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Research paper

Electric vehicle battery thermal management system with thermoelectric cooling

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ABSTRACT

An experimental investigation is performed on an advanced battery thermal management system for emerging electric vehicles. The developed battery thermal management system is a combination of thermoelectric cooling, forced air cooling, and liquid cooling. The liquid coolant has indirect contact with the battery and acts as the medium to remove the heat generated from the battery during operation. Forced air assisted heat removal is performed from the condenser side of the thermoelectric liquid casing. Detailed experiments are carried out on a simulated electric vehicle battery system. Experimental results reveal a promising cooling effect with a reasonable amount of power dissipation. Moreover, the experimental test shows that the battery surface temperature drops around 43 °C (from 55 °C to 12 °C) using TEC-based water cooling system for a single cell with copper holder when 40 V is supplied to the heater and 12 V to the TEC module.

1. Introduction

Limited reserve volume, imbalance distribution, and the increasing energy demand contribute a significant amount to the growing number of renewable substitutes to replace the fossil fuel based energy resources. Moreover, environmental impacts brought by traditional energy structures accelerated this transition process. A study predicted that, by 2035, the electricity amount generated by renewable sources would be 2.7 times larger than in 2010 (Ellabban et al., 2014). Renewable energy based applications, such as consumer electronics, vehicles, and even buildings, are emerging as the world turns 'green' (Srinivas and Reddy, 2014; Shukla et al., 2016). Electric vehicle and hybrid electric vehicle (EV/HEV) technology, as a green substitute for conventional combustion vehicles, has attracted a significant amount of attention globally and are quickly replacing internal combustion engine-powered vehicles.

Batteries play an increasingly critical role in renewable energy usage and storage. As an example, the performance of EVs and HEVs are highly dependent on battery capacity. Battery thermal management systems (BTMS') are developed to monitor and optimize the thermal status of batteries. The battery temperature is a critical factor for battery operating performance. Specifically, the charge/discharge capacity can be strongly influenced by temperature. This availability will further impact the performance of applications. For instance, the discharge rate will determine the acceleration process of electric and hybrid electric vehicles. The lifespan of batteries also greatly depends on the operating temperature. Under normal operating conditions, of say −30 °C to 60 °C, the battery health varies significantly from the optimal battery temperature range. However, studies suggest that working at above 50 °C can be harmful to the lifespan of batteries (Bandhauer et al., 2011). "Further studies indicated that a temperature range from 25 °C to 40 °C (a maximum 5 °C difference from this temperature range) provides the best working environment for batteries such as lead–acid, NiMH, and Li-ion (Pesaran, 2002)".

Efficient temperature management systems contribute significantly to battery health and extend the overall lifespan. Moreover, as the capacity and charge/discharge rate increase, battery security issues need more attention. Subsequently, various BTMS' has been developed to meet the demand for higher power, faster charge rates, and improved driving performance. Modern BTMS' are divided into two groups: active systems and passive systems (Rao and Wang, 2011). Passive BTMS generally employ phase change materials, heat pipes, and hydrogels. Zero extra power consumption is the most prominent feature of these systems. However, the cooling process is difficult to manage. Conversely, traditional active methods generally lead to forced circulation and circulation of specific cooling materials and substances such as water and air. The main issue is that the cooling effect can be very limited under certain circumstances. Thermoelectric power generation devices for vehicles have been developed for years (Liu et al., 2014a). In contrast, thermoelectric coolers (TEC)

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which employed by battery thermal management are a comparatively new candidate for electric vehicles. These benefit from strong cooling capacities and reliable working potential, and have attracted increasingly more attention for integration into BTMS.

Thermoelectric coolers (TEC) are based on the conversion of voltage to the temperature difference. This Peltier–Seebeck effect together with Thompson effect belongs to the thermoelectric effect. The thermoelectric effect refers to all of the transformation processes from heat to electricity, and vice versa. The main advantages of thermoelectric coolers are relatively quiet, stable, and reliable. Furthermore, the temperature can be easily controlled by varying the voltage supply. These technologies have been used in medical and instrumentation applications (Zhao and Tan, 2014) for years; however, for battery thermal management applications, the history is limited. In practical applications, batteries may be operated in either hot or cold ambient temperature. TEC modules can be used for both heating and cooling scenarios. The 'hot end' has heat dissipated and absorbed by the 'cold end'.

