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Experimental investigation of the cooling performance of hybrid nanofluid used in the thermal management system of an electric vehicle Li-ion battery

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Abstract
The increasing use of lithium-ion batteries, coupled with the increasing prevalence of electric vehicles, also increases the demand for battery thermal management systems. If the significant amount of heat generated by these batteries during operation cannot be adequately dissipated, the battery temperature rises, its performance decreases, and it can lead to failure. In this study, the effects of the use of an Al_2O_3-ZnO-water hybrid nanofluid on a cold plate for Li-ion electric vehicle batteries under various operating parameters on heat transfer rate, heat transfer coefficient, battery surface temperature and temperature difference, pressure drop, and voltage change were experimentally investigated. Experiments were conducted using three different volume flow rates (6 LPM, 7 LPM, 8 LPM), three different coolant inlet temperatures (10 °C, 15 °C, 20 °C), five different discharge rates (1 C, 2 C, 3 C, 4 C, 5 C), and four different nanoparticle volume concentrations (0.00625%, 0.0125%, 0.025%, 0.05%), and the findings were compared with pure water. As a result, the newly developed hybrid nanofluid was found to enhance the heat transfer rate by 42.5%, the heat transfer coefficient by 42.1%, and the pressure drop by 25.8%, while reducing the battery temperature and temperature difference by 3.8 °C and 32.8%, respectively, compared to pure water. In addition, the maximum PEC value of 1.15 indicates that the hybrid nanofluid is advantageous in terms of thermo-hydraulic performance. It was concluded that increasing volume concentration of the nanofluid and flow rate positively affects cooling performance and that battery cooling by natural convection is insufficient for discharge rates higher than 1 C. This research highlights the potential of Al_2O_3-ZnO-water hybrid nanofluid as an effective coolant to improve battery performance in electric vehicle applications.

Keywords Lithium-ion battery · Hybrid nanofluid · Battery thermal management · Al_2O_3–ZnO · Cooling performance

Introduction

Electric vehicles are increasingly gaining prominence in the global efforts to reduce the automotive industry's dependence on fossil fuels [1, 2]. Due to their high energy efficiency and potential for zero emissions, electric vehicles are regarded as a crucial solution for addressing energy challenges in the transportation sector and for reducing greenhouse gas emissions [3, 4]. The performance of electric vehicles largely depends on battery technology, which is essential for the growth and advancement of the electric vehicle industry. Among various battery technologies, lithium-ion batteries are widely preferred in electric vehicles due to their advanced features [3, 5]. These features include high operating voltage, impressive energy density, wide operating temperature range, long cycle life, low self-discharge rate, and no memory effect [5, 6]. Despite these attractive features, lithium-ion batteries are highly sensitive to temperature, and their performance is affected by temperature changes [7, 8]. Lithium-ion batteries suffer from a long life due to high temperature, in addition to the risk of thermal runaway and explosion at extreme temperatures that may occur during charging and discharging [7]. To overcome these disadvantages, a battery thermal management

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system (BTMS) that provides effective heat dissipation is required [2]. The main purpose of BTMS is to maintain the battery temperature within a certain range and ensure a uniform temperature distribution throughout the battery module [9]. A lithium-ion battery in an electric car operates optimally within a temperature range of 15–35 °C [10, 11]. In addition, to prevent the acceleration of the aging process and loss of usable battery capacity, the maximum temperature difference should not exceed 5 °C [12, 13].

BTMS generally encompasses both active and passive cooling methods, including air cooling, liquid cooling, phase change materials (PCM), and combinations thereof [3]. With its low energy consumption and cost advantages, air cooling is a simple and practical approach to heat dissipation [1]. However, this type of cooling is often inadequate due to the poor thermal properties of air and leads to temperature increases that may exceed safe operating limits [9]. The main disadvantages of PCM cooling are low thermal conductivity and heat buildup when the PCM melts [14]. In addition, a leak-proof design is required due to the volumetric development during the phase transition process, making the cooling system even more challenging [1]. Liquid-cooled BTMS emerges as a superior option due to its high specific heat capacity and thermal conductivity [5]. Many researchers [15–20] have reported that liquid BTMSs provide the best performance in terms of cooling efficiency, making them the most widely adopted BTMS type by commercial vehicle manufacturers [7, 21].

As the ever-increasing power demands of electric vehicles lead to higher thermal loads, scientists have focused on improving the performance of existing liquid BTMSs [7]. Advanced heat transfer fluids with superior thermophysical properties that can accommodate high thermal loads are investigated [22]. Nanofluids are innovative heat transfer fluids with significant potential to increase heat transfer efficiency and are increasingly used in various battery cooling systems in electric vehicles. Their superior thermal properties make them ideal for maintaining optimum battery temperatures and improving battery performance [3]. Nanofluids are formed by suspending metallic or non-metallic nanoparticles in base liquids such as oil, water, ethylene glycol, and other conventional fluids [23]. Nanosuspension particles show excellent thermal conductivity due to enhanced convection between liquid and solid particles [1, 11]. Recently, nanofluid-based cooling systems have attracted high attention from researchers due to their promising electrical and thermal conduction properties [14]. Wankhede et al. [10] experimentally investigated the cooling performance of Al_2O_3-water nanofluid at different operating parameters and found that the nanofluid reduced the battery temperature. In their study, Morali et al. [14] numerically investigated the effect of Fe_2O_3-water nanofluid on battery temperature at different operating parameters and emphasized that the increase in flow rate and volume concentration decreased the temperature. Hasan et al. [24] numerically investigated the use of SiO_2-water nanofluid with different diameters in BTMS and concluded that the Nusselt number increases with decreasing nanoparticle diameter. In the study conducted by Li et al. [25], the cooling of a cylindrical battery pack with nanofluid was investigated numerically, and it was stated that the increase in volume concentration increased the heat transfer coefficient. Wiriyasart et al. [26] numerically investigated the TiO_2-water nanofluid in cooling a cylindrical lithium-ion battery and stated that the nanofluid increased the cooling capacity compared to water. Tousi et al. [27] conducted a numerical study and concluded that AgO-water nanofluid increases the pressure drop while decreasing the battery temperature. Sarchami et al. [28] experimentally investigated the cooling of a cylindrical battery pack with Al_2O_3-water nanofluid and stated that increasing the volume concentration increased the pressure drop while decreasing the temperature. Liu et al. [29] also found in their numerical study that the addition of Al_2O_3 nanoparticles to water reduces the battery temperature and increases the pressure drop. In the numerical study conducted by Li et al. [30], it was found that the battery temperature decreased with increasing the SiO_2-water nanofluid concentration. Kiani et al. [31] experimentally investigated the use of different types of nanofluids in BTMS and stated that increasing volume concentration also increases the pressure drop. In the numerical study conducted by Liao et al. [32], it was emphasized that the cooling effect of the five different nanofluids used was better than water. In their numerical study, Yetik and Karakoç [19] concluded that the increase in Fe_2O_3-water concentration and flow rate decreased the battery temperature. In another numerical study by Yetik et al. [20], it was stated that increasing the Al_2O_3-water volume concentration decreased the battery temperature. Xu et al. [33] numerically investigated the effect of different types of nanofluids on cooling the battery pack and emphasized that the heat transfer performance of nanofluids is superior to that of conventional coolants.

