Lithium-ion battery thermal management system with Al$_2$O$_3$/AgO/CuO nanofluids and phase change material

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HIGHLIGHTS
- A novel design introduced for cooling Li-ion battery using active/passive methods.
- Surface temperature distribution of battery in the hybrid case didn’t exceed 5 °C.
- Heat sink with fins could remarkably prolong the working time of battery.
- AgO nanoparticles have the outstanding effect on reducing battery temperature.

ABSTRACT
Nanofluids are emerging heat transfer media. Notably, usage of these materials in electronic cooling applications exhibits many peculiar benefits. This paper attempts to analyze the battery thermal management system for pouch lithium-ion battery modules. The experiments were conducted for pure water and nanofluid type battery thermal management systems combined with copper foam filled with paraffin wax as a phase change material with massive heat storage potential. An aluminum heat sink—specifically designed for this purpose—was considered as the inlet duct. A battery surrogate was employed to simulate the heat generated by Li-ion battery at high current discharge and the onset of thermal runaway conditions. The results of experimental tests revealed that the cooling efficiency of the system based on nanofluids is improved significantly. Different oxide-nanofluid slurries were tested and among all AgO was the best candidate. The maximum temperature of the battery is reduced by about 4.1 K by AgO/water nanofluid with 2% vol concentration compared to the battery thermal management systems based on pure water. It is further found that the maximum battery temperature difference is reduced by approximately 77% in the presence of copper foam with/without phase change material. The results also proved the imperative role of active/passive system combination that benefits the advantages of both approaches at the same time.

1. Introduction
Given the contribution of fossil fuels to greenhouse gas emissions, much research has been devoted recently to developing electric vehicles (EV). Among the various available types of batteries for EVs, the lithium-ion battery is known as the most promising source of energy, notably because of its high energy density, long life cycle, and no memory effect [1]. However, the operating temperature of the battery must be maintained within a specific range [2]. A significant amount of heat is generated inside the battery within the charge and discharge processes, due to the considerable internal resistance and the thermal reactions occurring inside the cell. Hence, Battery thermal management system (BTMS) is vital to regulating the battery’s temperature within a safe range of operation [3]. Therefore, it is an important task to use efficient BTMS to keep operating the temperature of lithium-ion batteries in the range of 25–50 °C [4]. In general, the available methods in the literature for thermal management of batteries are divided into three main categories: active, passive, and hybrid, which is a combination of active and passive systems. In the active methods, energy is directly used for cooling, such as cooling systems that operate with...
forced convection airflow. In passive methods, cooling is performed without any external energy consumption, including natural convection heat transfer, heat transfer through heat pipes, and heat management using phase change material (PCM) [5],[6]. In an experimental work, Huang et al. [7], investigated the performance of combined PCM/heat pipe approach (air/liquid cooled system) for thermal management of battery pack.

Park and Jung [8], developed a 1-D thermal model of a cylindrical battery employing the finite difference method to solve for temperature, power usage, and operating conditions in the cell. Park’s BTMS analysis provides a numerical model for measuring either air or liquid-based systems. The numerical analysis indicates that a slim battery module with a small distance between cells is simply suitable for the liquid-based BTMS. They also reported that the air-based BTMS consumes more energy than the liquid-based BTMS. Also, Mahamud and Park [9], provided a novel method for thermal management of batteries using a reciprocating airflow for lithium-ion cylinders (LiMn₂O₄/C) using 2-D computational fluid dynamics model. Their numerical results show that the reciprocating current can reduce the cell temperature difference by about 4 °C and also the maximum cell temperature by up to 1.5 °C for a reciprocation period of 120 s. Battery cell temperature distribution is optimized by Chen et al. [10], for BTMS parallel cooling. The cell space distance from the battery pack in air-cooling is decreased because a regular battery in electric hybrid vehicles consists of many parameters should be considered, including cost, complexity in geometry, weight, cooling effects, temperature uniformity, and parasitic load. Chen et al. [16], examined four methods of cooling: air-based, direct liquid-based, indirect liquid-based, and fin cooling. The results show that the energy required by an air cooling system is 2–3 times higher than other methods to maintain the same mean temperature value. Indirect liquid cooling performs better in heat dissipation compared to direct liquid cooling, although its cooling performance is less. Chacko and Charmer [17], assessed the performance of an indirect liquid cooling battery and reported that this technique could be one of the most reliable ways of achieving battery thermal management. Panchal et al. [18], presented a comparative numerical and experimental study in small channel cold plates. The results show that increasing the discharge rate and operating temperature enhances the temperature of the cold plates. Basu et al. [19], proposed a cooling-based BTMS for the 18650-battery model. A novel BTMS with liquid coolant is described in which the cells are thermally connected by aluminum elements.