"Literature shows that the use of TEC for BTMS is inadequate due to the low thermal efficiency, novelty of the application of TEC. Starting from 2003, researchers have been considering TEC for better BTMS; however, only few literature has been came forward as reference. Siddique et al. (2018) presented a comprehensive literature survey on TEC based BTMS from 2003 to 2018. Most of the studies take air as the medium of heat transportation from the cold end to the battery. Alaoui et al. (Alaoui and Salameh, 2003, 2005) studied thermoelectric cooling for electric vehicle application in the early 21st century. Cold sides of the thermoelectric coolers are connected to the heat sink in these designs and maximum temperature was kept below 55 °C. The cold air was blown into the battery pack and cabin for cooling. Esfahanian et al. (2013) incorporated a heatsink-fan set for both the cold side cooling and the hot side heat dissipation. In another study, Kim et al. (2014) replaced the hot side design by water cooling for improved performance. Moreover, the cold side can also be attached directly to the battery surface. Similarly, air (Alaoui, 2013) and water (Liu et al., 2014b) are potential candidates to remove heat from the hot end. All these designs have shown the excellence of the TEC module used in battery thermal management. Still, the system performance needs to be continuously improved to meet the demand of the increasingly higher heat generation amount. In one study, it was reported that COP of the BTMS decreases gradually with increasing power supply to the TEC (Maral et al., 2017) and the maximum temperature of the battery was less than 36.2 °C. In another work, Zhang et al. (2018) concentrated on the structure of the TEC embedded BTMS system where they also used control unit for optimize the performance of the system. More recently in 2019, Li et al. (2019) presented a similar TEC based BTMS using direct cooling including temperature controller without any coolant or media".

This study focuses on the thermal management of batteries in the state of the art electric vehicles and proposes an advanced hybrid BTMS design. For the first time battery shells (i.e., copper holders) are used to protect the batteries from direct contact with the coolant and environmental friendly solid-state thermoelectric cooler (i.e., TEC) is used as a source of cooling medium which can be used as both heating and cooling purposes depending on the surrounding environmental conditions just by switching the current polarity. Moreover, no similar experimental work has been reported in the literature that deals with TEC-liquid based battery thermal management systems. This new BTMS design is a combination of TEC with forced air cooling and liquid cooling in which the liquid coolant works as the medium to remove heat from batteries. The experimental design, setup, and preliminary results are found in the following sections.

2. Experiment setup

A new design based on the combination of forced air cooling, liquid cooling, and TEC is investigated here. The battery is placed vertically in the center of the coolant container. Flowing liquid takes away a considerable amount of heat generated by the battery during operation. A water pump is used to drive liquid circulation. The TEC is used to manage the temperature of the coolant afterward. Lastly, the hot end of the TEC will be cooled by the heat sink and fan attached to it.

2.1. Components

The detailed specifications of each system component are as followings.

(1) *TEC module*

Thermoelectric cooler (TEC) refers to a solid-state semiconductor device which is noise free, environmentally friendly, and operational and maintenance cost-free, and. Basically, a single unit of TEC consists of an n-type and p-type TE legs where TE legs are connected electrically in series and thermally in parallel. TEC requires less voltage and current compared to typical refrigerator. Therefore, the performance depends on the power supply to TEC. Moreover, the power density required by the traditional refrigeration system is much lower than TEC due to its small size compared to typical refrigeration and power requirement. In addition, the maximum thermal efficiency of TEC is less than 10% (Liu et al., 2014b). However, this low thermal efficiency can be useful for many small applications specially where there is a waste of heat energy or access heat needs to be managed of the system without interfering the main system performance. Therefore, TEC can be a suitable candidate for battery thermal management system of the electric/hybrid vehicles. The design of the TEC module is a combination of the heat sink, forced air cooling, and liquid cooling (see Fig. 1). This design adopts two TECs connect in serial to cool down the fluid flow. Each of them has 127 couples between two ceramic plates in the sandwiched structure. With a rated voltage at 12 V, this TEC can tolerate maximum temperature difference up to 68 °C. The heat amount passed from the cold side and generated internal the TECs is quite large. Accordingly, an aluminum heat sink is placed on the hot end of the TEC modules to remove the heat timely from the TEC. Moreover, two fans are installed on the other side of this aluminum heat sink to accelerate the heat dissipation to the ambient. The rated power supply of DC brushless fans is 12 V at 0.3 A.