Hybrid nanofluids are a more advanced type of nanofluid created by combining multiple nanoparticles in the base fluid and are the focus of the current study [11]. Hybrid nanofluid exhibits improved thermal properties thanks to synergistic interactions between nanoparticles, improving heat transfer capabilities and becoming a suitable option for highly efficient cooling solutions in battery systems [3]. In the numerical study conducted by Saad et al. [2], it was stated that the use of Fe_3O_4–CuO water nanofluid in mini channels with different configurations increased the friction factor. Venkateswarlu et al. [3] numerically studied the heat transfer performance in a prismatic battery cooling system using hybrid nanofluid and found that Cu-Al_2O_3-water hybrid nanofluid

increased the heat transfer rate while reducing the battery temperature compared to Al_2O_3-water nanofluid. In the study conducted by Venkateswarlu et al. [5], the effectiveness of the Cu-Al_2O_3-water hybrid nanofluid was investigated numerically, and superior heat transfer capabilities of the hybrid nanofluid were determined compared to conventional cooling fluids. In their study, Sheikholeslami et al. [8] numerically evaluated the performance of Fe_3O_4-SWMCT-water hybrid nanofluid and found that the inclusion of nanoparticles in the coolant reduced the battery temperature. Venkateswarlu et al. [9] numerically studied the thermal management of a pouch-type lithium-ion battery cooling system using MoS_2-GO-water hybrid nanofluid and emphasized that the hybrid nanofluid increased the cooling efficiency. Selvarajoo et al. [12] performed a numerical investigation of BTMS containing water and Al_2O_3–GO-based mono- and hybrid nanofluids and stated that the hybrid nanofluid reduced the temperature by 7.47%. In the numerical study conducted by Esmaeili and Sheikholeslami [34], it was emphasized that the use of Fe_3O_4-SWCNT-water hybrid nanofluid in cooling channels with different fin designs increased the heat transfer efficiency. In their numerical study, Kumar et al. [35] reported that Cu-Al_2O_3-water-based hybrid nanofluid provides a higher heat transfer rate compared to mono-nanofluids. Mishra et al. [36] numerically investigated the performance of CNT-Al_2O_3-water hybrid nanofluid for five different cooling plate designs and showed that it reduces the battery temperature compared to pure water. Jino et al. [37] concluded in their numerical study that the hybrid nanofluid enhances battery thermal management. Dilbaz et al. [38] numerically investigated the thermal performance of ND-Fe_3O_4-water-EG hybrid nanofluid and concluded that increasing the nanoparticle volume fraction improves the temperature distribution and reduces the battery temperature.

The literature review led to the following conclusions.

- Most of the existing studies in the literature have been conducted numerically. Few studies have been conducted experimentally.
- Using nanofluids instead of traditional liquids for battery cooling systems is more beneficial in terms of thermal performance. For practical applications, however, the cost–performance balance of nanofluids should also be taken into account. Although the initial cost of nanofluids is higher, their ability to improve cooling performance can provide cost savings in the long run. This includes lower maintenance costs, longer battery life, and lower energy consumption for cooling [24]. For BTMS applications, the long-term stability of nanofluids is also crucial. Over time, cooling performance may deteriorate due to nanoparticle aggregation and sedimentation brought on by repeated heating and cooling cycles [39, 40].
- Hybrid nanofluids have not yet been widely used as coolants in battery thermal management systems. Further research on this topic is clearly needed. Among various hybrid nanofluids, the Al_2O_3–ZnO combination has attracted the attention of researchers due to the properties of Al_2O_3 nanoparticles such as chemical stability, mechanical strength, and relatively low cost, and ZnO nanoparticles such as thermal conductivity and heat transfer performance [39, 41, 42]. Combining these nanoparticles with different thermophysical advantages can create a synergistic effect between the nanoparticles and ultimately achieve better thermal performance compared to conventional coolants and other nanofluids [43, 44]. Many studies have shown that Al_2O_3–ZnO hybrid nanofluids can improve heat transfer properties and thermal efficiency in various thermal engineering applications such as photovoltaic thermal systems, heat exchangers, and electronic cooling systems [45–48]. However, despite these promising findings, no numerical or experimental studies have been found in the literature regarding the use of Al_2O_3–ZnO hybrid nanofluid in battery cooling systems.

In the current study, an Al_2O_3-ZnO-water hybrid nanofluid was used in an experimental examination to assess the thermal performance of an electric vehicle battery thermal management system. The utilization of Al_2O_3-ZnO-water hybrid nanofluid for battery cooling applications has not been thoroughly studied, although many studies in the literature have focused on traditional coolants and single-particle nanofluids. Thus, the main novelty of this study is the experimental evaluation of this hybrid nanofluid's hydraulic and thermal performance in a liquid-cooled battery thermal management system. The impacts of various operational parameters on battery temperature, heat transfer rate, heat transfer coefficient, pressure drop, and battery voltage were systematically examined within the scope of the study. The aim of this study is to maintain the battery within a safe operating temperature range using a hybrid nanofluid with advanced thermophysical properties, thereby improving the thermal management performance of lithium-ion batteries. The findings from this study are expected to contribute to the development of efficient battery cooling systems for electric vehicle applications.

Experimental

Preparation and thermophysical properties of hybrid nanofluids

The two-step method is the most common technique for nanofluid preparation. In this approach, nanoparticles are

produced as dry powders, and ultrasonic power is often used to disperse them in the base fluid. Optimum ultrasonication time is required to achieve satisfactory dispersion and long-term stability. However, even after dispersion using ultrasonic power alone, the nanoparticles still have high surface energy, which promotes further aggregation over time, leading to instability in the nanofluid. Therefore, this dispersion technique is often combined with chemical stabilization methods (such as surfactant addition, pH adjustment, and surface modification) to obtain a nanofluid with long-term stability [21]. In this study, a two-step method was used to prepare the hybrid nanofluid as shown in Fig. 1. Al_2O_3 and ZnO nanoparticles were preferred due to their properties, such as chemical stability, low cost, and high thermal conductivity. Figure 2 shows SEM (scanning electron microscopy) images of the Al_2O_3 and ZnO nanoparticles utilized in the experiments. The Al_2O_3 and ZnO nanoparticles are approximately 18 nm in diameter, white in color, and both nanoparticles have an approximately spherical basic shape. Commercially purchased Al_2O_3 and ZnO nanoparticles were added to 8 L of pure water in equal mass ratios (50:50) to obtain predetermined volume concentrations by precisely weighing. The preparation process of the hybrid nanofluid includes magnetic stirring for half an hour followed by bath ultrasonication for 2 h. Triton X-100 surfactant was used to prevent the sedimentation of nanoparticles in the base fluid and to increase the stability of the nanofluid. In their study, Ahmed Bin-Abdun et al. [49] stated that as the surfactant concentration increases, the heat transfer rate decreases by approximately 35% at low volume concentrations. Since relatively low volume concentrations were used in the present study, the surfactant concentration was kept at a low level (%0,05). The samples with the highest concentration were prepared and kept for different times to observe the nanofluid stability, as shown in Fig. 3. At the end of these periods, it was observed that there was no visible precipitation and the nanofluids had sufficient stability.

