Development of hybrid cooling method with PCM and Al₂O₃ nanofluid in aluminium minichannels using heat source model of Li-ion batteries

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HIGHLIGHTS

• Various thermal management systems are experimentally studied at three heat fluxes.
• Active/passive methods failed to keep battery within the safety limit at high rates.
• Copper metal foam increased heat dissipation to surrounding in battery pack.
• Al₂O₃-water nanofluid increased heat transfer from battery pack to surrounding.
• Increment in convective heat transfer was efficient in high discharge rates.

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ABSTRACT

Lithium ion batteries are considered as the main energy storage option. High temperatures cause capacity fading and can even produce fire. It is, therefore, essential to design an effective thermal management system (TMS) to keep battery temperature in the safe range. In this study, thermal response of lithium ion batteries is investigated in high discharge rates with a new TMS combining active and passive methods. Refined paraffin in blockform (P 42–44 #107150) combined with porous copper metal foam was considered as the passive part and aluminium mini-channel containing coolant flow was regarded as the active part of TMS. The experiments were conducted at three different Reynolds numbers in active and hybrid methods and it was shown that at higher flowrates the maximum temperature is lower. The research has also shown that passive cooling was inefficient in keeping the battery temperature below the safety limit of 60 °C in high discharge rates. The hybrid thermal management system (HTMS) reduced the steady-state temperature of batteries by 19.5% compared to active method at a Reynolds number of 340 and heat generation power of 3.7 W. The active method was also ineffective in controlling the battery temperature at high heat generation power levels while HTMS showed an appropriate thermal performance at the same condition. Furthermore, effect of utilizing Al₂O₃-water nanofluid with two different volume fractions was investigated in both active and hybrid systems. It was shown that, compared to the base case with water flow, nanofluid can reduce the maximum temperature of batteries by 15.5% and 8.5% in active and hybrid methods, respectively.

1. Introduction

Increasing amount of CO₂ in the atmosphere is one of the major concerns in the context of global warming. Currently, around 80% of energy consumption in the world is provided by fossil fuels [1]. Besides, a noticeable amount of fossil fuels are consumed in the transportation sector [2]. An acceptable way of reducing carbon emissions is replacing fossil-fuelled engines by vehicles which use clean energies. Recently, transportation market is affected by electric (EVs) and hybrid electric vehicles (xEVs). Cost, driving range, and lifetime of battery packs are some of the main obstructions in expanding share of EVs in global markets. Due to high energy density and long life span, Li-ion batteries (LIBs) are generally regarded as the first choice for power source in EVs [3]. However, LIBs are highly sensitive to the operating temperature. Temperature is one of the fundamental factors affecting lifetime and capacity of battery packs. Working at high temperature ranges reduces capacity of batteries noticeably [4]. In addition to capacity fading, increasing temperature can cause thermal runaway in the battery pack which eventually can leads to serious safety problems like fire and explosion of the pack. The optimum operating temperature for LIB is reported to be 15–40 °C [5], while maximum temperature for safe operation of batteries is at 60 °C [6]. The temperature uniformity is
Another important factor that influences the capacity of entire battery pack. The allowable temperature uniformity is \( \pm 5 \) °C according to the previous investigations [5]. In addition, the pumping power required for heat transfer enhancement within heat exchangers [7] and thermal management of battery, i.e. the coolant pressure drop along the battery pack, is of substantial prominence [8].

Because of the ohmic resistance in the battery cells, heat is produced in cells while current is passing through the Li-ion batteries. There are a considerable number of battery cells in each battery pack for providing required power for moving vehicles, and therefore there is a crucial requirement for battery thermal management systems (BTMS) for preventing rising cell temperature due to accumulation of produced heat in the battery packs. The BTMS should have features like low cost, light-weight, low volume, and should be able to operate in harsh climate conditions.

Thermal management systems are basically classified in two categories: active and passive. Active methods utilize forced convection to dissipate heat which is generated in cells. The coolant liquid can be air [9], water, ethylene glycol, or nanofluid [10]. Active BTMS may typically be implemented in two forms: direct and indirect cooling. In direct method, the coolant has direct contact with the cells; so, it must be dielectric to prevent short circuit. Liquids such as air and mineral oils are appropriate for direct cooling method. In the indirect cooling, there is an intermediate material to prevent direct contact of cooling liquid with the cells [11]. Wang et al. [12] investigated optimum cell arrangement in a battery pack and identified best place for inlet and outlet of forced air cooling. They examined thermal response of battery module at different flowrates, battery discharge rates, and ambient temperatures. Sabbah et al. [13] studied thermal response of batteries in different ambient temperatures and critical discharge rates. It was reported that air-based thermal management system is not a proper way to keep cells in safe temperature zone when ambient temperature is above 40 °C. Comparison of four cooling approaches based on liquid and air media in prismatic battery cells was studied by Chen et al. [14]. They considered power consumption, maximum temperature in the cells, and weight of each method and concluded that air cooling uses 3 times more energy than liquid cooling for maintaining the cell temperature in the same range. Since air has low thermal conductivity, higher flowrates are required to keep the temperature below a certain limit. Additionally, providing high flowrate consumes more energy and requires a greater space in TMS.