Sefidan et al. [20], investigated the thermal management with Al₂O₃ nanoparticle. For this direct liquid-cell contact, the ambient airflow dissipates the generated heat. The results show that the new method can reduce the maximum temperature of the cell significantly. Nanofluids and metal foams have also been extensively studied in various cooling applications [21]. The consistent experimental and numerical results show that the thermal performance of nanofluids is significantly influenced by many parameters that are difficult to control. Al₂O₃ is the most widely used nanoparticle due to its appropriate thermal and physical properties. These nanoparticles are among the most inexpensive types available on the market that can offer excellent performance and stability [22]. Two approaches are presented for using...
the nanofluid-cooling system. The cooling performance of the water-nanoparticles slurry is presented by Jilte et al. [23], at 2C and 4C discharge rates. Their results show using nanoparticles can improve the performance of the BTMS. Deng et al. [24], investigated the performance of cooling fluid containing nanoparticles in the BTMS. The results showed that water-based nanofluids perform better in controlling the maximum temperature and temperature deviation. It is due to the high thermal conductivity of pure water in comparison with the conventional base fluids (e.g., glycol). Khaleduzzaman et al. [25], investigated the thermal characteristics Al2O3-water, CuO-water, and SiC-water nanofluids. The nanofluids were analyzed at concentrations of 0.5–4% at two different input velocities of 0.5 m/s and 3 m/s. The results show that the case of Al2O3-water and CuO-Water nanofluid slurries, the maximum improvement for 4.0% volumetric fraction of nanoparticles was 11.98% and 11.36%, respectively. In Liu’s work [26], a cooling system was numerically investigated for various base fluids—water, ethylene glycol (EG), and motor oil—and the nanofluid was used as the coolant. Water, because of its high thermal conductivity, has a much better effect than EG and motor oil. Besides, a remarkable increase in performance was observed with the increase in the volume of suspended nanoparticles, while the cost of electricity increases simultaneously.

Al-Hallaj and Selman [27], introduced a new thermal management system for EV batteries with PCM [28]. The main advantage of the PCM thermal management system is that it stores the heat generated during the discharge process of the battery as the latent heat in the PCM. Duan and Naterer [29], investigated experimentally the thermal management of battery units with PCMs using an electric heater to simulate the battery’s heat source. This study examined the effectiveness of PCM under different heating rates, and different ambient temperatures. Rao et al. [30], discussed the performance of a thermal energy management system using PCMs. The results show that thermal resistance of the battery cells results in an inevitable temperature difference. It is also necessary to improve the thermal conductivity of PCM and reduce the melting point to increase the heat transfer rate. PCM composite materials including, paraffin and aluminum foam, were investigated experimentally by Wang et al. [31]. The experimental results showed that the paraffin and aluminum foam composite are capable of controlling the temperature rise within the Li-ion batteries during the discharge course. The additive aluminum foam structure improves the effective conductivity of the PCM significantly. Ye et al. [32], investigated numerically the latent heat thermal energy storage and using fins to improve the melting and solidification of PCM in dual-pipe [33].

The PCM required for lithium-ion batteries should usually have a melting point of less than 40 °C with a small temperature gap for the melting process [34]. Karimi et al. [35], developed a battery simulation to test heat production in a Li-ion battery. It was reported that the metal-PCM composite could reduce the temperature difference between the battery surface and the PCM composite by up to 70%. Li et al. [36], designed and tested a CF/PCM (copper foam/phase change material) battery management system for various types of Li-ion batteries with relatively high discharge rates. The results showed that the effect of PCM on temperature control was improved compared to the air-based BTMS in an insulated environment. Besides, it was found that the maximum temperature of the batteries coupled with CF/PCM can be controlled for longer periods at lower temperatures.

Recently, Salfardi et al. [37], investigated different configurations of the hybrid BTMS. The thermal management of the battery group is examined at the different charge and discharge periods. The results show that the use of latent heat of fusion as a passive coolant in the BTMS is effective and also the forced airflow channel is more efficient than other methods in cooling at a higher charge or discharge rate. Sun et al. [38], proposed new fin structures with longitudinal fins and cylindrical rings to enhance the rate of heat transfer. The PCM based BTMS usually suffers from low thermal conductivity of these materials.

The results showed that the PCM-fin system outperformed the PCM-free battery and even the systems with pure PCM. Passive heat management systems with PCM are an efficient solution to prevent overheating of Li-ion batteries. The temperature in a battery pack that works continuously is within the safety range of 60 °C after two cycles at a discharge rate of 1.5–2C. Ling et al. [39], have provided a hybrid system that includes composite paraffin/EG PCMs integrated with forced air transport. This hybrid system has successfully prevented heat accumulation and maintained the maximum temperature below 50 °C in all cycles. Samimi et al. [40], studied the weakness of PCM due to their low heat dissipation rate that was offset by adding carbon fiber-reinforced composites to cool down the Li-ion batteries. It was reported that carbon fiber improves the effective thermal conductivity of the system and thus affects the temperature distribution inside the cell. Wu et al. [41], designed a BTMS based on the combination of PCM with a heat pipe to make possible the widespread use of energy for electric and hybrid electric vehicles. The experimental results showed that the high temperature of the battery module could be managed by the heat pipes, which are activated at high discharge rates. Besides, with forced convection, the highest temperature can be kept below 50 °C even under the maximum discharge rate (5C) and have lower temperature fluctuations. An advanced BTMS for Li-ion batteries of electric cars can be categorized into air, liquid, or PCM-based. Although air-based systems are safe and economical, they still suffer from low thermal efficiency. PCMs can provide the proper operating temperature. Available studies suggest that hybrid systems can now overcome these problems [42], [43]. Mehrabi-Kermani et al. [44], used a system that includes a combination of forced air heat convection as the active part and paraffin PCM with a melting temperature range of 42–44 °C as the passive part. This system is injected into a copper metal foam as a skeleton structure of phase change material. The results showed that the use of paraffin, metal foam, and forced airflow could keep the battery surface temperature stable during normal and fast charge in the permissible temperature range (i.e., below 60 °C). In a follow-up investigation, Kiani et al. [45], performed the investigation with nanofluid and suggested that hybrid nanofluid cooling can significantly extend the operating time of the battery.