In heat transfer studies, the thermophysical properties of fluids significantly affect performance. Understanding and managing these thermophysical properties plays a vital role in maximizing their efficiency in various applications. These properties include thermal conductivity,

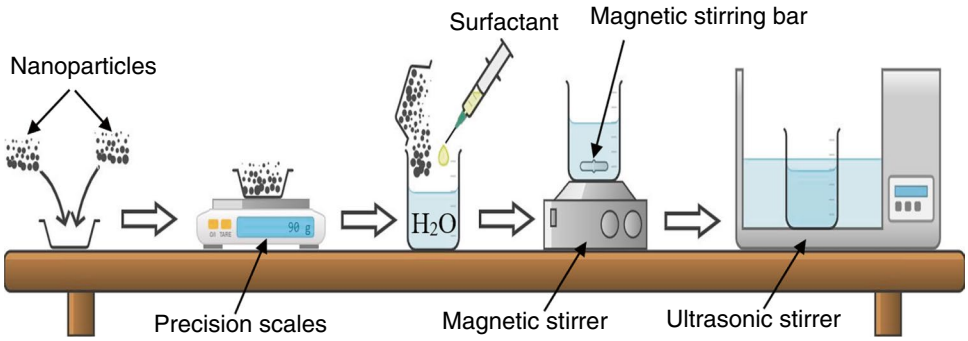


Fig. 1 Preparation of hybrid nanofluid

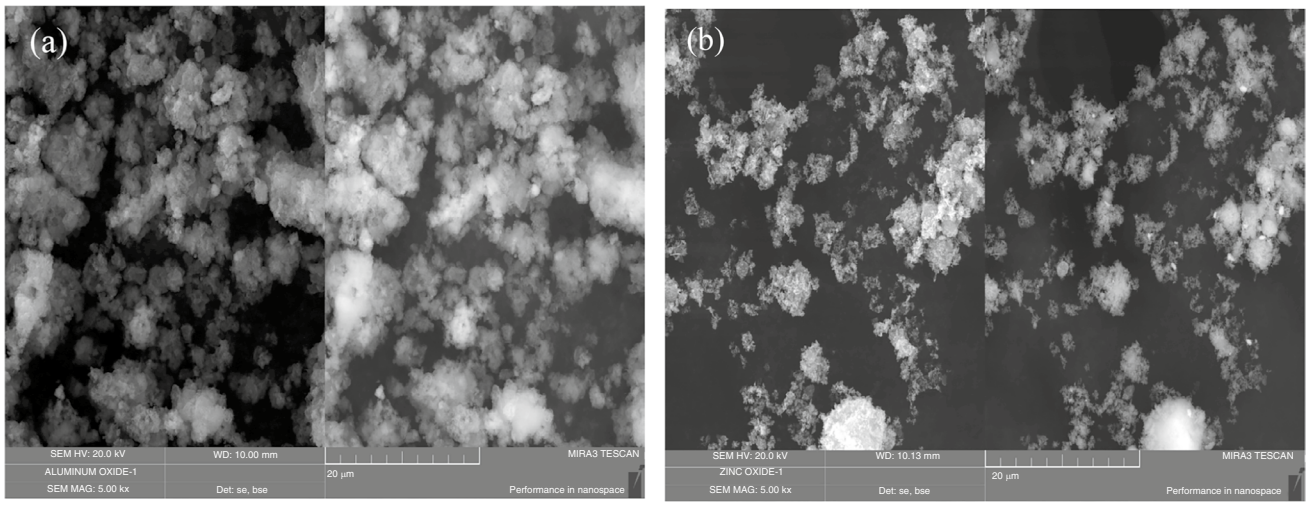


Fig. 2 SEM image of nanoparticles **a** Al_2O_3 and **b** ZnO



Fig. 3 Photographs of Al_2O_3-ZnO-water nanofluid at a 0.05% volume concentration taken after 1, 2, and 4 h

Table 1 Thermophysical properties of water, ZnO, and Al_2O_3 nanoparticles [50, 51]

Properties	Water	ZnO	Al_2O_3
Density/kg m^{-3}	997.1	5500	3970
Specific heat capacity/J kg^{-1} K^{-1}	4179	502.7	765
Thermal conductivity/W m^{-1} K^{-1}	0.613	58	40

viscosity, specific heat capacity, and density [3]. Thermophysical properties of pure water, Al_2O_3, and ZnO nanoparticles are given in Table 1.

In determining the thermophysical properties of the hybrid nanofluid used in the study, correlations widely used and validated in the literature were preferred. The density (ρ_{hnf}) and specific heat capacity ($c_{p_{hnf}}$) of the ZnO-Al_2O_3-water hybrid nanofluid are calculated via Eqs. 1 and 2, respectively [52].

$$\rho_{hnf} = \rho_{bf}\left(1-\varphi_{np2}\right)\left[\left(1-\varphi_{np1}\right)+\varphi_{np1}\left(\frac{\rho_{np1}}{\rho_{bf}}\right)\right]+\varphi_{np2}\rho_{np2} \tag{1}$$

$$c_{p_{hnf}} = \frac{\rho_{bf}c_{p_{bf}}\left(1-\varphi_{np2}\right)\left[\left(1-\varphi_{np1}\right)+\varphi_{np1}\frac{\rho_{np1}c_{p_{np1}}}{\rho_{bf}c_{p_{bf}}}\right]+\varphi_{np2}\rho_{np2}c_{p_{np2}}}{\rho_{hnf}} \tag{2}$$

where φ_{np1}, φ_{np2}, ρ_{np1}, ρ_{np2}, and ρ_{bf} indicate the volume concentrations of nanoparticles and the densities of nanoparticles and base fluid, respectively. $c_{p_{np1}}$ and $c_{p_{np2}}$ are the specific heats of the nanoparticles, and $c_{p_{bf}}$ is the specific heat of the base fluid.