On the cold side of each TEC, there is an aluminum block with a U shape fluid channel prepared. During the operation of the system, the heat will be passed quickly from the coolant to this cold side. The aluminum block and TEC are clamped to the heat sink by another aluminum strip and screws. It is noticeable that the ends of all bolts are covered by plastic to prevent possible heat communication from the two sides.

(2) *Heater and battery simulator*

In these experiments, the battery heat generation process was modeled by a cartridge heater and simulated battery. The reason is mainly the unpredictable behavior and possibility of thermal runaway of real batteries in extreme operation scenarios. By applying the power supply, the heater can generate appropriate heat conveniently without any safety concern. Aluminum rod (Same geometric size as the extensively used 18650 Li-ion battery) was prepared to cover the heater to simulate the thermal behavior of the real battery. There is a hole, the same size as the heater, in the top center of the simulator to hold the heater. The gaps between heaters and batteries will be evenly filled with thermal paste.

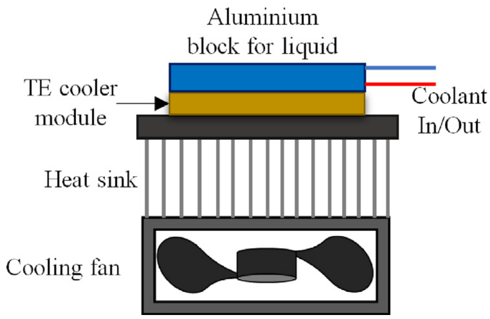

Fig. 1. Schematic illustration of the used single unit of TEC system for BTMS.

The selection of heater is based on the size of the battery and the power. The developed aluminum (Al) shell as the battery is the same size as standard 18650 Li-ion battery, and the heater needs to be properly fitted in the aluminum shell (see Fig. 2). The estimation of power is based on tests from published papers (Gadsden et al., 2011). Giuliano et al. (2011) tested a 50Ah Lithium-titanate battery under 2C, 4C and 6C condition and found that the heat generated was 16, 50 and 93 W respectively. Ye et al. (2015) measured the charging process heat generation of a 10Ah Li-ion battery for 3C, 5C and 8C and the results were 10.45 W, 25.4 W and 54.4 W respectively. As a result, the heaters employed in this work are CSH-02120 with rated power at 20 W provided by OMEGA engineering.

(3) *Container and pump*

The coolant flow needs to be driven by the applicable device. A pump will be installed along the coolant flowing loop. The pump used here is general brushless DC pump. The working voltage range is 5 to 12 V, and the maximum load occurs at 0.35 A. Maximum flow rate can be up to 4 liters per minutes horizontally.

2.2. Overall setup

The battery setups for battery-only experiments and battery-casing experiments are shown in Fig. 2(a) and 2(b). The copper casing is added to protect the battery from direct contact with the chosen coolant. For real battery, the coolant can be remarkably harmful to the cell in certain circumstances. Thermal paste evenly covers the heater-simulator and simulator-casing contacts.

Overall experiment setup is shown in Fig. 2(c) and (d). The TEC module can be divided into three parts namely TEC, fan, and heat sink. Coolant employed by all following experiments is water for safety and cost reason. Two thermocouples are attached to the surface of the battery by thermal tape in the cell alone tests and the exact positions are shown in each result graph. For the battery-copper casing experiments, two thermocouples are placed on the inside and outside surface in the middle of the casing. This inside thermocouple can also be treated as the battery surface temperature as the two parts were extremely close to each other. Moreover, there is one more thermocouple for air temperature. There may be one more thermocouple for water temperature when applicable.