Existing research recognizes that each battery must have a thermal management system, either passive or active, wherein always be maintained in a safe temperature range because thermal runaway impedes the desirable performance of lithium-ion batteries. Prior studies show that heat generated by batteries cannot be removed by the inefficient cooling of air convection, particularly at high charge/discharge rates which eventually leads to failures of the thermal management system. To the best of the authors’ knowledge, there is no study which combines all active and passive methods such as nanofluid, PCM, and heat sink with fins. Hence, hybrid thermal management can provide an effective solution for overheating periods of lithium-ion batteries. Indeed, this paper underscores the potential of a novel battery thermal management system, which comprises nanofluids with high thermal conductivity (AgO and CuO used as the first time in thermal management), heat sink (fins used for the first time), and embedded paraffine-copper foam composite to cope with the harsh thermal loads.

For safety reasons, the Li-ion battery pack was substituted with a film heater, because tests were performed under stressful and harsh conditions such as maximum battery temperature range and thermal runaway situation. The main aim of this work is, therefore, to integrate the nanofluids with high thermal conductivity and a composite form of phase change material within the copper foam to benefit from these heat transfer media simultaneously. The nanofluids were used as liquid coolants, and the effect of nanofluids on thermal battery management was experimentally investigated in terms of different nanoparticles with water-based fluid, volume fractions, flow velocities, heat fluxes, and pressure drop. The combined active and passive method introduced in this study can be considered as a highly promising candidate for battery cooling applications. Finally, one of the key issues in the thermal
management of Li-ion batteries is not only to control and keep the temperature below a certain limit, but also to have a homogeneous temperature within the pack. As such, in most real applications, the cylindrical batteries are being cooled from two sides. Therefore, in a symmetrical approach, we implemented two channels to cool the battery from both sides. This can be simply applied to the cylindrical battery cells. In addition, to control similar conditions for all experiments, we utilized various measures: recording/keeping the temperature of the inlet flow with thermal bath, controlling/recording the temperature/humidity of the environment etc.

2. Experimental study and procedure

2.1. PCM-Metal foam properties

Paraffin (P 42–44 #107150) has been used as the PCM in block form. The temperature range at which the melting occurs depends upon the type of PCM. The PCM supplied from MERCRO Company. The commercial paraffin is insoluble in water, non-toxic without regular decay, odorless, and chemically stable. The thermal conductivity of paraffin wax was evaluated by a KD2 Pro device which uses transient hot-wire technique and its accuracy was ± 0.01 W m⁻¹ K⁻¹. The measurement was carried out for liquid and solid samples. With the assistance of an FP40-HC constant temperature bath (Julabo GmbH), the temperature of the solid and melting phase was fixed at 25 ± 0.5 °C and 45 ± 0.5 °C, respectively. These temperature values are used to obtain the thermal conductivity of the paraffin. Therefore, paraffin’s thermal conductivities for the solid and liquid phases are 0.205 and 0.317 W m⁻¹ K⁻¹, respectively. Other thermal properties are presented in Table 1.

The melting temperature range is 37.80–44.23 °C and its latent heat of fusion is 249 kJ kg⁻¹. The specific heat of solid and liquid paraffin is 2.383 and 1.929 kJ kg⁻¹ K⁻¹, respectively [46]. The PCM density is 0.9 kg m⁻³ at 80 °C, therefore, the paraffin oil enters into the aluminum canal (with the effective surface) by the pneumatic hoses and the fluid molecules along with nanoparticles vacate from the output of the test section after oscillating with inside steps of the heat sink. The plate was 3 mm thick, and the height of each fin inside the plate is 2 mm. This design intended to increase the flow turbulence and therefore enhance the heat transfer. Also, the channel is sealed carefully by placing screws on the top and bottom in addition to using silicone insulators. Outer surfaces of the experimental setup made from transparent Plexiglas sheets with 2 mm thickness. Selecting this material was due to its specific properties, including lucidity (to see the paraffin melting process, the system monitoring during the test process), to resist against heat, and having a low thermal conductivity coefficient. The central part of the test section consists of two symmetrical parts including the liquid and nanoparticles are presented in Table 2.

2.2. Experimental set-up

Heat sink usually is used in electronic cooling applications. Expanding the heat transfer surfaces by fins in various dimensions and shapes is one of the methods to increase thermal performance. Fin is usually fabricated with the same material of the wall that has high thermal conduction. The used heat sink in this study is made of aluminum material (Fig. 2).

The fluid flow enters into the aluminum canal (with the 13 cm × 7 cm effective surface) by the pneumatic hoses and the fluid molecules along with nanoparticles vacate from the output of the test section after oscillating with inside steps of the heat sink. The plate was 3 mm thick, and the height of each fin inside the plate is 2 mm. This design intended to increase the flow turbulence and therefore enhance the heat transfer. Also, the channel is sealed carefully by placing screws on the top and bottom in addition to using silicone insulators. Outer surfaces of the experimental setup made from transparent Plexiglas sheets with 2 mm thickness. Selecting this material was due to its specific properties, including lucidity (to see the paraffin melting process, the system monitoring during the test process), to resist against heat, and having a low thermal conductivity coefficient. The central part of the test section consists of two symmetrical parts including the insulators, mica heater, steel plate, and copper foam. The foam was placed from outside into each part. Moreover, the fluid passage is between the two parts (see Figs. 3 and Fig. 4).