Thermal conductivity is the basic thermophysical property that is directly related to the heat transfer ability of the fluid, and the main principle in the preparation of nanofluids is to increase the thermal conductivity compared to the base fluid. The thermal conductivity (k_{hnf}) of the hybrid nanofluid used in the study is calculated via Eq. 3 [53].

$$k_{hnf} = k_{bf}\left[\frac{\frac{\varphi_{np1}k_{np1}+\varphi_{np2}k_{np2}}{\varphi}+2k_{bf}+2\left(\varphi_{np1}k_{np1}+\varphi_{np2}k_{np2}\right)-2\varphi k_{bf}}{\frac{\varphi_{np1}k_{np1}+\varphi_{np2}k_{np2}}{\varphi}+2k_{bf}-\left(\varphi_{np1}k_{np1}+\varphi_{np2}k_{np2}\right)+\varphi k_{bf}}\right] \tag{3}$$

Here, k_{np1}, k_{np2}, and k_{bf} indicate the thermal conductivities of nanoparticles and base liquid, respectively.

Changes in viscosity affect the pressure drops caused by liquids and the pumping powers required to pump those liquids. The dynamic viscosity (μ_{hnf}) of the hybrid nanofluid is found using Eq. 4 [54].

$$\mu_{hnf} = \mu_{bf}\left[1+32.795\varphi-7214\varphi^2+714600\varphi^3-\left(0.1941\times10^8\varphi^4\right)\right] \tag{4}$$

where φ is the total nanoparticle volume concentration and is calculated as in Eq. 5.

$$\varphi = \frac{\left(\frac{m}{\rho}\right)_{ZnO}+\left(\frac{m}{\rho}\right)_{Al_2O_3}}{\left(\frac{m}{\rho}\right)_{ZnO}+\left(\frac{m}{\rho}\right)_{Al_2O_3}+\left(\frac{m}{\rho}\right)_{H_2O}}x100 \tag{5}$$

Experimental setup and procedure

The general structure and schematic view of the experimental setup established for liquid cooling experiments within the scope of the study are shown in Figs. 4 and 5, respectively. The properties of the Lithium Iron Phosphate (LFP) pouch-type battery used in the experiments are given in Table 2. The experimental setup consists of a coolant tank, condenser, compressor, circulation pump, turbine flow meter, cold plate, Li-ion battery, pressure gauges, thermocouples, charger, discharger, data logger, and computer. The 20-L volume coolant tank, integrated into the cooling equipment consisting of the condenser and compressor, ensures that the fluid is kept at the desired temperature. The fluid is circulated by a pump with three different speed stages, and the volume flow rate is measured using a stainless steel turbine flow meter. A power supply was used for charging the battery, and an electronic load was used for discharging. The serpentine cold plate shown in Fig. 6 was created by placing

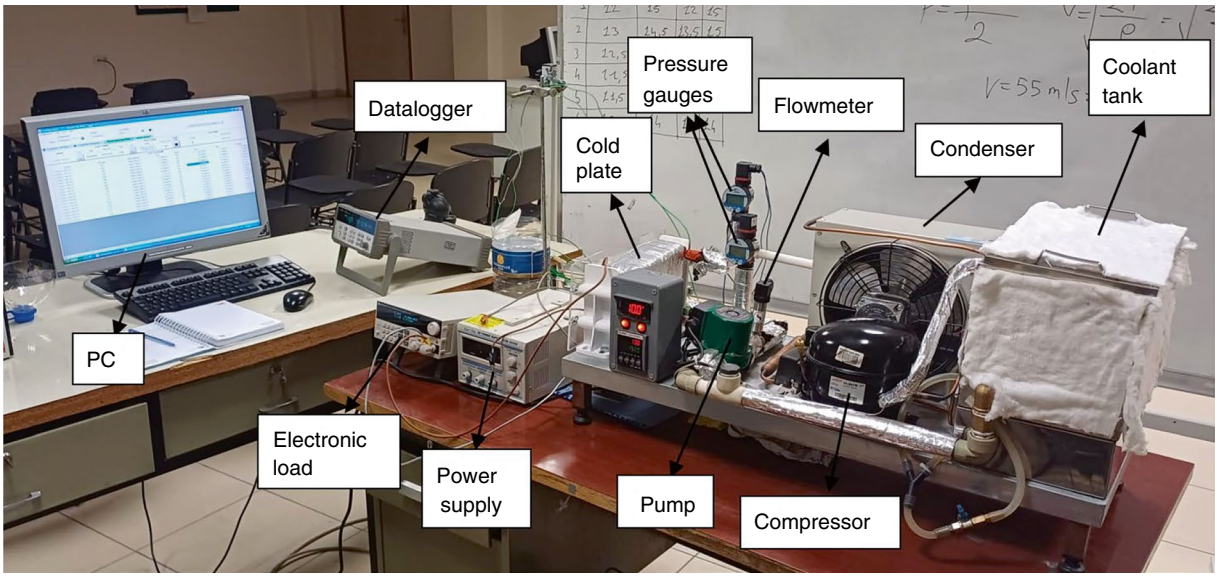


Fig. 4 Experimental setup

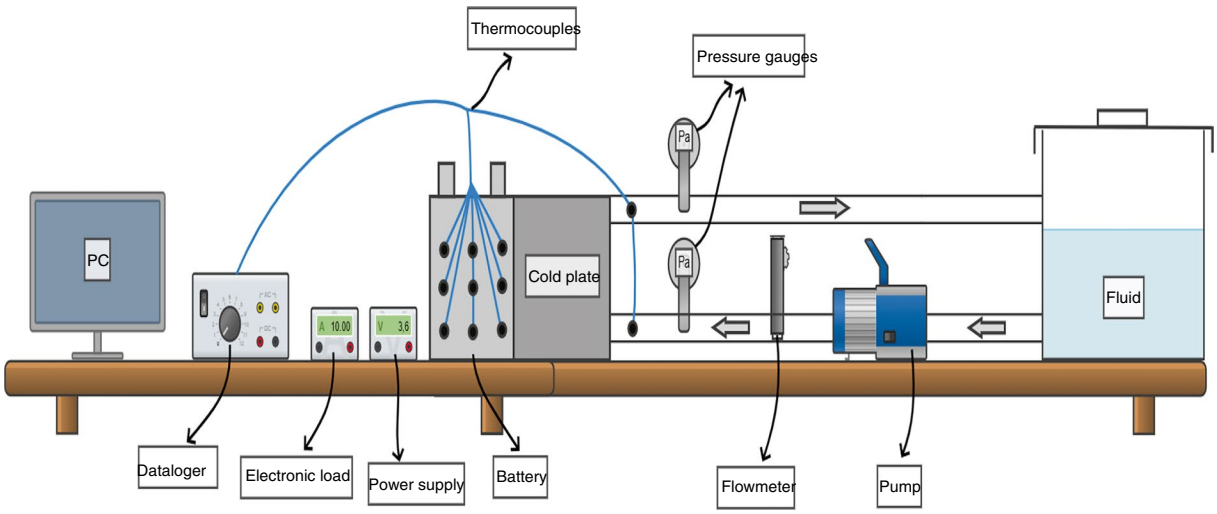


Fig. 5 Schematic view of the experimental setup

Table 2 Properties of the battery

Parameters	Value
Brand/model	GreenBatt/GLP10Ah
Anode/Cathode material	Graphite/$LiFePO_4$
Nominal capacity/Voltage	10 Ah/3.2 V
Discharge cutoff voltage	2 V
Operation temperature	− 20 to 55 °C
Mass	260 g
Dimensions	6.2 × 126 × 183 mm

copper pipes between two aluminum plates. Measurements were made using thermocouples and pressure gauges placed at the inlet and outlet positions of the fluid on the cold plate. Additionally, as shown in Fig. 7a, nine *K*-type thermocouples were fixed at different points on the battery surface to measure the average battery surface temperature. Thermocouples are connected to a data logger to record temperature readings. All thermocouples used in the experiments were painstakingly calibrated in ice water and boiling water. In order to transfer the heat released from the battery during

