCM in Li-ion battery BTMS through experiments. PCM absorbed heat during cycles, reducing peak temperature to around 54.4 °C to 12.3 °C lower than natural convection. Zhang *et al.* [10] introduced a dual method employing heat pipes and thermoelectric coolers in a Li-ion BTMS. Results showed heat pipes managed 1 C to 2 C discharge rates, while additional thermoelectric cooling was needed for higher rates. Liu *et al.* [17] investigated BTMS employing TEC through simulations and experiments. The findings indicated TEC's efficacy in cooling batteries during elevated ambient temperatures, both in simulation and actual testing. However, initially, the simulated temperature slightly exceeded the experimental result at the end of discharge, with a maximum temperature difference of 2.6 °C after 10 minutes of testing. Li *et al.* [8] compared forced convection with a combination of TEC and forced convection in BTMS. They demonstrated that the latter, TEC coupled with forced convection, achieved the most effective cooling, reducing battery temperature by 16.44% during a 3.0 C discharge. Lyu *et al.* [26], evaluated thermoelectric cooling (TEC), forced air cooling, and liquid cooling methods for electric vehicle BTMS. The experiments revealed that the combination of TEC and liquid cooling achieved a significant surface temperature reduction of approximately 43 °C (from 55 °C to 12 °C). Behi *et al.* [27] studied fast discharging of lithium titanate oxide EV batteries using air cooling and heat pipes. Results showed temperatures of 56 °C, 46.3 °C, and 38.3 °C with natural convection, heat pipe, and combined cooling, respectively—reducing temperatures by about 17.3% (heat pipe) and 31% (combined) compared to natural convection. Alaoui *et al.* [28] presented a solid-state hybrid BTMS with Peltier heat pumps, sinks, spreaders, and fans. Tests across -20 °C to 40 °C showed it effectively maintained 0 to 25 °C ambient temperatures. Zhang *et al.* [29] explored liquid effects on heat dissipation in lithium-ion BTMS via simulations varying inlet size, flow rate, and temperature. Ideal conditions were identified as 10 mm diameter, 0.02 m/s flow, and 298 K temperature.

However, the previously discussed methods have distinct limitations. For example, techniques like air-cooling, while straightforward, fall short of meeting cooling demands due to limited heat dissipation efficiency. HPC technology is still in research stages due to its complexity and higher costs than other cooling methods. PCM, renowned for energy efficiency, entail intricate structures and demanding manufacturing. In contrast, liquid cooling utilizes water to lower battery temperatures. The strategic fusion of liquid cooling and thermoelectric cooling, commonly used in air conditioning [30], [31], electronic device [32], medical science [33], as well as agricultural applications [34]. Moreover, Abirami *et al.* [35] proposed to create a solar-powered device converting atmospheric moisture into drinkable water, with potential large-scale use and the idea of revolutionizing cooling engineering using low-power thermoelectric cooling devices.

This study presents an experiment investigating a BTMS that combines water cooling and thermoelectric cooling techniques to address Li-ion battery overheating during high discharge rates (1.0 C to 3.0 C). The BTMS utilizes a DC pump for variable water flow rates, ensuring precise temperature control. The study's primary goals are to assess the performance of this cooling system in maintaining batteries within the optimal operating temperature range and to evaluate its efficiency across different discharge rates. The outcomes will provide valuable insights for developing practical BTMS solutions in electric vehicle applications.

The rest of this paper is organized as: i) Section 2 provides a comprehensive review of related literature and state-of-the-art BTMS technologies; ii) Section 3 details the experimental setup and test

scenarios used in the investigation, iii) Section 4 presents the results and discussion, offering a critical analysis of the cooling system's performance; and iv) Section 5 presents the conclusions drawn from this study and outlines potential future research directions for battery thermal management in electric vehicles.

2. METHODOLOGY AND TEST SCENARIOS

2.1. Battery thermal management system (BTMS)

BTMS is the device responsible for managing/dissipating the heat generated during battery's chemical processes occurring in cells, allowing the battery to operate safely and efficiently. The BTMS aims to maintain ideal temperature conditions, preventing rapid battery degradation caused by excess heat from its components. This ensures continuous and optimal battery performance.

There are numerous battery thermal models, and most research [10], [17], [23], [27], the temperature behavior of batteries is described within the discharge range of 1.0 C to 3.0 C, which is suitable for investigation. This range indicates a relatively low discharge rate where the heat generated and exchanged is not excessively high, making it suitable for in-depth investigation and analysis. In the experiments, the cartridge heater was used as a model for the battery heat generation, as it potentially exhibited similar behavior to thermal batteries. The heater was prepared to cover the thermal behavior of a real battery, specifically the 18650 Li-ion battery.