2.2.1. Experimental procedure

The setup consists of the fluid passage, heater, and the steel plates connected to it, thermocouples, the metal foam, paraffin, pressure drop measurement device, and data acquisition system for temperature
recording. The Variac voltage transformer was used to determine voltage for each test, enable the heater, and provide a constant thermal flux on the steel plate surface.

While the pump is being adjusted, the fluid flow gets to the set temperature simultaneously by passing through the copper coils inside the constant temperature bath. Then, the fluid enters the flowmeter and continues toward the channel. First, bypassing via the flow-parallelizer, the turbulence level decreases inside the channel. Then fluid enters the channel with nine steps.

Eight K-type thermocouples (Class A, Testo Company, Germany, uncertainty 0.75%) are installed in various sections of the setup. The bulk temperature of nanofluid recorded in the inlet and outlet of the heat sink and the other thermocouples are used to measure the temperature of the battery surface. As the surface of the mica, the heater is insulated and not deemed suitable for attaching thermocouples, these thermocouples attached to the copper sheet with 0.25 mm thickness behind the film heater. The copper sheets mentioned above were employed because of their high thermal conductivity. Finally, all data are saved by the data logger throughout the test and sent to the computer for further processing.

2.3. Battery surrogate

The heat generation by lithium-ion batteries during charging and discharging operations mainly arising from two factors namely irreversible and reversible heat. Bernardi et al. [50], proposed a heat generation equation to estimate the heat generation rate in the cells of a LIB as a result of electrochemical processes, as follows:

![Fig. 2. Heat sink with fins.](image)

![Fig. 3. The flow diagram of the experimental setup.](image)

![Fig. 4. Schematic of the test section.](image)
\[ \dot{Q} = I(E - V) - I \left[ T \frac{dE}{dT} \right] \]  

(2)

Where \( V \), \( E \), and \( I \) represent the operating voltage, open-circuit voltage, and charge/discharge current, respectively. \( T \) denotes the local temperature and its unit is K. It should be noted that Joule heat and reaction heat are mainly considered in \( \dot{Q} \). In equation (1), irreversible heat including ohmic heat and polarization heat constitutes the first term on the right hand (denotes joule heat) and the second term is a reversible heat originated from entropy change related to the electro-chemical reactions (denotes reaction heat).

In the common electric vehicle rates, the first term is larger than the second term [51]. During stressful conditions, a sharp increase in temperature results in runaway operation where the reaction rates within the battery increase drastically, and as a result, temperature raises. Runaway condition is rather perilous as it leads to a battery explosion, therefore testing real batteries in thermal management research is relatively dangerous. Besides, operating at high discharge rates has debilitates the battery performance, which means that all tests would not have a similar condition. In harsh modes of battery operation, the high raising of temperature eventuates to thermal runaway. This runaway mode can lead to explosion and battery failure, which is the main reason for not using real batteries in thermal management experimental tests [35],[44],[52]. The only way to impose stressful conditions in the experimental test is to use an alternative method, which is a substitution of real batteries by a film heater. Mica sheets are therefore used for making the film heater and an aluminum sheet with 0.2 mm thickness attached to the inner surface of the film heater. The mica material is employed for the heater to avoid any electrical contact. The outer surface of the aluminum sheet, which is the battery packing simulation is in contact with the PCM-copper foam composite. The outer side of the film heater is attached to a cooper sheet to prevent heat dissipation from the backside of the setup and use for thermocouples contact installations. For providing the electrical voltage and current of the simulated battery, an AC power supply was employed with a voltage rating of 0–300 V and current rating of 0–3 A. The heating power of the heater can be obtained by ohmic law:

\[ P = \frac{V^2}{R} \]  

(3)

Where \( V \) is voltage and \( R \) is the utilized electrical resistance which is 900 ohms for the heater. The ratio of heater thickness to its surface is small; therefore, surface cooling operation dominates the side heat transfer. An elastomeric layer with a heat transfer coefficient of 0.03 W m\(^{-1}\) K\(^{-1}\) isolated the lateral surfaces of the heater to prevent other heat losses.

### 2.4. Nanofluid preparation

In the present study, three nanoparticles—alumina (\( \text{Al}_2\text{O}_3 \)), copper oxide (CuO), and silver oxide (AgO)—were initially employed at a nominal diameter of 30 nm and purity of 99%. These nanoparticles were selected for the preparation of properly stable nano fluids. They have been prepared by two-step method in 1%, 2%, and 4% volumetric fractions. Aggregation of nanoparticles could be broken up by the ultrasonic process and improve these nanoparticles into the water as a base fluid [53],[54]. To stir the nanofluid, an ultrasonic agitator, manufactured by Hielischer, was used. The prepared nano fluids from alumina and copper oxide are shown in Fig. 5.