3. Experimental tests, results, and discussion

All the devices and instruments are in the lab in which room temperature is between 20–25 °C. Ambient pressure is the standard air pressure. All the following experiments are based on a single simulated battery cell. The comparisons are made between natural air cooling, pure liquid cooling, and hybrid TEC with liquid-based forced air cooling.

3.1. Single battery in air

The heater voltage supply was changed between 30 V to 60 V to check the behavior of the battery set under different power

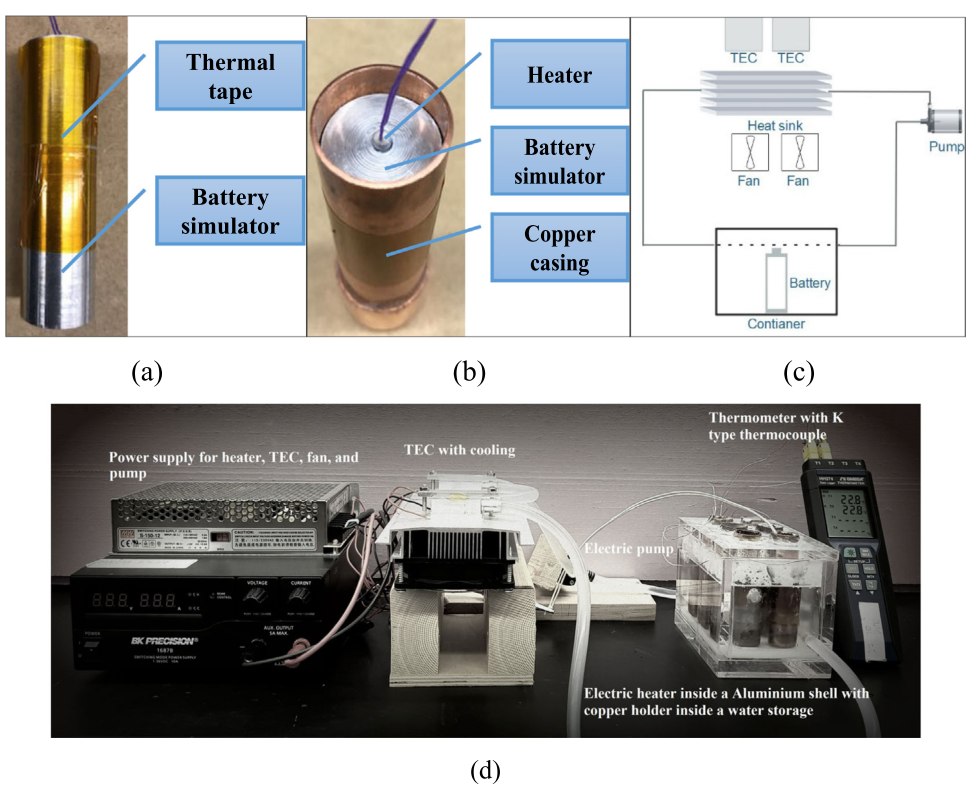

Fig. 2. (a) Heater and battery simulator, (b) simulated battery in the copper casing, and (c) Schematic overall view and (d) experiment setup of the proposed system.

supply in the air (see Fig. 3). These experiments were lasts for about 60 min in total. The air temperature remained relatively constant during the test. Battery temperature rose fast in the first 30 min and gradually reached steady state after this period. However, the stable temperature for each voltage supply was entirely different. Meanwhile, the temperature for the top and the middle of the battery are generally several degrees Celsius in difference after the one hour long tests. When the voltage supply was thirty volts, the temperature of the battery top was about 46.6 °C. The middle temperature was only 45.4 °C at the same time. For the 40 V group, the top temperature was 64.7 °C while at the same time the middle temperature was 62.4 °C. In 50 V test, the temperature was 75.7 °C at the top and 73.6 °C in the middle. The last test on 60 V, the temperature at the top 91.1 °C, but in the middle, it was only 86.3 °C. It can also be concluded from these experiments that higher voltage inevitably leads to faster temperature change and higher battery temperature.