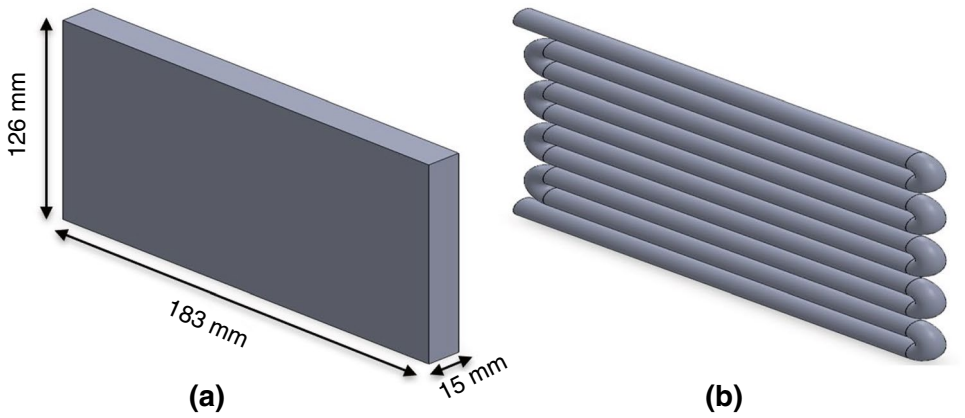


Fig. 6 **a** External view and dimensions of the cold plate, and **b** flow channel

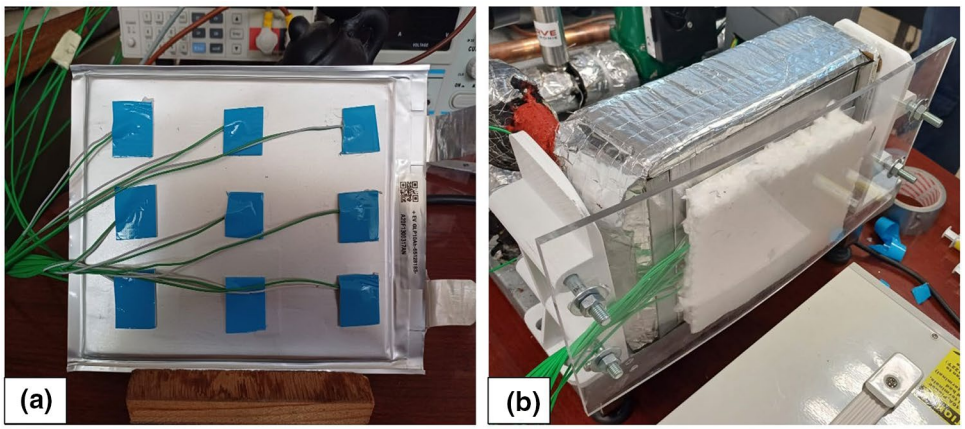


Fig. 7 **a** Placement of thermocouples on the battery surface and **b** battery test section

Table 3 Basic specifications of the equipment

Equipment	Operation range	Accuracy
Thermocouple (*K*-type)	−50 to 250 °C	±0.2 °C
Flow meter	0–10 LPM	±0.5%
Pump	0–25 LPM	–
DC power supply	0–30 V	±0.1 V
DC electronic load	0–150 V	±0.3%
Pressure gauge	0–2.5 bar	±0.5%
Data logger	–	±0.004%

Table 4 Operating parameters

Parameters	Value
Inlet temperature of the coolant (°C)	10, 15, 20
Volume flow rate of the coolant (LPM)	6, 7, 8
Volume concentration of nanoparticles (%)	0.00625, 0.0125, 0.025, 0.05
Battery discharge rate (C)	1, 2, 3, 4, 5

discharge to the cooling liquid without any loss, thermal isolation of the battery and the cooling plate from the environment is provided by insulating foam. To ensure full contact between the battery and the cold plate, a transparent plastic glass was used as a compression plate, thus creating the battery test section shown in Fig. 7b. The basic specifications of the equipment used in the experimental setup are given in Table 3.

Within the scope of the experiments, the effects of the coolant flowing in the cold plate on the heat transfer rate, heat transfer coefficient, battery surface temperature, temperature difference, and pressure drop at different operating parameters were investigated. Operating parameters are given in Table 4. Previous studies on liquid cooling of electric vehicle batteries show that the coolant inlet temperature is generally chosen between 15 and 30 °C. In the present study, the coolant inlet temperatures used were chosen both within this range and outside of it to observe the performance of the newly developed hybrid nanofluid at values outside the generally studied range. The inlet temperatures used in this study are also available in the literature [14, 55]. The pump used in this study has three different stages. Therefore, three different volume flow rates (6, 7, and 8 LPM) for the coolant could be analyzed within the scope of this study. These volumetric flow rates correspond to

turbulent flow conditions (11,129 ≤ Re ≤ 19,597). Discharge rates ranging from 1 to 5 C were used to investigate various electric vehicle operating conditions, such as low-load driving, standard operating conditions, and high power demand scenarios. The nanofluid volume concentration was kept at low levels to prevent sedimentation, agglomeration, clumping, and pumping difficulties. Measurements were repeated three times for each flow rate, inlet temperature, and discharge rate at the examined volume concentration values.

The following procedure was followed in the calculations of average heat transfer rate, average heat transfer coefficient and pressure drop. The heat transfer rate ($\dot{Q}$) from the battery surface is calculated from the conservation of mass and energy as in Eq. 6.

$$\dot{Q} = \dot{m} c_p (T_{out} - T_{in}) \tag{6}$$

Here, $\dot{m}$ is the mass flow rate, c_p is the specific heat capacity, and T_{in} and T_{out} are the inlet and outlet temperatures of the coolant to the cold plate, respectively. The density and specific heat of the coolant were calculated at the average bulk temperature. Equation 7 is used to calculate the heat transfer coefficient (h).

$$h = \frac{\dot{Q}}{A_s (T_w - T_b)} \tag{7}$$

where A_s is the surface area and T_w and T_b are the average wall temperature and the average temperature of the coolant, respectively. The average temperature of the fluid is calculated by Eq. 8.

$$T_b = \frac{T_{in} + T_{out}}{2} \tag{8}$$

The pressure drop (ΔP) of the coolant flowing across the cold plate is calculated by two pressure gauges integrated at the inlet and outlet, as in Eq. 9:

$$\Delta P = P_{in} - P_{out} \tag{9}$$

Heat transfer and pressure drop analyses must be considered together to accurately evaluate the change in system performance. Therefore, a performance analysis including these two criteria was carried out. The performance evaluation coefficient (PEC) expression defined for performance analysis is given in Eq. 10 [56].

$$\mathrm{PEC} = \frac{h_{hnf}/h_{bf}}{\Delta P_{hnf}/\Delta P_{bf}} \tag{10}$$

Battery heat generation

In his study, Li [57] estimated the time-dependent expressions of battery heat production as given in Eq. 11. The polynomial coefficients of heat generation during the battery discharge process are given in Table 5. Figure 8 shows the heat generation rates of the battery over time for different discharge rates. The heat generation rate graphs in Fig. 8 were created by substituting the coefficients given in Table 5 into Eq. 11.