Mintsa et al. [55], presented an equation for calculating the thermal conductivity of alumina nano fluid at different nanoparticle sizes and temperatures:

\[ \frac{K_{\text{eff}}}{K_{\text{fl}}} = 1 + 4.4 \text{Re}^{0.4} \text{Pr}^{0.06} \left( \frac{T}{T_f} \right)^{10} \left( \frac{K_{\text{eff}}}{K_{\text{fl}}} \right)^{0.03} V F^{0.66} \]  

(4)

Where \( \text{Pr} \) is the base fluid’s Prandtl number, \( T \) is the nano fluid temperature, \( T_f \) is the freezing point of the based liquid, \( \text{Re} \) is the nano fluid Reynolds number, \( K_{\text{eff}} \) is the thermal conductivity of nanoparticles, and \( VF \) is the suspend nanoparticles’ volumetric fraction. Reynolds is obtained by:

\[ \text{Re} = \frac{\rho_f u_b d_p}{\mu_f} \]  

(5)

Where \( \mu_f \) and \( \rho_f \) are the dynamic viscosity and density of the based fluid, respectively, and \( d_p \) and \( u_b \) are the nanoparticles’ diameter and mean Brownian velocity.

### 3. Results and discussion

In this section, the results of the experiments, using the parameters listed in Table 3, are presented. The parameters of the baseline experiment and the following eight experiments carried out under different operational conditions are shown in Table 3.

BTMS performance is adjusted so that temperature variation on the battery surface (i.e., the heater temperature) meets the melting point of paraffin wax. Therefore, in the battery runaway condition, phase change within the PCM is completed. This study aims to prolong Li-ion battery life (i.e., postponing the runaway condition) in one hand and

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Fig. 5. Prepared nano fluid of CuO-Water (a) and Al\(_2\)O\(_3\) (b).
mitigate the maximum possible temperature of the battery (i.e., battery discharge process) on the other hand. Repeatability of the experiments is carefully assured by reiterating the tests. All experiments are carried out in the ambient temperature (i.e., 25 °C). This temperature is also set as the inlet temperature of the fluid flow into the aluminum channel. Experiments are conducted at three-volume fractions of nanofluids (VF-1%, VF-2%, and VF-4%) and for three different Re numbers of 400, 600, and 900. The heating power of the battery surrogate is set to 40, 65, and 81 W, which corresponds to BTMS normal and stressful conditions in the presence of copper foam, Al channel, and PCM, respectively (see Fig. 6).

Maximum temperature of the battery, $T_{\text{max}}$, and the temperature difference between top and bottom battery cells are two important parameters in the study of the thermal performance of a battery under different cooling systems. Though experiments are generally performed in a transient state, in some experiments cooling system could remain the battery temperature in a steady-state and safe condition, as well.

The maximum temperature ($T_{\text{max}}$) variation of the battery over time by using AgO nanofluid as the base case (Table 3) is illustrated in Fig. 7. The effect of utilizing AgO as additive nanoparticles in water in comparison with pure water could be clearly distinguished from the graph. As can be observed, using AgO nanofluid instead of purified water accounts for prolonging the complete melting time by 950 s. Hence, the nanofluid of AgO is considered as the base case for all tests.

### 3.1. Effect of nano fluid type

In the first set of experiments, the volume fraction of nano fluids and Re number are fixed at 2% and 600, respectively. Deionized (DI) water

<table>
<thead>
<tr>
<th>Case</th>
<th>Nano</th>
<th>Re</th>
<th>q (W)</th>
<th>φ</th>
<th>HS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>AgO/water</td>
<td>600</td>
<td>65</td>
<td>2%</td>
<td>Without fin</td>
</tr>
<tr>
<td>I</td>
<td>AgO, Al$_2$O$_3$, CuO</td>
<td>600</td>
<td>65</td>
<td>2%</td>
<td>Without fin</td>
</tr>
<tr>
<td>II</td>
<td>AgO</td>
<td>600</td>
<td>65</td>
<td>1, 2, 4%</td>
<td>Without fin</td>
</tr>
<tr>
<td>III</td>
<td>AgO</td>
<td>600</td>
<td>65</td>
<td>2%</td>
<td>With/without fin</td>
</tr>
<tr>
<td>IV</td>
<td>AgO</td>
<td>400, 600, 900</td>
<td>65</td>
<td>2%</td>
<td>With fin</td>
</tr>
<tr>
<td>V</td>
<td>AgO</td>
<td>600</td>
<td>40, 65, 81</td>
<td>2%</td>
<td>With fin</td>
</tr>
</tbody>
</table>

VI Plots of hybrid and non-porous for the base case  
VII Plots of $\Delta T$ for hybrid and non-porous for the base case  
VIII Plots of $\Delta P$ for case II and case III  

Fig. 6. Circulation of DI water and nano fluids.  
Fig. 7. Temperature variation in the baseline experiment.
is used as a base-fluid, and three different nanofluids are dissolved in the slurry. Fig. 8 demonstrates the effect of the existence of Al₂O₃, CuO, and AgO nanoparticles on the battery temperature. Abscissa and ordinate in Fig. 8 are time, and the maximum temperature rises inside the battery, respectively. Fig. 8 shows the additive nanofluids can significantly improve the influence of forced convective heat transfer. Therefore, the battery can remain in a safe condition for a longer time in the presence of nanofluids. Highly thermally conductive metal oxide nanofluids which are uniformly dispersed within the base fluid (i.e., pure water) can enhance the slurry heat transfer coefficient.