There are numerous investigations on thermal response of batteries with active BTMS which have used liquids with a thermal conductivity higher than air. Zhao et al. [15] numerically analysed thermal behaviour of cylindrical battery cells under mini-channel liquid BTMS by changing flowrate, entrance size, and number of channels. Heat dissipation reduced by increasing channel entrance size at a specified flowrate. To explore the influence of flow direction on the cell temperature and required pumping power, Lan et al. [16] conducted a comprehensive numerical research using aluminium mini-channel attached to prismatic cells. In another study, Zhao et al. [17] numerically analysed effect of interface contact between channel and module on the maximum temperature and temperature uniformity of the battery pack. Their results demonstrated that by increasing interface of liquid channel and battery module, maximum temperature reduces noticeably, but temperature uniformity decreases dramatically. It was shown that in higher discharge rates, flowrate has a major influence in lowering the maximum temperature. Deng et al. [18] proposed a novel...
geometry for cooling of Li-ion battery and investigated the effects of various geometrical/flow parameters, e.g. width, length, thickness, and mass flowrate.

Nowadays, nanofluids have several applications, from heat transfer improvement to enhanced oil recovery [19]; and therefore characterization of nanofluids/nanoparticles is of high importance [20]. Adding nanoparticles to fluid is an effective way to increase convective heat transfer coefficient in forced liquid flow [21,22]. Convection is amplified because of increasing thermal conductivity of fluid [23–25]. There are few researches on the effects of using nanofluids in BTMS and investigated because of increasing thermal conductivity of fluid [23–25]. There are few researches on the effects of using nanofluids in BTMS and investigations are generally based on numerical modelling of BTMS [26]. Effect of adding Al₂O₃ to the base fluid was studied numerically by Huo et al. [27]. According to their modelling results, using nanofluid can effectively decrease maximum temperature of the battery cells. They also demonstrated that using nanofluid with 4% volume fraction can decrease maximum temperature of cells up to 7%. Influence of different nanofluids with different base fluids was investigated by Mondal et al. [28] numerically in two kinds of flow configuration which had variable number of channels. Nanofluids were prepared with two different nanoparticles at various volume fractions. They showed that the efficiency of BTMS was improved by using base nanofluids with higher thermal conductivities.

Thermal response of batteries in active cooling method is generally efficient, but using active method has expense of complexity, cost, and energy because of the need for using pumps, compressors, and ducts. Active method obtains its required energy from the battery module. Consequently, designing methods which consume less energy is essential. Tran et al. [29] used heat-pipe as a passive method for controlling temperature of batteries. An innovative method which use phase change material (PCM) was investigated recently. Because of high latent heat of PCM, they can store noticeable amount of energy during phase change in a narrow temperature range. Sabbah et al. [13] compared two BTMSs using forced air cooling and PCM. They concluded that in harsh ambient conditions, forced air method failed to retain the temperature under the critical zone. By using PCM, even in high ambient temperatures, the battery cells remained in an acceptable temperature range. Lazark et al. [30] investigated the effect of using different PCMs on single cell which had different melting points. It was revealed form their study that using PCM with a higher melting point would improve the thermal performance of BTMS.

Although PCM have remarkable capacity for storing energy, because of its poor thermal conductivity, limitation in transferring stored energy to outside of PCM limits the amount of energy PCM can store. Pure PCM is not primarily an appropriate method for using battery cells in high discharge for long time. Numerous investigations are performed for improving thermal conductivity of PCM. There are three major approaches for improving the thermal conductivity of PCM: embedding metal sheets or matrix in PCM, adding nanoparticles with high thermal conductivity to PCM, and using porous metal foam [31]. Karimi et al. [32] added different types of metal nanoparticles to paraffin to increase thermal conductivity and study its influence on battery thermal management. It was concluded that Ag nanoparticles were the best choice for PCM-composite. Zou et al. [33] studied the effect of nanocarbon fibres in PCM experimentally. Different types of nanocarbon fibres and graphene fibres were used in their experiment to obtain optimum amount of additives which keep high latent capacity and improve thermal management. It was revealed that using MWCNT/graphene can improve thermal conductivity of pure PCM up to 124%. Influence of aluminium sheets plate were examined by Azizi et al. [34], where they reported that by using aluminium wire plates, the maximum temperature can be reduced up to 26% at the highest discharge rate.

Furthermore, the experimental results demonstrated that the effect of using PCM is more evident in high discharge rates. Embedding PCM into porous metal foam is another way for improving thermal conductivity of PCM. Yang et al. [35,36] investigated improvement of heat transfer in tubular thermal energy storage filled with PCM, experimentally and numerically. It was depicted in either solid or liquid phase PCM, adding copper metal foam can increase heat transfer through PCM embedded inside the tubes and so increase the Nusselt number in liquid flow in shell part of the tubular arrangement [37,38]. It was revealed that adding copper metal foam with porosity of 0.94 and pore density of 15 pore per inch to PCM may increase heat transfer up to 5186.91% [39]. Tiari et al. [40] investigated numerically the effect of porosity of porous copper metal foam on performance of storage system consisting PCM embedded in high porous media with heat pipe. It was shown that increasing the quantity of embedded heat pipe and impregnating copper foam with potassium nitrate affect the time of charge and discharge for the storage system.

Effect of using copper nickel metal foam on thermal response of cylindrical 18650-type batteries was studied by Hussian et al. [41]. The results were compared with two other cases of natural air cooling and using pure PCM. The geometric feature of metal foam was examined by changing its porosity. It was concluded that using nickel metal foam can reduce temperature by 24% compared to the pure PCM and by reducing porosity of metal foam, battery surface temperature decreases. Heyhat et al. [42] compared performance of adding nanoparticles, fins, and porous media to PCM and discussed their effect on thermal performance of battery cells. Porous metal foam was the most effective approach in retaining the battery temperature in the allowable range. It was further reported that using porous metal foam lead to 4–6 K reduction in temperature of 18,650 batteries compared to pure PCM cooled by natural convection.