3.2. Single battery in water

This part tested the battery performance in the flowing water first. Power supply for the heater was 40 V constant. The pump was driven by the 10 V power supply. The curves are shown in Fig. 4(a) with the prefix "no TEC". This part is an investigation of pure liquid cooling. Top temperature, middle temperature, and the water temperature rose slightly at the same time in pure liquid cooling. The battery temperature reached 24.5 °C in about 50 min and stayed almost constant starting from there. The middle temperature of the battery is generally higher than the upper one. Water temperature remained lower than the battery most of the time. This liquid cooling is enough to handle the heat generated by one cell and the heat from the pump itself at the given parameters here.

The second part tested the battery in flowing water with the pump and TEC module. Fan, pump, and TEC were all supplied with 10 V power. The corresponding curves show the declining trend of all the curves along with the experiment. In this test, the water temperature was always the lowest among them. The excellent cooling effect of this TEC module can be seen from this graph. In addition, a real battery (Li-ion battery, BRC 18650, 5000mAh, 3.7 V) was tested inside the water without any copper holder and TEC cooling system and plotted battery surface temperature along with time for 70 min (see Fig. 4(b)). Fig. 4 shows the transient temperature behavior of single cell exposed to air and water, respectively. T-type thermocouples were used to measure the temperature and Omega-HH374 data logger was used to record the data. Measured temperature data remains within the accuracy limit posed by the measurement system. In the original manuscript, line plots were used show the temperature variation with time, which is replaces by the symbols only in the revised manuscript. This modification significantly reduces the unnecessary noises in the data presentation segments arises mainly due to the simple line plot without any fit.

3.3. Single battery in copper holder in air

The battery was then placed into the copper holder, and this set stood on a wood plate to test the thermal behavior in the air. The experiments were carried out with 30–60 V voltage supply for the heater. It is evident from Fig. 5 that temperature rise speed and steady temperature increase as the heater voltage increase. What the temperature rose was 20.95 °C, 34.05 °C, 48.65 °C and 66.4 °C on average in 60 min for 30, 40, 50, 60 V respectively. Besides, as the heater was inside the holder, the temperature of the thermocouple inside the copper holder was always higher than the outside one. The temperature difference between these

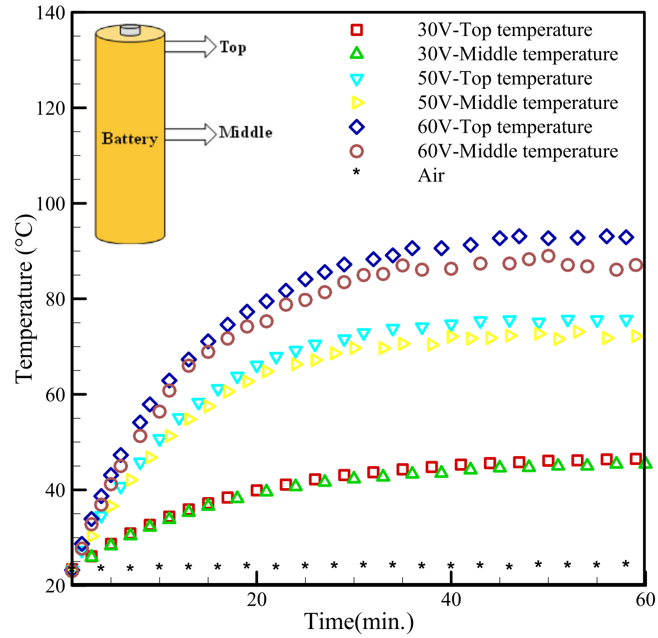

Fig. 3. Single cell in air thermal response test (natural air cooling, varying heater voltage supply 30–60 V).

two spots was 1.1 °C, 1.6 °C, 2.9 °C and 4.7 °C respectively (30–60 V). By comparing these results to the battery only in air heating test, the temperature rose for one hour in 60 V group experiment was 66 °C which is 0.4 °C lower than this holder added one. But the temperature was several degrees Celsius lower in 30–50 V groups in here compared to battery only tests.