2.2. Experimental set up

A schematic diagram of the battery thermal cooling system, utilizing water cooling and thermoelectric cooling with different water flow rates techniques, is shown in Figure 1(a). The system can be divided into four parts: i) An adjustable heater, serving as a substitute for a thermal battery (heating element single-ended 1×12.6 cm^2 cartridge heater AC 220 V 300 W electricity generation), ii) The water cooling system (25 °C, with flow rates of 0.2, 0.4, 0.6, 1.0, 2.0 and 4.0 l/min), iii) The thermoelectric cooling system (TEC) model type TEC1-12715, size 50×50 mm^2 with internal resistance ranging from 0.72 to 0.98 ohms, and iv) a thermocouple (type K, with an accuracy of $\pm$ 1.5 °C) used for temperature measurement. The experimental devices and instruments were set up in the laboratory as shown in Figure 1(b), with the ambient temperature maintained at 25 $\pm$ 2 °C. The cooling systems, including air cooling, water cooling, and thermoelectric cooling with different water flow rates, were compared. All particular tests were conducted under various charge and discharge rates conditions.
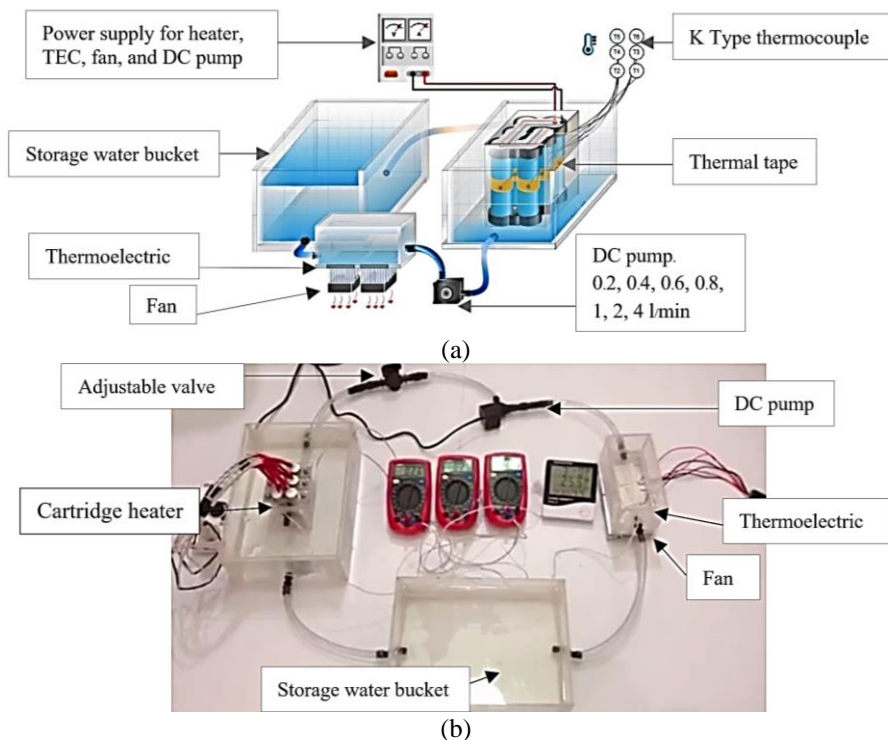

(a)

(b)

Figure 1. Shows elements used for experiment test set-ups (a) schematic of experiment setup and (b) photograph of setup

2.3. Cooling system mode

Cooling systems used as heat exchangers were categorized into three types: air cooling (AC), water cooling (WC), and thermoelectric cooling combined with a water flow rate system (TEC+WF):

a) Air cooling (AC): In this system, the air directly sourced from the atmosphere was utilized for dissipating heat from the battery.

b) Water cooling (WC): Water, chosen for its safety and low cost, was employed as the medium for heat exchange between the heater and cooling system. Water was at 20 °C ± 2 °C for each testing.

c) Thermoelectric cooling TEC and water flow rate system (WF): This system involved the use of thermoelectric cooling in combination with a water flow rate system.

Thermoelectric cooling (TEC) utilizes the Peltier effect as its main working principle. When an electric current is applied, it generates a temperature difference between the hot and cold sides of the device. The cold ends of a thermoelectric module in this study provided a temperature of 20 °C ± 2 °C (they should be stored between 20 °C and 25 °C to avoid dramatic reduction in operating lifetime) [36], [37] and water was circulated through the system.