Since, heat emission by natural air convection is limited in passive BTMS, it is necessary to combine passive method with a reliable active system. Hybrid BTMS has both advantages of controlling temperature in critical conditions and low consumption of energy [43]. Phase change process plays the main role in keeping temperature of cells low while using PCM for passive BTMS. Hybrid thermal system prolongs duration of phase change which leads to lower maximum temperatures. However, in most studies just one type of passive or active BTMS are investigated. Few researches are focused on combination of passive and active method for optimization of energy consumption and efficient cooling effect. Lopez et al. [11] numerically analysed effect of PCM properties and configuration of 2.6 Ah 18,650 battery cells in HBTMS. The HBTMS consisted of PCM and cold plate beneath the battery module, cooled by liquid flow. Zhang et al. [44] investigated temperature behaviour of battery cells in HTMS consisted of heat pipe and porous metal foam saturated with PCM which was cooled by air flow. They compared the results with passive cooling and forced air cooling method. It was depicted that in high discharge rates, combination of heat pipe and PCM retained temperature of batteries in allowable limit while forced air cooling failed to maintain the temperature in the permitted range. Even in high discharge rate of 5C, HTMS improved the effect of combination of passive and active methods.

Recently, Mehrabi-Kermani et al. [45] investigated prismatic cells response in HBTMS composed of copper metal foam saturated with PCM cooled by air flow. They showed that PCM can use 76% and 100% of its latent heat capacity in HBTMS while in passive BTMS it can use just 13% of its capacity. It was shown that in high ambient temperature of 40 °C, HBTMS is not able to maintain the battery cells in the desired temperature range.

From the above review, it is evident that neither passive nor active cooling methods are efficient in stressful conditions. This investigation, therefore, aims to cover the gaps in recent researches in order to benefit both active and passive advantages and be practical even in critical working conditions. This research investigated the influence of using nanofluid as active part of the HTMS experimentally for the first time and compared efficiency of using HTMS compared to active and passive cooling methods in different heat generation powers. The work further discussed optimum thermal management system in each heat generation powers thoroughly. Because of the specific geometrical feature of cylindrical batteries, it is important to make sufficient surface contact.
between the active coolant and batteries. The current HBTMS is focused on increasing contact surface of coolant channels and battery cells through conduction by using porous metal foam. The examination of study is based on effect of increasing convective cooling around the battery module by using different coolants in the channel at various flowrates. Natural air convection heat dissipation mode is considered as the reference case for comparison of various methods. Cylindrical heater is used to emulate battery in different discharge rates. Nanofluids with two different concentrations are used in the experiment to increase convective cooling in channels and results are compared with pure water flow. HBTM are compared to passive and active liquid cooled systems.

2. Experimental method

2.1. Characterization of PCM and metal foam

Commercial paraffin in blockform (P 42-44 #107150) was acquired from MERCK Company and employed as PCM. Thermal conductivity of the PCM was measured by the thermal properties analyser, KD2 Pro instrument, in both solid and liquid states. The deviation from the manufacturer reported data was ± 1%, while the accuracy of KD2 Pro is 0.01 W m\(^{-1}\) K\(^{-1}\). The fusion point, latent heat, and specific heat capacity of paraffin were obtained from the producer. Thermal properties of PCM are shown in Table 1.

To increase the conductivity of paraffin, copper metal foam was obtained from Nano-Pooshesh-Felez Co., Iran. The specifications of metal foam is selected according to the recommended figures in the literature based on the best thermal response for increasing thermal conductivity [46]. The copper metal foam had a porosity of 0.9 and PPI (number of pores per inch) of 20. Two metal foams with dimensions of 95 × 26 × 32 mm were used, each having three holes with diameter of 18 mm. Fig. 1-(a) shows structure of the metal foam used in the study.

The PCM-CF (phase change material - copper foam) composite was prepared by injection of liquid paraffin into the CF structure which was located in a leak-free stainless-steel container. Liquid paraffin was prepared by putting solid paraffin in constant temperature bath of 70 °C. To prevent formation of bubbles in the CF, the container was vibrating continuously. The paraffin shows volume change in the solidification process. To fill the voids after solidification, injection was done in four steps. After completion of each step, the rest of liquid paraffin was injected into the container. Because of volume expansion during the melting phenomenon of PCM, top of the container was left with a 2 mm gap.

2.2. Preparation of the battery pack

In this study, high critical discharge conditions are examined during the tests. For exploring the efficiency of BTMS in high critical discharge condition, the battery cells are not used because of the safety issues and cost of degradation of LIBs. Besides, high discharge conditions and thermal consequences of such circumstances in long tests causes losing equal condition of LIBs during the tests. To investigate thermal response of LIB in critical discharge conditions, precise electrical heaters were used to model batteries in BTMS and prevent any inequality in the LIB’s characteristics. The cylindrical lithium-ion 18650-type battery cell (18 mm × 65 mm size, slightly larger than a AA battery) with capacity of 3400 mAh was selected to be emulated in this investigation. Three cylindrical cartridge heaters were utilized which were able to provide the target Watt density. The heaters were made with 18 mm diameter and 65 mm height. Two K-type thermocouples were attached to each heater in order to measure the performance of heaters continuously. Fig. 1-(b) shows the location of each thermocouple. A box made of stainless steel with dimensions of 95 × 26 × 66 mm with three holes in it was used as the container. Three heaters were placed inside the container with distance of 4 mm and the gaps were filled with paraffin-CF composite. In addition, the gap between the channel and the container wall was filled with elastomeric insulation sheets and beneath the container were coated with thermal insulating epoxy to minimize heat loss from the battery pack. Fig. 1-(c) shows the top view of the battery pack arrangement.