3.4. Single battery in copper holder in water (varying tec voltage)

This part tested the new TEC-liquid-air cooling system for battery cell-copper holder set. The voltage supply for the TEC module was modified between 8 V to 12 V while the voltage for fan and pump kept constant at 10 V. The heater voltage supply was fixed to 40 V. As shown in Fig. 6, battery temperature in all the listed groups decreased dramatically during the experiments. In another word, all the battery temperature measurement values were even never rose. The battery surface temperature dropped 9.4 °C in the first 60 min, compared to 12.8 °C temperature drop at the same spot for battery alone counterpart. Also, there is a noticeable cooling effect difference between the different voltage groups. During the first 80 min, 10 V group decreased 10.4 °C and 10.5 °C on battery surface and copper holder surface. For the same time domain, the 12 V group declined 9.9 °C and 10.5 °C on inside and outside temperature. The 8 V group enjoyed the least decrease for the same period at 9.1 °C, and 9.5 °C specifically.

4. Conclusion

The battery thermal behavior by natural air cooling at different voltage supplies was investigated first. The temperature rises in volume and the rate of change increases significantly as the voltage supply increases. When the heater voltage changed from 30 V to a 60 V, the steady temperature almost doubled. Next, a study was carried out for a proposed liquid cooling and hybrid TEC-liquid–air cooling system. At a 40 V voltage supply baseline for the heater, the hybrid system showed an improved cooling effect compared to the liquid cooling; which is more desirable than natural air. A copper casing was added to mitigate rust on

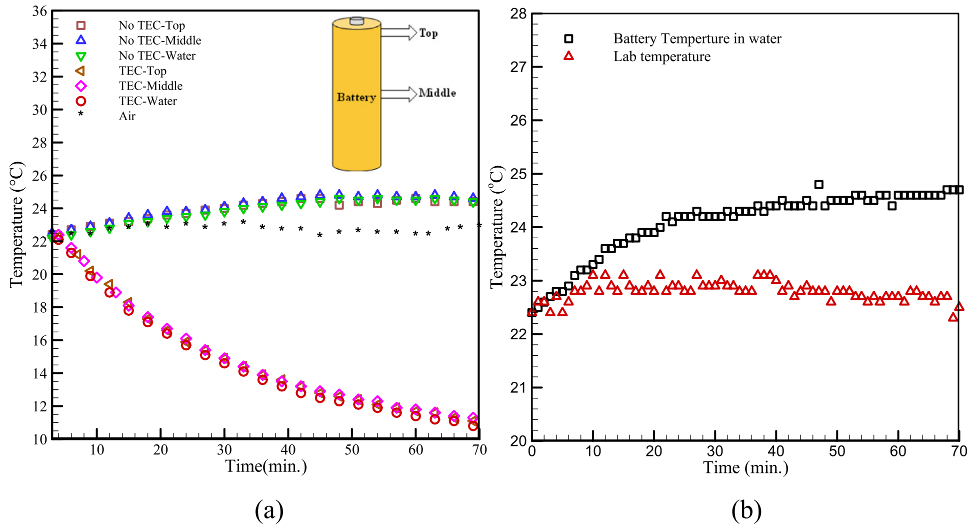

Fig. 4. (a) Single cell in water thermal response test (pure liquid cooling and TEC based BTMS, heater voltage supply 40 V). (b) Real battery surface temperature inside the water without TEC.