Water flow (WF) was facilitated by a brushless DC pump. The pump (model TL-B03, 5.16 W 12 V_{DC}, Max flow 6.5 l/min) was installed within the cooling system's flow loop. It enabled the generation of water flow rates ranging from 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, and 4.0 l/min.

2.4. Experimental test scenarios

The experimental test rig was set up and tested to obtain results for comparing the temperature of heater at discharge C rates of 1.0, 1.5, 2.0, 2.5, and 3.0 C. The test scenarios are divided in to three parts as:

a) Temperature characteristic curve of the heater for each particular testing cooling mode under different C rates testing conditions.

b) Average temperature characteristic curves of the heater for each particular testing cooling mode under different discharge C rates testing conditions.

c) Normalized values of the heater temperature with each particular cooling modes (AC, WC, and TEC with WF) under different discharge C rates testing conditions.

3.   RESULTS AND DISCUSSION

The results are organized as follow: the measured temperature surface is reported for each cartridge heater under each particular testing C rate level and different cooling modes. The average surface temperature (T_s) of each heater surface is recorded for different testing C rate conditions. Additionally, the normalized values of the temperature surface for particular testing mode condition are also documented.

3.1. Experimental results of the AC, WC, and TEC with different water flow rates under different C rate of a battery conditions

Table 1 shows the temperature readings of six heaters under different cooling modes: AC, WC, and TEC with water flow rates of 0.2 l/min. Table 2 shows TEC with water flow rates 0.4, 0.6, 0.8 l/min. Table 3 shows TEC with water flow rates 1.0, 2.0 and 4.0 l/min. It can be observed each TEC with water flow that the temperature of the first row, which received cooling water at 20 °C as shown in Figure 1, was slightly lower than the temperatures of the other rows. In the TEC cooling mode, with a water flow rate of 4.0 l/min, the temperature of each heater increased at a slower rate compared to the AC and WC cooling modes. This was attributed to the accelerated water flow rates facilitated by TEC, which improved the heat dissipation capacity for all the heaters. However, TEC combined with water flow rates of 1.0, 2.0, and 4.0 l/min demonstrated the ability to effectively dissipate heat for all battery discharge rate conditions, as depicted in Table 1. Similarly, Table 2 shows the temperature readings for TEC combined with water flow rates of 0.4, 0.6, and 0.8 l/min, and 1.0, 2.0, and 4.0 l/min in Table 3.

3.2. The measured average of each surface temperature T_{avg} of heater under different testing C rate conditions

Previously in 3.1 presents the surface temperature for 6 cartridge heaters. For this part presents the average of each surface temperature. Figure 2 displays the measured average surface temperature T_{avg} of the heater under different discharge rate conditions: 1.0, 1.5, 2.0, 2.5, and 3.0 C respectively. The cooling models AC, WC, and TEC with water flow rates of 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, and 4.0 l/min were applied. Figures 2(a)-(e) correspond to the respective discharge rates mentioned above. The results demonstrate that both WC and TEC, at all water flow rates, achieved lower T_s values compared to AC. WC consistently provide approximately 14 °C lower T_s compared to AC across all tested discharge rates. TEC with a water

flow WF rate of 4 l/min exhibited the lowest T_s among all tested discharge C rate levels, reducing T_s by approximately 35.25 ºC at the maximum temperature point.