Slurry heat transfer coefficient is directly proportional to the thermal conductivity of nanofluids and inversely proportional to thermal boundary layer thickness. Heat transfer in solid-liquid suspensions (e.g., nanoparticle-water slurry) occurs in the nanoparticle-particle-based fluid interface. Therefore, increasing the number of particles can improve the heat transfer rate. Much research shows an increase in effective thermal conductivity and chaotic movement of nanofluids contribute dramatically for an enhancement in the slurry heat transfer coefficient. Heat transfer in nanofluids stems mainly from the random chaotic motion of particles which is addressed as Brownian motion. The particle-particle, liquid particle, and wall-particle interactions due to Brownian motion in the nanoparticle-carrier fluid slurry generate micro-convection around the particles that increase the effective thermal conductivity of a two-component fluid.

Also, Fig. 8 shows additive nanoparticles can significantly enhance the heat transfer rate. The higher the thermal conductivity of nanoparticle, the more the reduction in maximum battery temperature. For instance, the AgO-Water slurry trend in Fig. 8 shows the most drastic effect on temperature drop. It is because of the high thermal conductivity of silver (i.e., 429 W m⁻¹ K⁻¹). Therefore, among all available candidates, AgO-Water slurry can remain in a safe condition for the longest time period. As can be seen in Fig. 8, all tests show similar general behavior for different nanoparticles as coolants. During the first 420 s, the maximum temperature in the battery increases rapidly. Afterward, the curves evolve gradually. This plateau is followed by a sudden increase in temperature while the battery is in a runaway condition. The temperature value corresponds to this second sharp increase in temperature, depends strongly on nanoparticle material (e.g., for CuO and Al₂O₃, it happens after 2950 s and 2600 s, respectively). Adding VF-2% AgO nanoparticle to pure water (heat flux and Re are 65 W and 600, respectively) after 2200 s leads to a 4.1 °C drop in maximum battery temperature. This temperature drop value for Al₂O₃ nanoparticle is 1.9 °C where all other parameters and operating conditions remain intact. In summary, adding Al₂O₃, CuO, and AgO nanoparticles can improve the thermal performance of the battery 23.8%, 40.5%, and 45.2% concerning pure water, respectively.

3.2. Effect of nanoparticle volume fraction

In this section, the effect of nanoparticles on the heat transfer coefficient is evaluated. Fig. 9 shows the evolution of maximum battery temperature for three different concentration values of nanoparticle volume fraction. All experiments are performed for AgO-pure water slurry in 65 W power and Re = 600. It is observed that more volume fraction nanoparticle, more reduction in maximum battery temperature, is achieved. For instance, at Re = 600 it takes 2450 s for 1% volume fraction paraffin wax to be melted completely while increasing the volume fraction to 2% and 4%, postposes the complete phase change of paraffin to 2850 s and 2900 s, respectively.

Fig. 9 validates increasing volume fraction of nanoparticles in the slurry can prolong the battery life. The increasing volume fraction of nanoparticles, enhance the possibility of particle-particle, liquid-particle, and wall-particle interactions which in turn stress out the Brownian motion. This Brownian motion, in turn, generates micro-convection around the particles that increase the effective thermal conductivity of a two-component fluid. The momentum and energy exchange continuously between nanoparticles in one hand and between carrier fluid and slow-moving particles on the hand.

3.3. Effect of a heat sink

Fig. 10 illustrates a comparison between the performance of finned and non-finned canals. By comparing the graphs, it is clear that the existence of fins results in a considerable prolonging of the complete melting time from 3650 s to 4100 s. The ambient temperature is regulated to ensure all experiments are carried out in constant ambient temperature. As well, the inlet temperature of the fluid into the aluminum canal remains intact. The temperature of a Li-ion battery can significantly impact its performance. Moreover, evenly distributed temperature profile can prolong battery life and enhance its performance and efficiency [58].

3.4. Effect of Reynolds number

Fig. 11 shows the evolution of battery temperature for different values of Re number. In all experiments, the coolant inlet temperature is 25 °C, and 65 W power is applied. Cascade heat sink along with AgO nanofluid is used. Fig. 11 verifies, the higher Re number, the better performance of BTMS. As the coolant can absorb more heat of battery at high Re numbers (i.e., gentle temperature gradient corresponds to high Re values in Fig. 11), the useful life of battery prolongs. On the other word, enhancing Re number helps BTMS to postpone the battery runaway condition. For instance, in an experiment corresponds to the greatest Re number (i.e., Re = 900) runaway condition occurs after 5600 s. At this time, battery surface temperature (thin copper plate) and aluminum surface are measured as 327.61 K and 322.3 K, respectively. Fig. 11 shows a similar behavior for all plots. During the first 200 s, while the PCM (paraffin wax) is still in the solid phase, the maximum battery temperature for all cases abruptly increases with time. The role of PCM is insignificant at this stage. Afterward, the paraffin wax starts to melt gradually, and the rate of battery cooling is increased dramatically due to the heat absorption by the PCM. This heating process continues until the entire paraffin wax is in the liquid phase. After this stage, the PCM can no longer absorb further energy by phase change, as its phase transformation is completed. At the completion of this phase, the maximum temperature of the battery starts to increase abruptly, and BTMS runaway condition starts. It is possible to postpone this abrupt change by tuning the inlet canal velocity with a greater Re number (e.g., Re = 900).