Table 5 Polynomial coefficients of heat generation during battery discharge process [29]

Coefficients	Discharge rates		
	1 C	2 C	3 C
A_1	4.9132×10^{-16}	1.2578×10^{-13}	3.2235×10^{-12}
A_2	-3.7742×10^{-12}	-4.8310×10^{-10}	-8.2542×10^{-9}
A_3	1.0679×10^{-8}	6.8347×10^{-7}	7.7851×10^{-6}
A_4	-1.3417×10^{-5}	-4.2934×10^{-4}	-3.2303×10^{-3}
A_5	0.0076	0.1216	0.6157
A_6	−2.2208	−17.7630	−59.9607
A_7	17,151.7482	66,623.3365	148,414.7651

$$\dot{Q}_{gen} = A_1 t^6 + A_2 t^5 + A_3 t^4 + A_4 t^3 + A_5 t^2 + A_6 t + A_7 \tag{11}$$

Uncertainty analysis

Uncertainty analysis is a critical step in any engineering analysis. It involves identifying and quantifying sources of uncertainty in the analysis and then reflecting these uncertainties in the final results [1]. If the quantity to be calculated as a result of any experimental study is R, and n independent variables affecting this quantity are selected, R can be written as in Eq. 12:

$$R = f(x_1, x_2, \ldots, x_n) \tag{12}$$

When the fixed error amounts of each independent variable effective in the experiments are expressed as $w_{x_1}, w_{x_2}, \ldots, w_{x_n}$, the error amount in the calculation of R can be found as shown in Eq. 13 [58].

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \tag{13}$$

The uncertainty for the heat transfer rate (Q) was calculated in the range of 3.9–8.1%, while the uncertainty for the heat transfer coefficient (h) was calculated in the range of 3.7–7.8%.

Result and discussion

In the experiments carried out in accordance with the procedures mentioned in the experimental study section, the effects of different operating parameters on the heat transfer

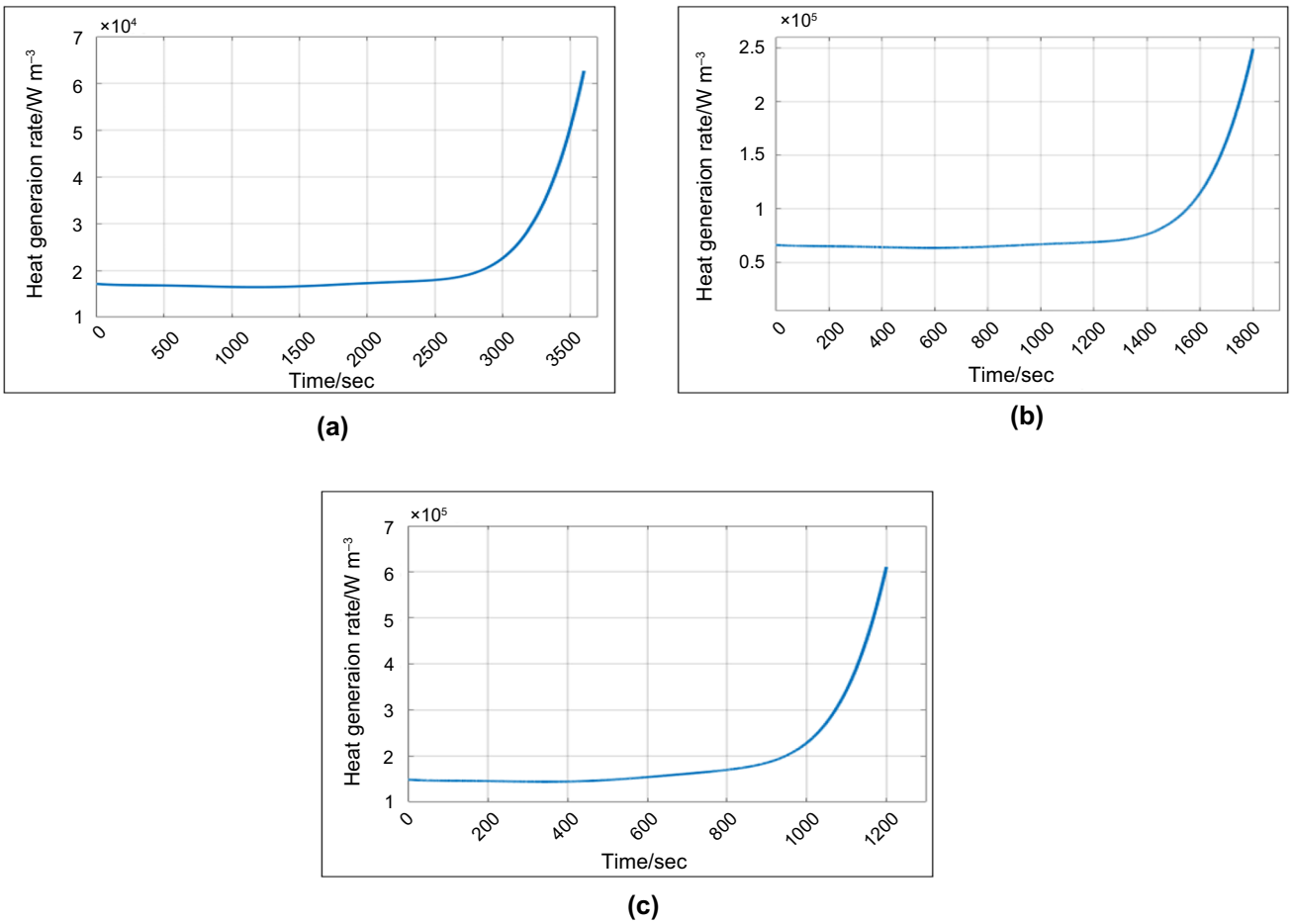


Fig. 8 Heat generation of the battery according to time **a** 1 C, **b** 2 C, and **c** 3 C

rate, heat transfer coefficient, battery surface temperature, temperature difference, pressure drop, and voltage change were examined, and the results were presented under separate headings.