Table 1. The temperature of 6 heaters with different cooling modes: AC WC and TEC with various water flow rates (WF) at 0.2 l/min
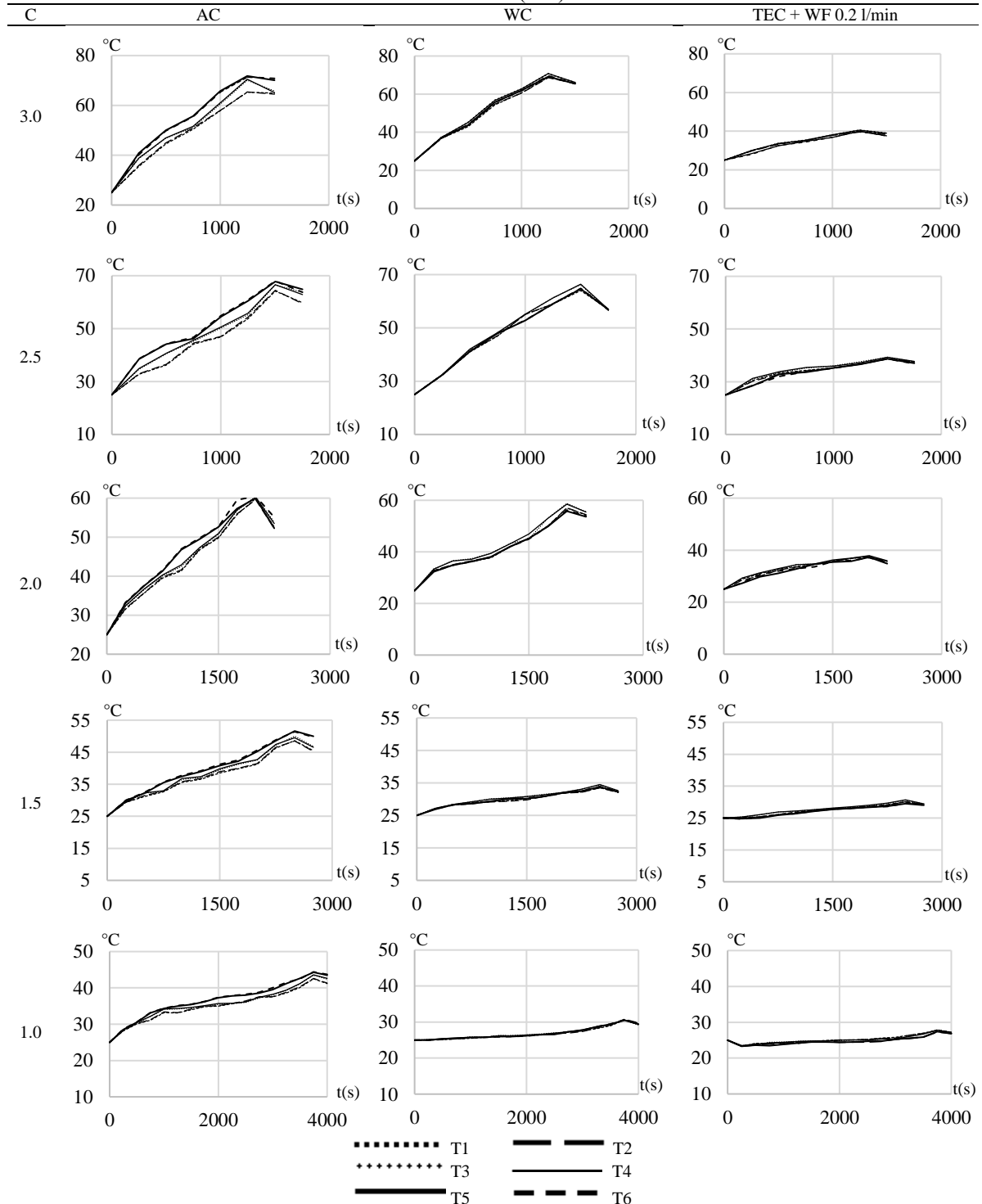
Table 2. The temperature of 6 heaters under TEC+WF at 0.4 0.6 and 0.8 l/min at different testing C rate