Fig. 8. Effect of various nanofluids on the cooling system.
Fig. 11 also shows in the realm of low Re number flow regime, BTMS is not efficient (e.g., at Re = 400, 600). It can be explained by considering how evenly nanoparticles are dispersed within the aluminum canal. Nanoparticles likely avoid regions in the vicinity of the canal walls and instead tend to occupy inner sections of the canal. Increasing Re number causes the accumulation of nanoparticles in the wall neighborhood, which in turn enhances the heat transfer rate.

3.5. Effect of battery heating power

Fig. 12 represents the evolution of temperature for both pure water and nanofluid. The nanofluid in these set of experiments is a silver oxide (AgO), and heating power is set to constant values of 40, 65, and 81 W. Comparing the graphs, it is evident that target steady-state temperature is solely achieved at the low level of heating power (e.g., 40 W). Thus, the coolant nanofluid is not capable of absorbing the heat generated within the battery efficiently.

Fig. 12 verifies through pure water scenario cannot perform efficiently as a coolant at a heating power of 81 W, but 2% volume fraction Ago-nanofluid slurry remains the battery still in the safe condition at the same heating power scenario.

Adding PCM to the nanofluid slurry generally improves the performance of the battery thermal management system. However, this promising impact on battery cooling is quite limited to its operation below a complete phase change temperature. Thermal resistance between cells and the environment drastically increases when the entire PCM is in the liquid phase. Therefore, at this stage (e.g., when phase change in PCM is completed), it is needed to avoid the nanofluid coolant (i.e., coolant air is simply adequate), as its presence leaves a negative impact on the overall cooling process.

3.6. Hybrid system

The effect of the presence of a hybrid (metal foam-paraffin) system in contrast to pure paraffin on the cooling process of battery is considered in this subsection. Fig. 13 shows the variation of battery surface temperature for both systems with and without metal foam under the condition of the base case, i.e., Reynolds number of 600 and heat sinks without fins for AgO-nanofluids. The coolant is AgO-nanofluid slurry in these two experiments.

Heat transfer occurs at a low rate in paraffin wax due to its low thermal conductivity value (i.e., $k = 0.205 \, \text{W m}^{-1} \, \text{K}^{-1}$). Therefore, the
PEC region which melts initially (i.e., regions in the vicinity of battery cells) acts as a heat sink, and keep the temperature constant close to the melting region. Consequently, the melting process of the entire PCM is postponed severely, due to the important insulating role of liquid PCM. Eventually, in test without copper foam as time goes on the maximum battery temperature gradually increases up to 56 °C, owing to the natural convection in liquid paraffin. Hybrid (metal foam-paraffin) system is an alternative to paraffin wax which can keep the battery in a safe condition for a longer time. Metal foam molecular structure helps the heat to be distributed evenly inside the battery. As a result, the time of reaching to maximum temperature dramatically increases, which in turn prolongs the battery life. Finally, the accumulation of thermal energy within the PCM structure would fail the BTMS.

Melting area and melting time of paraffin-metal foam composite in the experiment, confirmed in Fig. 14.

Besides, the process of phase change begins later when the PCM is embedded in the copper foam in comparison to the test without copper foam. This phenomenon is attributed to using copper foam in the hybrid test, which enhances the heat transfer rate. Indeed, the copper foam acts as a conductive structure to enhance the phase change process. After around 50 min, maximum heater temperature reaches of 51.4 °C, indicating copper foam leads the PCM fusion process complete. Afterward, thermal runaway begins.

The behavior of maximum temperature profile within the battery is presented schematically in Fig. 15 for both in the presence and absence of PCM scenarios. The entire battery cooling process is summarized in three following stages.

Stage I: The maximum temperature is increasing continuously. Battery surface temperature is relatively low and the temperature difference between nanofluid and battery is insignificant, as well. Battery temperature quickly increases, as the pure water coolant is unable of removing the entire heat generated in the battery. In this stage, battery maximum temperature can be regulated by tuning nanoparticles volume fraction properly. Higher volume fraction, higher heat transfer coefficient, and a consequently slower increase in maximum temperature is achieved. Moreover, enhancing the heat transfer coefficient mitigating the temperature difference between the battery interior and battery surface.

Stage II: Heat is absorbed by paraffin as its latent heat of fusion and paraffin melts gradually. Therefore, in this stage battery surface temperature approximately remains constant. This stable temperature condition delineates the generated heat within the battery is completely removed by nanofluid-paraffin combination.

Stage III: battery temperature is increasing, and the runaway condition is inevitable. The battery internal resistance significantly increases at the end of the battery discharge process, which finally results in a battery runaway condition. The augmented heat in this stage can be regulated with a nanofluid volume fraction.

PCM absorbs and releases heat at a preset temperature. Due to their relatively high values of latent heat of fusion, they can store and release large amounts of energy during the phase change process. The storage capacity of PCM is used to remove the heat dissipation of the battery. This process postpones the unfavorable battery runaway condition which promotes battery performance and eventually prolongs its useful life. As seen in Fig. 15, prior to start of the phase change (i.e., while PCM is in solid phase) conduction heat transfer prevails within the PCM. After reaching the transition point—while PCM starts to melt—the heating power of the battery is absorbed by the PCM.

Albeit PCM can keep the battery temperature in the safe operational condition in the vicinity of its melting region, removing the stored heat within the PCM is still an issue. This issue is caused by the low value of paraffin wax thermal conductivity. Porous media is introduced as a remedy for the low thermal conductivity of pure PCM.