Heat generation in the battery cells originate from two factors: (1) ohmic heating (2) entropy change due to electrochemical reactions. Eq. (1) shows total amount of heat generated in battery cells [47]. The first term is the amount of heat generated due to ohmic resistance and the second term is generated by entropy changes.

\[
Q = I(E - V) - I \left( \frac{dT}{dt} \right)
\]

where \( I \) (A) is the discharge current, \( E \) (V) is the open circuit voltage, \( V \) (V) is the operating voltage, and \( T \) (K) is the battery cell temperature. To model heat generation and thermal response of the battery, the amount of heat generated in the LIB in different discharge rates were obtained from equation (2) which is representative for 18650-type battery cells [48].

\[
\dot{q} = R i^2 - T_b \Delta S \frac{i}{n F}
\]

where \( i \) (A m\(^{-3}\)) is the discharge current per unit volume, \( n \) is the number of electrons in reactions, \( F \) (96485 C mol\(^{-1}\)) is the Faraday constant, \( \Delta S \) (J mol\(^{-1}\) K\(^{-1}\)) is the entropy change, \( T_b \) (K) is the temperature in the battery unit, and \( R \) (Ω m\(^3\)) is resistance of the battery. Equation (3) shows the empirical relations for calculation of \( R \) [48].

\[
\begin{align*}
R &= 2.258 \times 10^{4} \times 10^{-8} \times \text{SOC}^{-0.3952} & T &= 20°C \\
R &= 1.875 \times 10^{4} \times 10^{-8} \times \text{SOC}^{-0.2787} & T &= 30°C \\
R &= 1.659 \times 10^{4} \times 10^{-8} \times \text{SOC}^{-0.1692} & T &= 40°C
\end{align*}
\]

where \( \text{SOC} \) is the state of charge in the battery cell. Entropy change term in Eq. (2) was calculated by equation (4) [49].

\[
\begin{align*}
\Delta S &= 99.88 \times 100 - 76.67 & 0 \leq \text{SOC} \leq 0.77 \\
\Delta S &= 30 & 0.77 \leq \text{SOC} \leq 0.87 \\
\Delta S &= -20 & 0.87 \leq \text{SOC} \leq 1
\end{align*}
\]

Total heat generated in the battery cell was calculated as the average amount of heat generated in different SOC states by the above-mentioned equations. In fact, the average typical variation of power generation due to SOC was calculated and used in the experiments. Based on the heat capacity of 18650-type battery cells [13,50], the temperature time history of LIB was detected. Ohmic resistance of each heater was 125 Ω, measured by multimeter AKB-DT8205A with accuracy of ± 1 Ω. For simulating similar thermal response for the heater, the required voltage was set by AC power supply with voltage rating of 0–300 V, according to equation (5).

\[
Q = \frac{V^2}{R_h}
\]

where \( V \) is the supplied voltage and \( R_h \) is electric resistance of the heater.

By applying a certain power on the insulated heater in the ambient temperature and recording the temperature response, the heat capacity of each heater was measured to be 211 J °C\(^{-1}\) according equation (6).

\[
Q = c_p(T_f - T_i)
\]
where \( Q \) (J) is the amount of heat generated in the heater, \( c_p \) (J°C\(^{-1}\)) is the heat capacity of the heater, \( T_2 / T_1 \) (°C) are its final / initial temperature.

Three different heat generation power levels were used for simulation of 1C, 2C, and 4C constant and continuous lithium ion battery cell discharge. For each cell, the required voltages of 65, 119, and 218 V were provided to reach power levels of 3.7, 12.5, and 42.5 W, respectively. The uncertainty of measured quantities—voltage and resistance—can be considered as the accuracy of the measuring devices, i.e. \( \Delta V = \pm 1 \) V and \( \Delta R = \pm 1 \) Ω, and the uncertainty of calculated power and heat capacity of heaters were obtained from equations (7) and (8).

\[
\Delta Q = \sqrt{\left(\frac{2V}{R_0}\Delta V\right)^2 + \left(-\frac{V^2}{R_0^2}\Delta R\right)^2}
\]

(7)

\[
\Delta c_p = \sqrt{\left(\frac{\Delta Q}{(T_2 - T_1)}\right)^2 + \left(-\frac{Q}{T_2^2}\Delta T_2\right)^2 + \left(\frac{Q}{T_1^2}\Delta T_1\right)^2}
\]

(8)

The uncertainty for heat generation is derived according to Eq. (7). As voltage is amplified for heat generation, the major uncertainty increases. The most critical error for heat generation was 3.1% at the maximum voltage which were provided for heat generation of 42.5 W. Table 2 shows maximum uncertainties of different parameter in the current study.

2.3. Aluminium channel and nanofluid

Two aluminium minichannels were used for the experiments. Aluminium was selected because of its high thermal conductivity and low weight. To decrease thermal resistance between the cooling liquid and the battery pack, an aluminium sheet grade 1000 series with thickness of 0.5 mm was used. The inner dimensions of the aluminium channel were 4 × 65 mm which corresponds to a hydraulic diameter of 7.54 mm. The aluminium channel is connected to a rectangular plexiglass channel (item No. 7 in Fig. 3) which converted flow from circular tube to rectangular channel. Fig. 1-(d) shows a schematic of the
plexiglass and aluminium channel located in the battery pack. Three different flow regimes are considered to be investigated based on Reynolds number which was obtained by equation (9).

\[ Re = \frac{\rho UD}{\mu} \]  

(9)

where \( \rho \) (kg m\(^{-3}\)) is the density of the fluid, \( U \) (m s\(^{-1}\)) is the mean velocity of the flow, \( D_h \) (m) is the hydraulic diameter of the aluminium channel and \( \mu \) (Pa s) is the fluid viscosity.