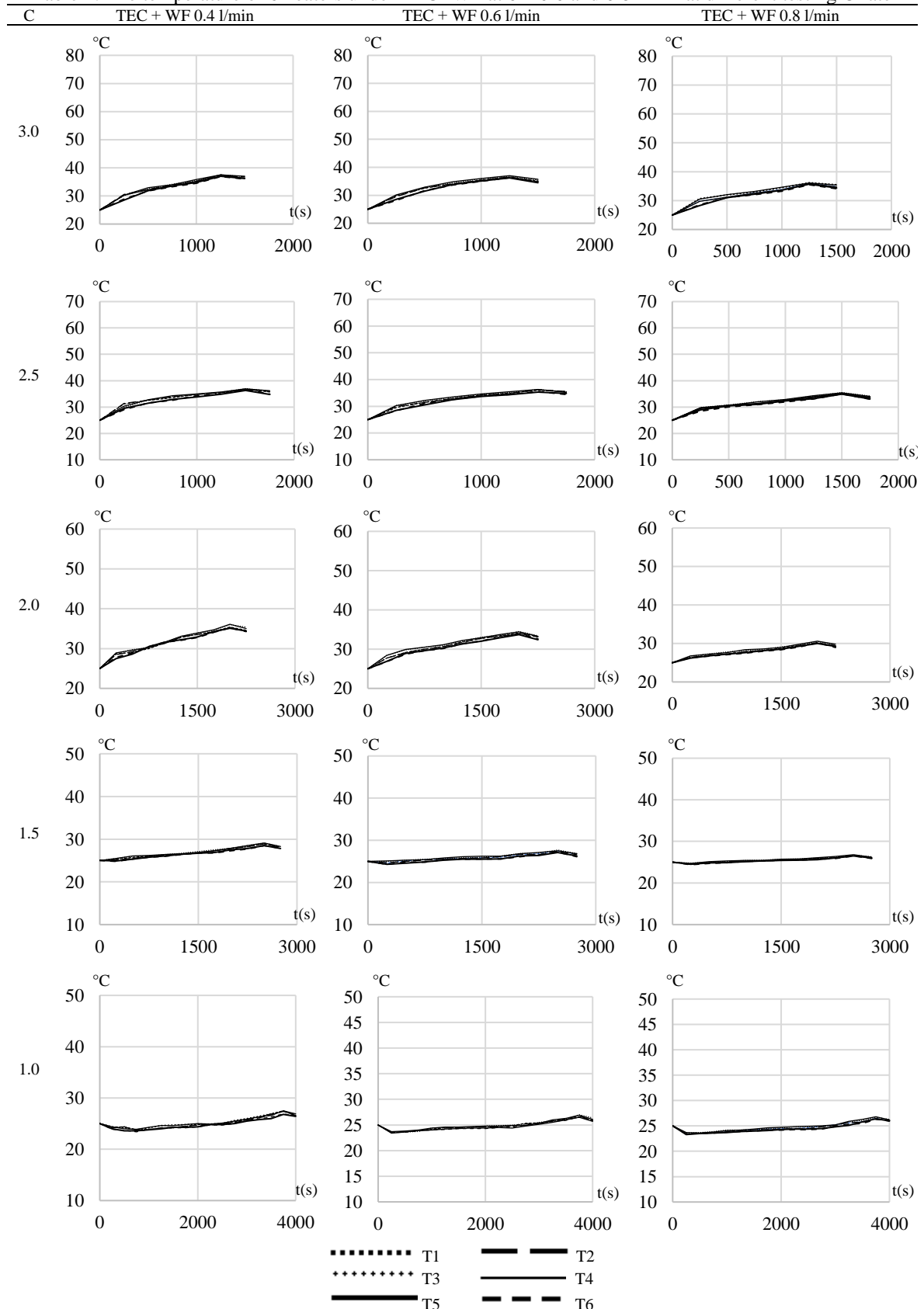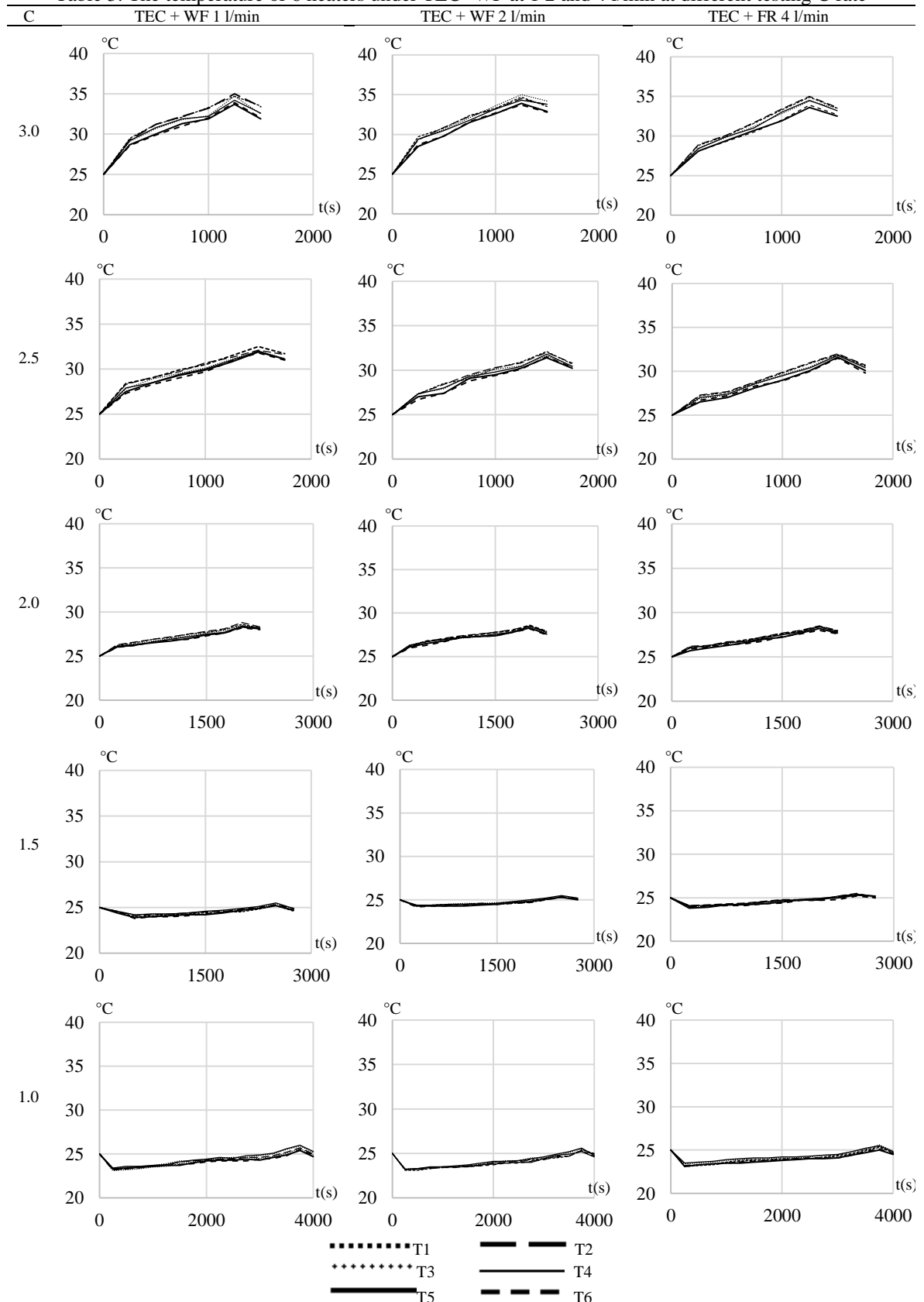
C	TEC + WF 0.4 l/min	TEC + WF 0.6 l/min	TEC + WF 0.8 l/min