Heating power of the battery is divided into two different parts. In the first part, the generated heat is absorbed by PCM as its latent heat of phase change, i.e., melting. In the second part, heat of battery is conveyed to the heat sink by the conduction mechanism. In the absence of porous medium, i.e., pure paraffin wax, where all heat is stored in PCM, the completion of phase change occurs much shorter than the similar case with porous medium (e.g., hybrid/metal-foam paraffin). For instance, according to Fig. 13, time corresponds to the complete melting of paraffin is increased by 2800 s when a porous system (i.e., hybrid/metal-foam paraffin) is replaced by a non-porous one (i.e., pure paraffin wax).

It can be observed in Figs. 13 and 8 that aluminum surface temperature of the battery is increasing in the range of 43.5–54.1 °C during paraffin phase change (400 s) compared to non-porous experiment. PCM-metal foam composite (paraffin-copper skeleton), postpones the unfavorable battery runaway condition, thus favorably impacts battery life and safety. This is vital for the improvement of battery
performance, especially in charge and discharge cycles. High thermally conductive copper foam promotes the overall heat transfer coefficient of copper foam-paraffin composite which in turn postpones significantly the complete melting process of paraffin.

High temperature differences in batteries can lead to reliability issues such as reduced battery life and battery efficiency. The temperature difference was kept below 5 °C during the experiment, while this value increased to 21.7 °C for non-porous testing (Fig. 16). The results are in agreement with the observations in previous studies [59],[60].

The presence of copper foam with/without PCM permits for an alike role of porous structure on enhancing the heat distribution by conduction. The effective thermal conductivity of foam (ɛ = 0.903) which was measured empirically was 11.98 W m⁻¹ K⁻¹.

3.7. Pressure drop

Pressure drop is a key parameter that plays a major role in nanofluid applications. The pump power usage is straight connected to the pressure drop in the trenches. At high pressure drops, large pumps and high pumping powers are required, which on one hand increases the system cost and on the other hand reduces the overall efficiency of the battery. The pressure drop between the inlet and the outlet of the test section is measured by a differential pressure transducer (Endress Hauser, UK). Fig. 17 shows the pressure drop in BTMS versus Re number for both pure water and AgO-nanofluid slurry. The nanofluid flow through the cooling arrangements leads to a higher pressure drop compared to pure water.

Obviously, pressure drop increases with the volume fraction of nanoparticles in the nanofluid. Although higher flow rates result in greater pressure drops, the adverse effect of nanofluid 2% in increasing the pressure drop is being reduced at higher Reynolds numbers. However, for the nanofluid 1%, it is almost independent of the Reynolds number.

At Re = 420, BTMS with the nanofluid 1%, 2%, and 4% produces 54.9, 59.2 and 72.4 Pa pressure drop, respectively, which is 19.3%, 28.6% and 57.3% greater than the pressure drop caused in the water-cooling scenario which is in good agreement with previous studies [61–64].

Experimental data for the pressure difference (ΔP) at different Reynolds numbers for case III that include the experiments with/without fins in channels are plotted in Fig. 18. Generally, the flow pressure drop in channel containing fins is higher than channel without fins. It should be noted that the pressure drop in the test section is mainly due to energy dissipated due to friction. These results are in good agreement with the literature [65].

4. Conclusion

This paper proposes a novel battery thermal management system, which is the combination of the active and passive cooling method comprises nanofluid cooling, heat sink, and embedded paraffin-metal foam composite. The proposed system has good potential for the thermal management of batteries. The following conclusions can be drawn:

- The presence of the suspended particles in the nanofluid causes increasing in its thermal conductivity, hence, the existence of suspended particles in cooling fluid enhances the heat transfer efficiency.
- Test results demonstrated that adding an appropriate amount of nanoparticles to the base fluid causes a remarkable improvement in the convective heat transfer coefficient. With increasing volumetric fraction of nanoparticles, the efficiency increases. It is clear that the sedimentation of nanoparticles in the base fluid as a deficient should be considered.
- Generally, enhancing the heat transfer rate with using nanofluids has unfavorable consequences such as pressure drop in operating fluid flow.
- The pressure drop will increase by increasing the Reynolds number of flow and nanofluid volumetric fraction as well. The effect of additive nanoparticles on the pressure drop is because of increased nanofluid’s viscosity at the presence of nanoparticles.
- The experiments showed that the permissible maximum temperature of the battery was significantly decreased by using an integrated cooling method, including, nanofluid cooling and phase change material-metal foam cooling. The temperature uniformity of the battery was also improved.
- In the best test case, when cooling fluid was AgO/water nanofluid with 2% volumetric fraction at Reynolds number of 900, the melting point of paraffin for completing process of melting is 44 °C which was approached in t = 5620 s.
- Phase change materials, despite having valuable pros, bring about some disadvantages including low heat transfer coefficient and leakage in battery system, which highlights the need that the tests should be done cautiously. However, the thermal performance of battery thermal management system can be improved by modifying the liquid channel configuration and cooling fluid's characteristics.
- The present system exhibits excellent and robust thermal performance for the battery pack, particularly by prolonging the working
Fig. 17. Pressure drop along with the cooling system at various Re numbers.

Fig. 18. Effect of fins on the pressure drop.

time at an operational temperature range.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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