Heat transfer rate ($\dot{Q}$)

As a result of experiments carried out under different operating conditions, heat transfer rates for each case are calculated using Eq. 6. Heat transfer rates obtained according to discharge rate and nanofluid volume concentration in experimental operating conditions at specific inlet temperatures are shown in Fig. 9 and Fig. 10. The maximum heat transfer rates achieved at the end of the experiments conducted between 1 and 5 C discharge rates were evaluated. It is observed that as the discharge rate increases, the heat transfer rate enhances and the hybrid nanofluid increases the heat transfer rate compared to pure water under all operating conditions. The maximum heat transfer rate was obtained with the nanofluid having a concentration of 0.05% under the conditions of 5 °C discharge rate, 8 LPM flow rate, and 10 °C inlet temperature and was calculated as 197.8 W. The heat transfer rate obtained with pure water under the same conditions is 158.4 W. The percentage increase in heat transfer rate achieved with the use of hybrid nanofluid compared to pure water was also calculated, and the maximum increase in heat transfer rate with hybrid nanofluid was obtained as approximately 42.5%. Increasing the volume concentration of the hybrid nanofluid also had a positive effect on heat transfer. When analyzing nanofluid, which is a suspension mixture of solid and liquid, it is clear that heat transfer occurs mainly at the fluid interface line based on particle number. Therefore, the increase in heat transfer rate with volume concentration can be related to the amount of particles present [27, 28]. Similar results have been reported in various studies in the literature [10, 25, 35, 37, 49].

The temperature of the coolant in an electric vehicle's battery cooling system is important for maintaining optimal performance and extending the life of the battery [10]. Within the scope of the study, coolant inlet temperature values ranging from 10 to 20 °C were determined to investigate the thermal behavior of the electric vehicle battery under

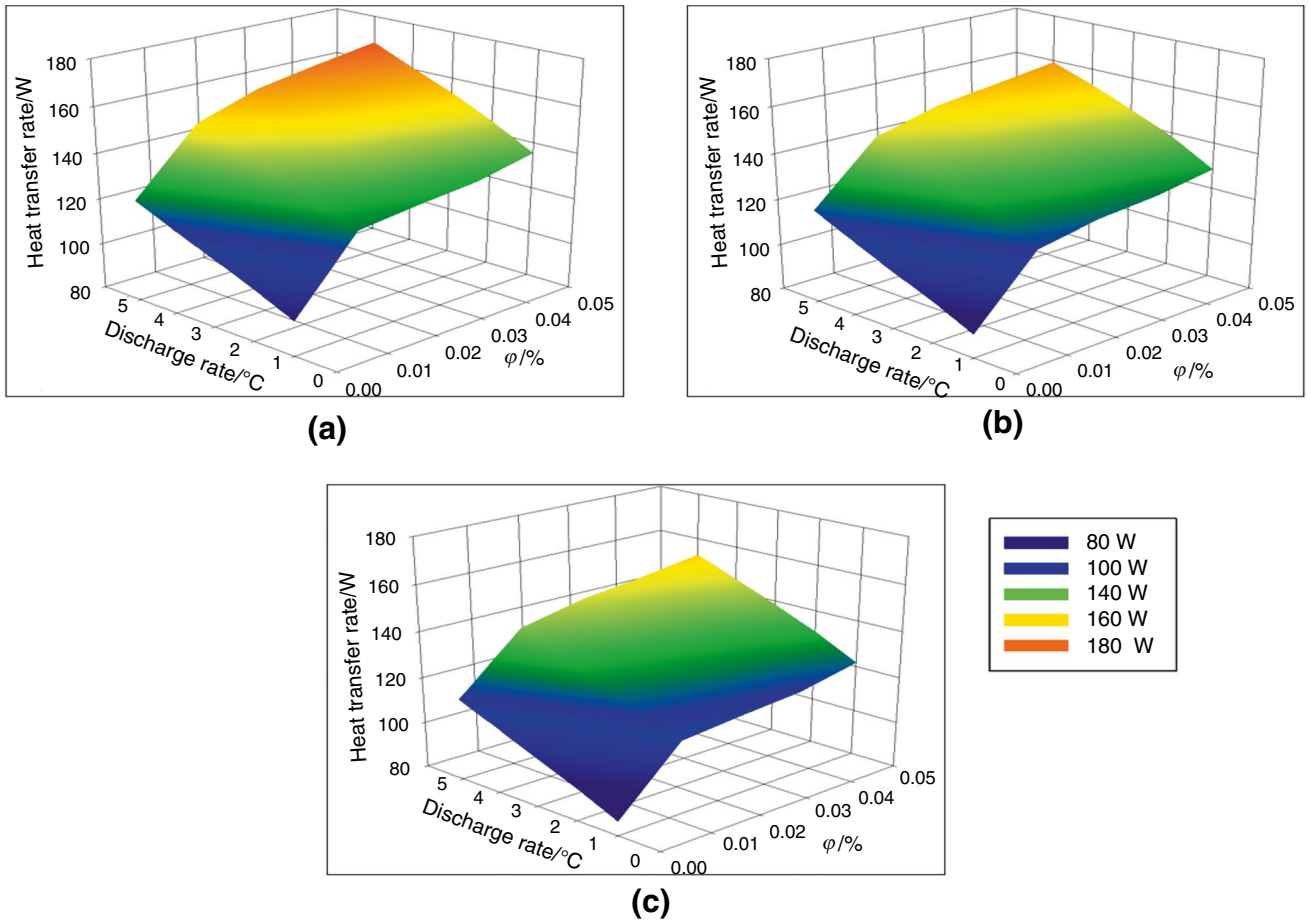


Fig. 9 Effects of discharge rate and nanofluid volume concentration on the heat transfer rate at a flow rate of 6 LPM **a** 10 °C, **b** 15 °C, and **c** 20 °C

different conditions. When Figs. 9 and 10 are examined, it is seen that the heat transfer rate enhances as the coolant inlet temperature decreases. At high coolant inlet temperatures, the difference between the battery temperature and the coolant temperature decreases, which also leads to a relative decrease in heat transfer [59]. For pure water, at a 1C discharge rate and 6 LPM flow rate, the heat transfer rates obtained at 10 °C and 20 °C fluid inlet temperatures are 95.1 W and 86.1 W, respectively. The flow rate of the coolant is also an important factor affecting the cooling performance. If the flow rate of the coolant is too slow, the heat generated by the battery cannot be removed in a timely manner, and the temperature of the battery rises rapidly, affecting the normal operation of the battery and causing safety problems. If the flow rate of the coolant is too fast, it will lead to increased energy consumption and excessive heat dissipation capacity, and the increased energy loss is meaningless. Therefore, it is necessary to examine the relationship between the coolant flow rate and the thermal performance of the battery [32]. From Figs. 9 and 10, it can be seen that the rate of heat transfer increases directly in proportion to the increase in volume flow rate. The rise in flow rate increased the mobility of nanoparticles in base fluid and resulted in the rise of enabling a higher heat transfer rate [12]. Considering the values under the conditions of pure water, 10 °C fluid inlet temperature, and 1C discharge rate, increasing the volume flow rate from 6 to 8 LPM enhanced the heat transfer rate by approximately 22.1%.