The water-based alumina nanofluid was synthesized by two-step method. Alumina powder of type alpha with diameter and purity of 50 nm and 99% and density of 3890 kg m\(^{-3}\) was used as nanoparticle. Firstly, the required mass of nano powder for synthesizing was calculated, thereafter the nanoparticles were dispersed in base fluid. Water and alumina were stirred by mechanical stirrer for 1 hr. In the next step, an ultrasonic wave homogenizer machine (400 W power and 24 kHz frequency, produced by Hielscher) was used for synthesis of nanofluid for 4 hr in 4 stages. No particle agglomeration and sedimentation was observed in the homogeneous nanofluid even after 7 days. Fig. 2 shows the synthesized nanofluid after 6 days in comparison with pure water. No stabilizer was used during the synthesis process in order to preserve thermophysical properties of nanofluid. Nanofluid volume fraction affects the power required to circulate nanofluid through tubes and channels. Two nanofluid volume fractions of 1% and 2% were used in this study in order to minimize the power consumption in the thermal management system which circulates nanofluid. Kinematic viscosity and density of nanofluid were measured by a CANON-Fenske opaque viscometer and picometer, respectively. Thermal conductivity of nanofluid was measured by the thermal properties’ analyser, KD2 Pro instrument. Properties of the nanofluids are presented in Table 3. Prandtl number has specific influences on the Nusselt number which affects convective heat transfer coefficient in various flow regimes. Considering the issue, the Prandtl number obtained by equation (10) for nanofluid with volume fractions of 1% and 2% are 7.14 and 7.21, respectively.

\[ Pr = \frac{c_p \mu}{k} \]  

(10)

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(10)

where \( c_p \) (J kg\(^{-1}\) K\(^{-1}\)) is the specific heat capacity of nanofluid, \( \mu \) (Pa s) is its viscosity, and \( k \) (W m\(^{-1}\) K\(^{-1}\)) is the thermal conductivity of nanofluid.

### 2.4. Experimental setup and procedure

Heaters were carefully placed in the container. Three K-type thermocouples were attached to surface of the heaters in order to measure the temperature response of heaters. Calibration of the thermocouples were done using a constant temperature bath of 10–90 °C. Accuracy of the thermocouples was ±0.1 °C. To attach the thermocouples to the heaters and avoid any gaps between the metal foam and the heater, thermocouples were pushed in a 1.5 mm narrow trench and then were stuck to the surface by silicon glue. The sides and bottom of the container were insulated to minimize heat loss to the surrounding. In the NC (natural convection) cooling scenario, three different cases of bare batteries, pure paraffin, and paraffin-CF composite were tested. The ambient temperature near the battery pack was 25 °C during the tests. In the active method, the convective heat transfer coefficient is increased by placing two aluminium channels around the pack in order to cool the pack surrounding with coolant flow instead of natural air convection. Because of special geometry of cylindrical battery cells, the contact surface between the batteries and the constructed aluminium channel is low. To increase heat transfer from the batteries to the aluminium channel through conduction, and considering the negative effect of weight increment, copper metal foam was placed between the two components in the active method. Two different cases of pure paraffin, and paraffin-CF composite were investigated in the hybrid thermal management scenario where convection coefficient is increased compared to the NC case by placing aluminum channels on both sides of the battery pack.

A schematic of the entire test section and the corresponding flow diagram is illustrated in Fig. 3. The test setup consists of a reservoir which contains the cooling liquid, a pump which circulates the liquid at different flowrates through plexiglass convertor toward the aluminium mini-channel which is embedded inside the container, a constant temperature bath for keeping inlet flow at temperature of 24 °C, a flowmeter with accuracy of ± 0.1%, the battery pack and AC power

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**Table 2**

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>Temperature</td>
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<tr>
<td>Applied voltage</td>
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<tr>
<td>Resistance</td>
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<tr>
<td>Heat capacity</td>
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<td>Heat generation</td>
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**Table 3**

<table>
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<th>Characteristic</th>
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<td></td>
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<tr>
<td>Density (kg m(^{-3}))</td>
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</tr>
<tr>
<td>Viscosity (mPa s)</td>
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<tr>
<td>Thermal conductivity (W m(^{-1}) K(^{-1}))</td>
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<td>Specific heat capacity (J kg(^{-1}) K(^{-1}))</td>
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Fig. 2. (a) Alumina nanofluid, (b) pure water.
supply for providing heating power, and a data acquisition system (PROVA800 data logger) for recording the temperature of heaters every 5 s. The pressure drop for each cooling liquid and in different flowrates was recorded by a differential pressure transmitter (Endress + Hauser PMD75) with accuracy of ±0.075%. Average temperature of the inlet and outlet flow was recorded by K-type thermocouples every 5 s.

For every BTMS, heaters were powered by the AC power supply with three different power of 3.7, 12.5, and 42.5 W. The tests continued until the heaters’ temperature reached 60 °C or the temperature profile became steady.

3. Results and discussion

The main purpose of this study was to keep the maximum temperature of batteries under the safety limit, i.e., 60 °C. In addition, in the critical discharge rate condition, the goal is to increase the time window for reaching to the safety limit. Thereby, the effect of using HTMS compared to active and passive methods is investigated at different heat generation power levels. Effect of different flowrates of water and Al₂O₃ nano-fluids in both active and hybrid thermal management systems are also investigated under variable heating powers. Maximum temperature of batteries and the temperature uniformity within the battery module which is defined as the difference between maximum and minimum temperature of batteries are discussed in different cases.