Legend: T1 (dotted), T2 (thick dashed), T3 (plus markers), T4 (thin solid), T5 (thick solid), T6 (dashed)

Table 3. The temperature of 6 heaters under TEC+WF at 1 2 and 4 l/min at different testing C rate

C	TEC + WF 1 l/min	TEC + WF 2 l/min	TEC + FR 4 l/min
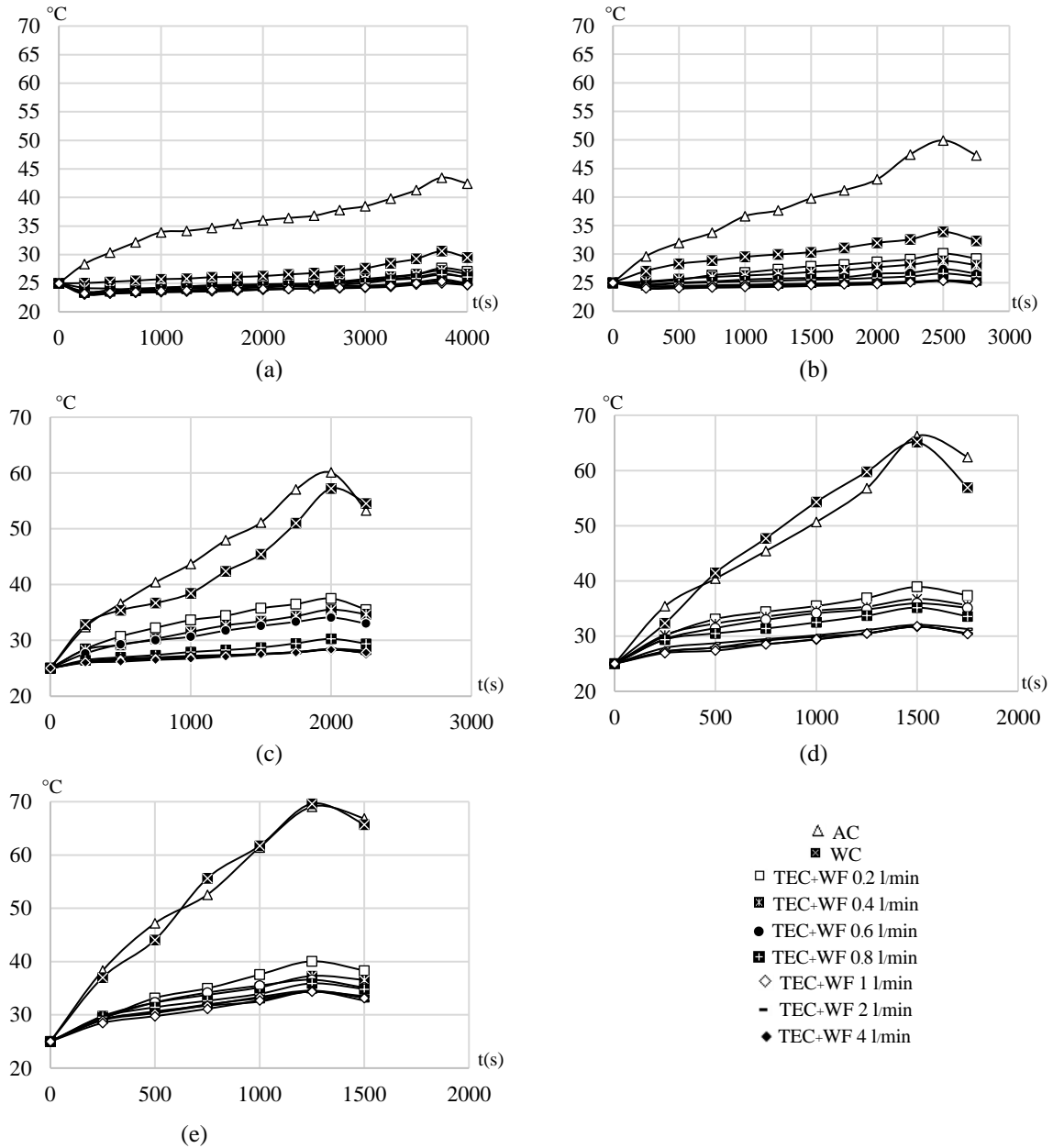
Figure 2. Average temperature of 6 heater at different rates of battery (a) 1.0 C, (b) 1.5 C, (c) 2.0 C,
(d) 2.5 C, and (e) 3.0 C. Case: AC, WC, and TEC +WF at 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, and 4.0 l/min