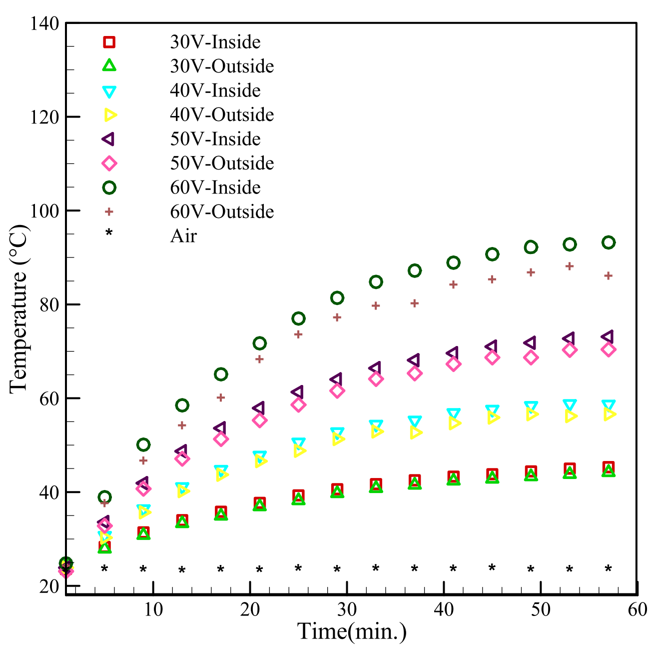

Fig. 5. Single cell in the copper holder in air thermal response test (natural air cooling, varying heater voltage supply 30–60 V). Here, inside indicates the temperature inner surface of the copper shell and outside refers to the outer surface of the copper shell of the battery holder.

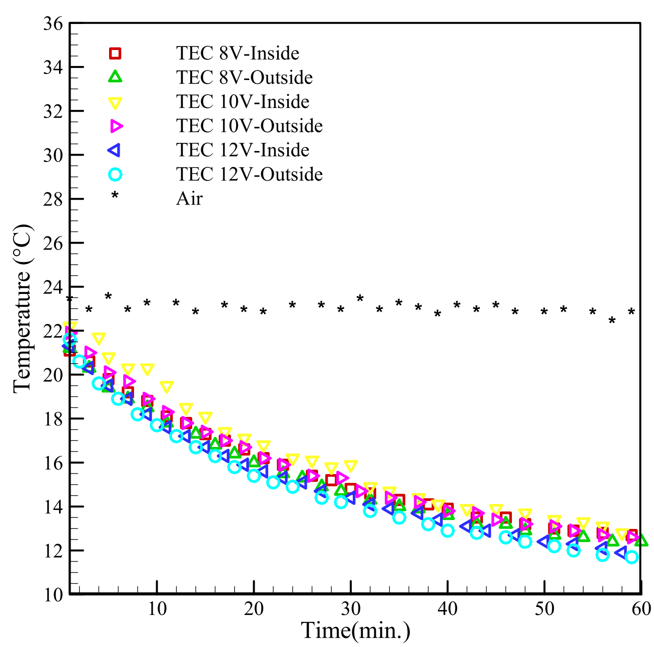

Fig. 6. Single cell in the holder in water thermal response test (TEC based BTMS, varying TEC voltage supply 8–12 V, heater voltage supply 40 V). Here, inside indicates the temperature inner surface of the copper shell and outside refers to the outer surface of the copper shell of the battery holder.

the battery and reduce corrosion issues brought by the coolant in real applications. Experiments in air and water were taken accordingly. In the air, the inspection showed a similar temperature trend as the non-protected group. In water, the investigation revealed a similar dramatic temperature decline in the hybrid thermal management system. However, the temperature drop in this group was slightly slower than the solo battery group. Nevertheless, a significant thermal management potential can be expected for the proposed hybrid BTMS system. Moreover, the experimental test shows that the battery surface temperature drops around 43 °C (from 55 °C to 12 °C) using TEC based water cooling system for a single cell with copper holder when 40 V is supplied to the heater and 12 V to the TEC module". In one of the recent studies, researchers used TEC for BTMS without any coolant where their temperature drop was 31.5 °C which is 11.5 °C less compared to the current work (Li et al., 2019).

Further investigations will focus on battery packs that have more heat dissipation and cooling requirements. Additionally, thermal models will be created and explored for numerical simulation and optimization of design parameters.

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