3.1. Performance of passive, active, and hybrid thermal management systems

The temperature history over time for the second battery under conditions of NC, pure paraffin with NC cooling, CF-PCM composite under NC cooling, pure PCM and CF-PCM cooled by NC, and flow of water and pure metal foam cooled by water flow are shown in Fig. 4. The temperature of battery is approximately 25 °C at the beginning of
the discharge process. The tests are performed at a constant flow with Reynolds number of 340 and inlet temperature of 25 °C. The tests are continued until the battery temperature exceeds the allowable temperature or it reaches a steady state value.

At the heating power of 3.7 W, the maximum temperature reached 60 °C after 2740 s under pure NC cooling. In case of pure PCM, the battery temperature increased with a steep slope until reaching the melting temperature of PCM. The rate of temperature augmentation reduced during melting range of PCM and after 2190 s—when all the PCM around the heater is melted—the temperature increases with a higher speed compared to the melting range. The slope of temperature rise after the phase change is lower than before melting as illustrated in Fig. 4. This observation is deemed to be connected to the higher temperature difference between PCM and ambient which increases the heat dissipation to the surroundings. On the other side, using pure PCM considerably increased the time of reaching 60 °C, i.e. to 4225 s. In the case of adding metal foam to PCM, it can be seen that because of more heat transfer to the surrounding of the battery pack, the time required for phase change has increased despite reduction of latent heat absorption in the composite PCM, and the slope of temperature rise is reduced compared to the case with pure PCM. The surface temperature of batteries for pure PCM and CF-PCM reduced by 15.6% and 20.5%, respectively, compared to bare batteries, while surface temperature of batteries under NC cooling reaches 60 °C. In all passive methods, while working under critical discharge conditions, it was not possible to keep temperature of the batteries below the safety limit because of various reasons including: low convective heat transfer coefficient around the battery pack, limited heat dissipation to the ambient, and consequently accumulation of heat inside the battery pack. Temperature profile in the passive method demonstrates that this TMS exposes batteries to undesirable conditions which threatens the battery life especially if the surrounding is in harsh conditions such as an ambient temperature of 35–40 °C. Aluminium mini-channels with water flow are placed around the battery pack for increasing the convective heat transfer coefficient. In pure PCM case, increased convection around the pack was not effective in lowering the battery temperature as shown in Fig. 4-a. Use of aluminium channels increased the time of reaching the safety limit temperature by 395 s at Reynolds number of 530. Because of low thermal conductivity of pure PCM, heat was not transferred effectively to the surrounding of pack and water flow was not able to keep the batteries temperature below 60 °C. In case of pure metal foam, because of higher thermal conductivity of metal foam, by using water flow the surface temperature of batteries reached steady state temperature of 44.5 °C. Pure metal foam has voids which are filled by air and, therefore, it doesn’t have maximum contact surface with the aluminium channel and batteries through conduction. Adding PCM to the metal foam structure made more contact surface available between the battery and aluminium channel for transferring heat from batteries to the

Fig. 4. Maximum surface temperature for NC, PTMS, ATMS, and HTMS at ambient temperature of 25 °C and Re = 340 for heater power of (a) 3.7 W and (b) 12.5 W.
aluminium channel through conduction, hence heat was able to be dissipated to the outside more effectively. Besides, PCM can absorb considerable amount of heat in such a scenario. The PCM temperature in HTMS was not risen to the melting range, so no phase change process occurred in the hybrid case. This implies better heat conduction to the surrounding in CF-PCM compared to pure PCM. Finally, adding PCM lowered steady state temperature of batteries down to 35.8 °C which is 19.5% less than pure metal foam. Surface temperature of batteries reduced 30.6% and 41.5% for pure metal foam and CF-PCM, respectively, compared to bare batteries temperature cooled by natural convection at the safety limit temperature.

Thermal response of simulated batteries for high discharge rate of 12.5 W undergoing five heat dissipation cases are depicted in Fig. 4-b. It is demonstrated that in the NC scenario, the battery temperature rises to 60 °C only after 630 s. As shown in Fig. 4-b, neither active nor passive methods were able to maintain batteries under the safety temperature. Using water flow increased the time for reaching the critical temperature to 1580 s, 1255 s, and 875 s compared to NC, pure PCM, and CF-PCM, respectively. Hybrid thermal management system showed more effective cooling process. After 1600 s, the PCM layer attached to the surface of batteries started to melt and at 2770 s the whole PCM around the batteries were melted and surface temperature of batteries increased with a higher rate until reaching a steady state level of 52 °C. It is obvious from the temperature profiles that using water flow, as the active part of HTMS, could transfer more heat to outside of the pack; so, time for starting phase change and its duration increased considerably compare to the passive method.

Fig. 5 shows battery temperature variation over time in 4C discharge rate case. In this high discharge rate, surface temperature of battery exceeds the critical temperature only after 170 s under the NC cooling. All different cases of thermal management systems failed to maintain temperature of batteries below the safety limit for the 4C discharge rate conditions. The longest time for reaching the temperature of 60 °C is 2105 s when HTMS is used for cooling. In HTMS, the sharp increase rate of temperature declined when the temperature reached the melting range of PCM. During this process, the heat dissipated from batteries were stored in PCM as latent heat and transferred to the contact surface between aluminium channel and CF-PCM composite through conduction. The water flow with Reynolds of 340 was not able to control the temperature after phase change of PCM. Small gaps between adjacent batteries limit the amount of paraffin located between gaps, so the amount of heat absorbed by PCM is not enough to maintain the temperature below the critical range.