3.3. The normalized values of average surface temperature heater under different testing C rate conditions

Previously part presents the average of each surface temperature for all testing C rate condition. The explanation would be clearly shown in Figures 3(a)-(e) for testing 1.0, 1.5, 2.0, 2.5, and 3.0 respectively in term of normalized values. The maximum reduces surface temperature of heater about from ~49%, ~52%, ~51%, ~47%, and ~41% respectively for all testing C rate condition. For case TEC+WF at 4.0 l/min could reduce maximum surface temperature about ~52%, for testing at discharge rate 2.0 C.

The combination of liquid cooling and thermoelectric cooling for battery thermal management offers advantages such as high heat transfer coefficient, large heat capacity, and faster cooling rate. However, there are limitations to consider, including increased complexity, potential energy efficiencies, and size/weight of system challenges, presented Table 4 overcoming these limitations will be crucial for the practical implementation and widespread adoption of this proposed method.
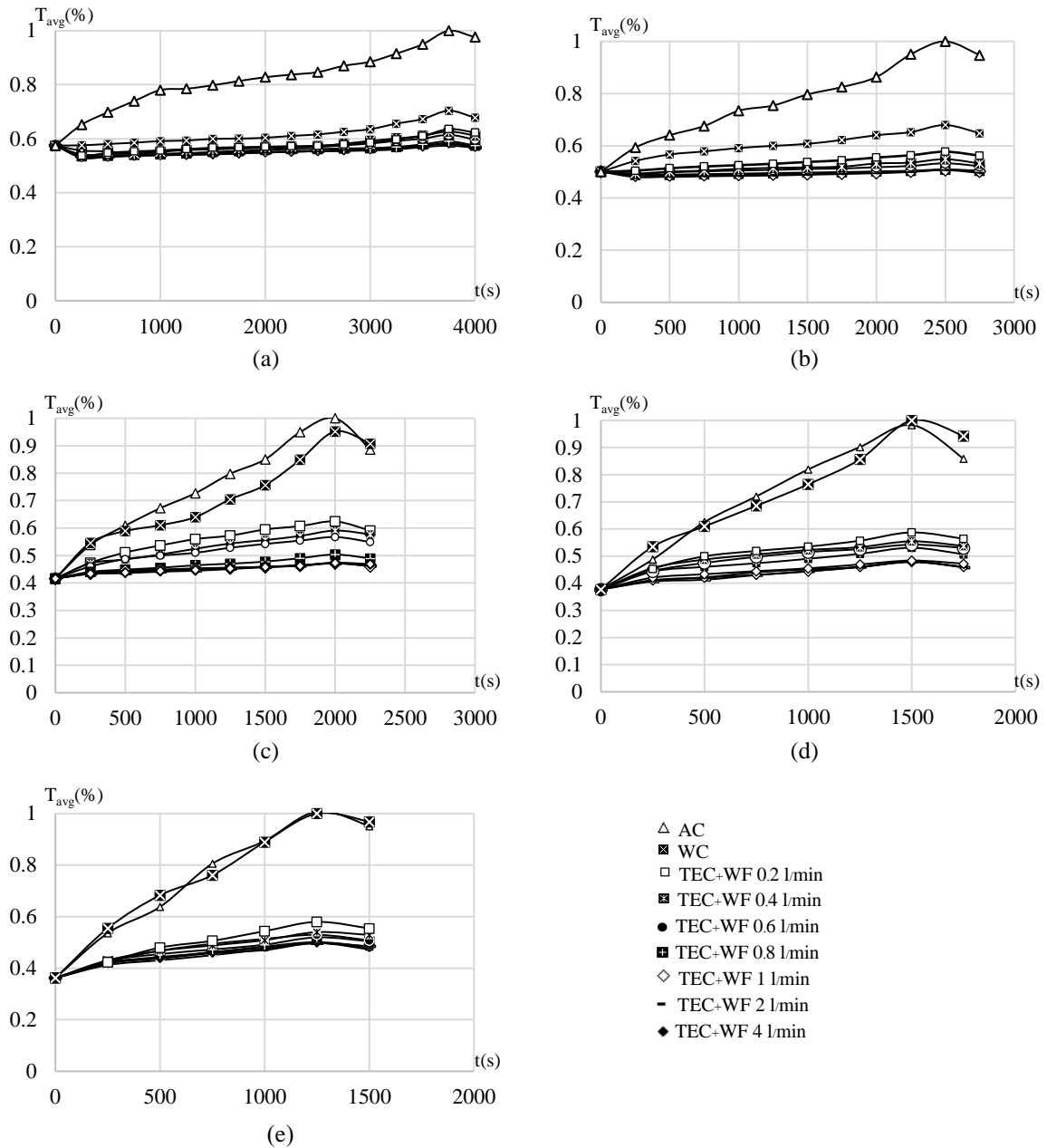
Figure 3. Normalized average temperature value at different rate of battery (a.)1.0 C, (b.) 1.5 C, (c.) 2.0 C (d.) 2.5 C and (e.) 3.0 C. Case: AC, WC, and TEC +WF at 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, and 4.0 l/min

Table 4. Advantages and disadvantage of different cooling systems for battery thermal management system

Ref.	Cooling system	Costs	Reliability	Complexity	Weight	Energy consumption	Cooling capacity
[38], [39]	Refrigerant	High	Low	High	Medium	High	High
[40], [41]	Phase change material	Very high	Very low	Low	Heavy	None	Small
[42], [43]	Air force convection	Low	High	High	Light	Low	Very small
[44], [45]	Heat pipe (HP)	High	High	Very high	Light	None	Medium
[46], [47]	Liquid	Medium	Medium	High	Medium	Medium	High
[48]	HP + air	High	High	Medium	Light	Low	High
[49]	HP + liquid	Very high	Medium	Complex	Medium	Medium	Very high
[50], [51]	Thermoelectric (TEC)	High	High	Medium	Light	Medium	Medium
[52], [53]	TEC + air	High	Medium	Medium	Light	High	Medium
[54]	TEC + air + liquid	Very high	High	Complex	Heavy	Very high	Very high
This paper	TEC + air + water flow rate	High	High	Medium	Heavy	Very high	Very high

The overall testing of the proposed BTMS. Air, water and different water flow rates techniques were compared under different testing discharge C rate condition. TEC keep constant inlet water temperature. For case TEC + WF at 2 l/min could maximum reduce surface of heater. However, it adds significant weight and complexity to the cooling system.

4.   CONCLUSION

In this study, the BTMS of an 18650-type battery was simulated using six temperature heaters. The dissipation rates of batteries were compared among AC, WC, and TEC with different water flow rate (WF) in the cooling system. The temperature behavior and distribution in the different battery modules at various discharge rates were investigated through experiments. The experimental results showed that BTMS with, especially with the highest WF rates, provided the most significant dissipation effect. The dissipation rates reached, 49%, 52%, 51%, 47%, and 41% at the 1.0 C, 1.5 C, 2.0 C, 2.5 C, and 3.0 C discharge rate respectively, effectively maintaining the temperature of the heater. This positive effect on battery temperature contributed to an extended battery life.

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