3.2. Effect of flowrate

In active and hybrid methods, mass flowrate is an important factor in energy consumption of the thermal management systems. Accordingly, effect of three different Reynolds numbers of 340, 530, and 720 in cooling performance are investigated in this study. The temperature history of batteries with heat generation power of 3.7 W is depicted in Fig. 6. It can be observed that for the active method, compared to the base case (Re = 340), the maximum steady state temperature decreased by 1.5 °C and 2.6 °C as Reynolds number increased to 530 and 720. However, as shown in Fig. 6-(b), the effect of mass flowrate is negligible in the HTMS setup. At this state, increasing Reynolds to 530 and 720 reduced the maximum temperature by only 0.5 °C and 0.9 °C, respectively. Hence, it can be concluded that increment of flowrate in improvement of maximum temperature is more notable in severe conditions where heat transfer to the channels is limited. In HTMS, because of more contact surface between the batteries and aluminium channel through conduction, more heat is dissipated to the outside compared to active method and increasing flowrate has a negligible effect on the cooling performance. At heating power of 12.5 W, however, increment of mass flowrate indicated more effect on the cooling performance. Higher Reynolds numbers in the active methods resulted in a longer time for reaching the safety limit temperature. The time for rising temperature to the safety limit increased from 2210 s to 2850 s and 3455 s, respectively for Reynolds numbers of 530 and 720. At higher flowrates, the slope of temperature increment is decreased which implies better heat dissipation to the surroundings. Temperature of batteries is reduced by 6.1% and 10.2% compared to the lowest flowrate when temperature reaches 60 °C for Reynolds number of 340. For HTMS, it is shown that increasing the flowrate declines the slope of temperature increase and prolonged the phase change duration which corresponds to a lower steady-state temperature. Mass flowrate showed more significant effects at heating power of 12.5 W compared to 3.7 W.

Increment of Reynolds number to 530 and 720 in the hybrid scenario, caused temperature reduction of 1.4 °C and 2.6 °C respectively, compared to the minimum mass flowrate. Temperature history of simulated batteries at 12.5 W is demonstrated in Fig. 7.

As illustrated in Fig. 8, for the case of 4C discharge rate, the time window where the temperature is below the critical point is enlarged by increasing the inlet flowrate. It is due to the fact that increasing duration of melting has considerable effect in time requirement for reaching 60 °C. The corresponding time has increased by 29.7% and 75.4% at
higher mass flowrates. The temperatures at high Reynolds have reduced 5.3% and 9.5% when the battery surface temperature reached 60 °C at the minimum mass flowrate.

### 3.3. Nanofluid effect

Effect of water-Al₂O₃ nanofluid with volume fractions of 1% and 2% on cooling performance of active and HTMS in different heat generation power levels has been investigated in this section. Adding Al₂O₃ nanoparticles increased the thermal conductivity of cooling fluid which corresponds to a higher convective heat transfer coefficient around the battery pack. Fig. 9 shows effect of using nanofluid as cooling fluid on the thermal performance of batteries in active method at different Reynolds number in heat generation power of 3.7 W. As illustrated in Fig. 9, using nanofluid decreased the maximum steady-state temperature by 1.8 °C and 2.2 °C for volume fractions of 1% and 2%, respectively. As Fig. 9 shows, increasing nanofluid volume fraction did not have a considerable effect on lowering the temperature. Effect of increasing the mass flowrate is less in nanofluid than in pure water. Increasing Reynolds from 340 to 530 and 720 in nanofluid with volume fraction of 2% corresponds to a reduction in the maximum temperature by 1.2 °C and 2.1 °C, respectively. These numbers clearly show lower effectiveness of flowrate in the nanofluid case compared to water. For the case of HTMS, it was illustrated that increment of convective heat transfer coefficient around the battery pack was not effective in lowering the temperature; therefore, for the heat generation power of 3.7 W with nanofluid, only active method was investigated.

Temperature variation with time for the heat generation power of 12.5 W is illustrated in Fig. 10 for the active method and HTMS scenario. In the active method, using nanofluid prolonged time duration of reaching the safety limit temperature. As mass flowrate increased, the rate of temperature increase is declined. At Reynolds number of 720, the maximum temperature of batteries was kept under the critical level at a steady-state temperature of 59.6 °C. The influence of using nanofluid is more considerable when heat generation power is higher in the batteries. In the active method, as shown in Fig. 10-(a), the temperature decreased 9.3% compared to the case using water at Re = 340, when temperature of battery reached the safety limit. So, reduction of temperature after adding nanoparticles to the water is more evident at higher heat generation power levels. As depicted in Fig. 10-(b), same trend of temperature variation is seen by using nanofluid. The maximum temperature increased with a high slope and after 1800 s the rate is being damped as the melting process of paraffin has begun. After 3315 s—melting process—temperature rose gently up to the steady-state temperature of 49.7 °C for the volume fraction of 2%. In HTMS, using nanofluid increased the time of melting compared to water as shown in Fig. 10-(b) which resulted in a temperature reduction of 2.3 °C. This shows a more effective value (4.5%) for nanofluid with volume fraction of 2% compared to water at Reynolds of 340. In higher flowrates, the influence of using nanoparticles on improving thermal
Fig. 7. Effect of Reynolds number on maximum temperature of module at heat generation power of 12.5 W in (a) active method (b) hybrid method.

Fig. 8. Effect of Reynolds number on the maximum temperature of module at 4C discharge rate condition in hybrid method.
Fig. 9. Maximum temperature of battery module with different coolant flows for heat generation power of 3.7 W in active method.

Fig. 10. Maximum temperature of battery module with different coolant flows for heat generation power of 12.5 W in (a) active method (b) hybrid method.
performance of batteries is declined. At $Re = 720$, adding nanoparticle decreased the steady-state temperature by 1.8 °C compared to the same conditions with water, when the battery temperature reaches safety limit.

Thermal response of battery in 4C discharge rate condition by using nanofluid is depicted in Fig. 11. As illustrated in Fig. 11-a, at Reynolds number of 340 using nanofluid in the active method reduced the temperature by 12.6% and 15.5% for volume fractions of 1% and 2% compared to pure water when the battery temperature reaches the safety limit. The temperature reduction in the hybrid system was 7% and 8.5% for volume fractions of 1% and 2%, respectively. By increasing the Reynolds number of nanofluid to 720, the temperatures were kept below the safety limit at a steady state temperature of 59.2 °C and 57.5 °C for nanofluid-1% and 2%, respectively. As shown in Fig. 9–11, the influence of using nanofluid is more remarkable in improving the performance of thermal management system under critical situations, e.g., lower contact surfaces and higher heat generation in the battery pack.

3.4. Temperature uniformity

It is essential to keep the temperature of batteries uniform within the battery pack in order to prevent capacity fading of the entire module. To characterize this aspect, the temperature difference between heater 1 and 2 in the pack are measured under different conditions of cooling in active and hybrid methods for three heat generation power levels. Fig. 12 shows the maximum temperature difference in the experiments. At the heat generation power of 12.5 W and 4C discharge rate condition, the temperature difference for active method was measured by continuing the experiment until the maximum temperature reached the safety limit, in order to record the highest temperature difference. Indeed, lower temperature difference between the cells corresponds to more effective temperature uniformity. Utilizing nanofluid has improved the temperature uniformity in the active system. The maximum temperature difference in the active cooling using water was measured as 1.1 °C, 2.7 °C, and 4.3 °C for three heat generation power levels which indicates that the temperature gradient increased at higher heat generation power levels. By using nanofluid with volume fraction of 2%, the maximum temperature difference reduced to 0.9 °C, 2 °C, and 3.4 °C at various power rates in the active cooling method. As shown in Fig. 12-b and Fig. 12-c, the best temperature uniformity is observed in the HTMS system with nanofluid, where the temperature difference is decreased to 0.5 °C and 0.9 °C for 12.5 W and 4C discharge at $Re = 720$. The improvement in uniformity for HTMS confirms that the heat is conducted more efficiently through CF-PCM composite and more thermal contact is available between the batteries and cooling channel through conduction which prevent heat accumulation in the critical points. Mass flowrate is also

![Fig. 11. Maximum temperature of battery module with different coolant flows for 4C discharge rate condition in (a) active method (b) hybrid method.](image-url)
influencing the temperature uniformity. As Fig. 12 shows, by increasing the flowrate, heat is dissipated more effectively from the critical points of heat accumulation and therefore more temperature uniformity is observed. In HTMS, increasing Reynolds number shows a negligible effect in the temperature homogeneity especially in low heat generation power levels. Using nanofluid and increasing flowrate is more effective in improving uniformity for active method since more heat is dissipated to the cooling channel through CF-PCM composite.

3.5. Power consumption

Fig. 13 shows the power consumption—obtained from the measured pressure drop of the circulating coolant—at different mass flowrates. Since the power for circulating coolant through the module is obtained from the batteries, it is essential to minimize it. As illustrated in Fig. 13, at higher flowrates more power is required for nanofluid compared to water. By increasing the Reynolds number of water from 340 to 530, the power consumption increases 195%. Power consumption increment in the same mass flowrate was 34.3% and 51% for nanofluid volume fractions of 1% and 2%. It was depicted in the last sections that utilizing nanofluid with the same mass flowrate can demonstrate a better thermal performance than increasing the flow. Therefore, it can be concluded that in cases where there is a need for increasing mass flowrate, it is more effective to use nanofluid instead.

Taken together, these results suggest that in hybrid method, for low heat generation power of 3.7 W, water flow with Reynolds number of 340 had the lowest power consumption and the best performance for keeping temperature in the safe limit. At 12.5 W, nanofluid with volume fraction of 2% and Reynolds number of 530 had the best performance considering both temperature control and power consumption. For high critical power heat generation of 42.5 W, nanofluid with volume fraction of 2% and Reynolds number of 720 outperformed the other cases.

4. Conclusion

Thermal performance of a novel hybrid thermal management system, consisting phase change material embedded in copper metal foam and nanofluid coolant flow was experimentally investigated in this study. Thermal response of batteries under passive, active, and hybrid thermal management systems were compared. Temperature history of the simulated batteries were examined under two kinds of fluid: water and water-based nanofluid. The major findings are summarized below:

(1). It was observed that because of poor convective heat transfer coefficient around the battery pack, the passive method failed to control the temperature of simulated batteries within the safety limit. It was found that by increasing the convective coefficient for pure PCM, because of its low thermal conductivity, heat was not dissipated to the surrounding efficiently and caused accumulation of heat which consequently led to failure in controlling the temperature.

(2). It was further depicted that active method was able to maintain the temperature in a steady state level of 44.5 °C at the heat generation power of 3.7 W. In higher heat generation power levels, active method failed to maintain the temperature of batteries under the desired limit.

(3). Investigating the effect of coolant flowrate showed that mass flowrate has more influence at higher heat generation power levels. Temperature reduction by increasing Reynolds number from 340 to 720 was found to be 2.6 °C and 10.5 °C at heat generation power of 3.7 W and 4C discharge rate condition, respectively.