Heat transfer coefficient (*h*)

In order to examine the coolant performance used in liquid cooling experiments, the average heat transfer coefficients for each case are calculated via Eq. 7. Figures 11 and 12 illustrate the change in the heat transfer coefficient depending on the nanofluid volume concentration and flow rate at different fluid temperatures. As shown in Figs. 11 and 12, the heat transfer coefficient increases with the nanofluid volume concentration. Similar to the heat transfer rate, we observe that the hybrid nanofluid enhances the heat transfer coefficient when compared to pure water. This increase can be attributed to synergistic effects between Al_2O_3 and ZnO,

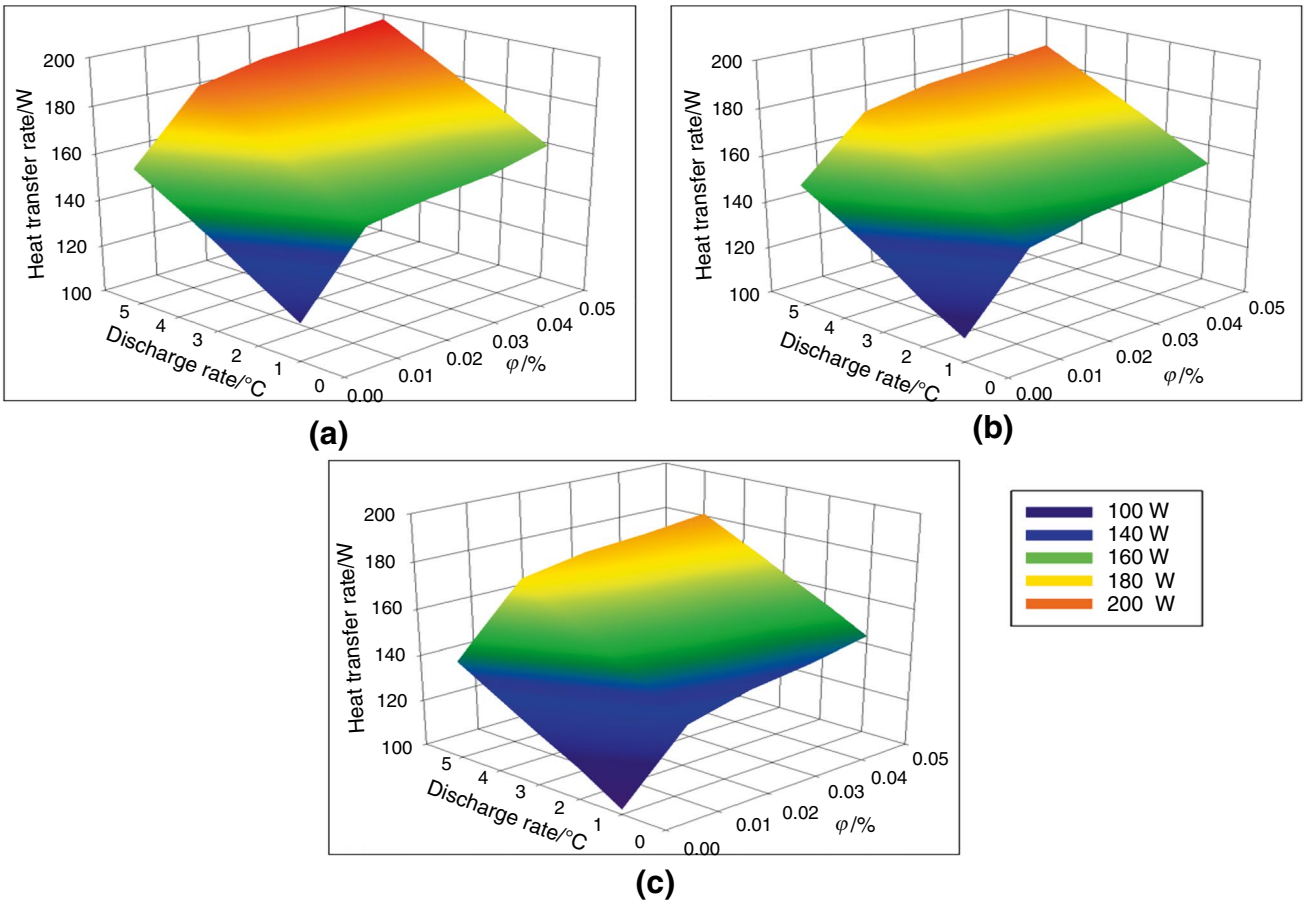


Fig. 10 Effects of discharge rate and nanofluid volume concentration on the heat transfer rate at a flow rate of 8 LPM **a** 10 °C, **b** 15 °C, and **c** 20 °C

which enhance thermal conductivity and flow properties and positive interactions between the nanoparticles and the base fluid [44]. The Brownian motion enhances the energy and momentum exchange between Al_2O_3 and ZnO nanoparticles, leading to higher energy transfer and resulting in increased convective heat transfer in the hybrid nanofluid compared to the base fluid [12, 44]. Among all the cases investigated, the maximum heat transfer coefficient was obtained as 215.3 W m^{-2} K^{-1} at 10 °C fluid temperature, 8 LPM volume flow rate, 5 C discharge rate, and 0.05% volume concentration conditions, similar to the heat transfer rate. The heat transfer coefficient obtained with pure water under these conditions was 173 W m^{-2} K^{-1}. The highest increase in heat transfer coefficient achieved with hybrid nanofluid compared to pure water was calculated to be approximately 42.1%. When Figs. 11 and 12 are examined, it is seen that the heat transfer coefficient increases with the volume flow rate and decreases with the fluid inlet temperature. When the values under pure water and 6 LPM flow rate conditions were examined, it was determined that the heat transfer coefficient decreased by 14% and 12% for 1 C and 5 C discharge rates, respectively, as a result of increasing the fluid inlet temperature from 10 to 20 °C. The heat transfer coefficient is enhanced by approximately 18% by increasing the volume flow rate from 6 to 8 LPM at 0.05% concentration, 1 C discharge rate, and 10 °C fluid inlet temperature. It is also seen that increasing the discharge rate increases the heat transfer coefficient. In their study, Selvarajoo et al. [12] stated that the heat transfer coefficient increases with an increase in discharge rate.

Battery surface temperature and maximum temperature difference

Overheating of batteries causes a decrease in capacity and shortening of life and can lead to serious safety problems such as fire or explosion. Scientific studies generally indicate that the ideal temperature range for Li-ion batteries is between 15 and 35 °C [20]. The time-dependent variation in the average battery surface temperature under different flow rates, coolant inlet temperatures, and nanofluid volume concentration conditions depending on the discharge rate

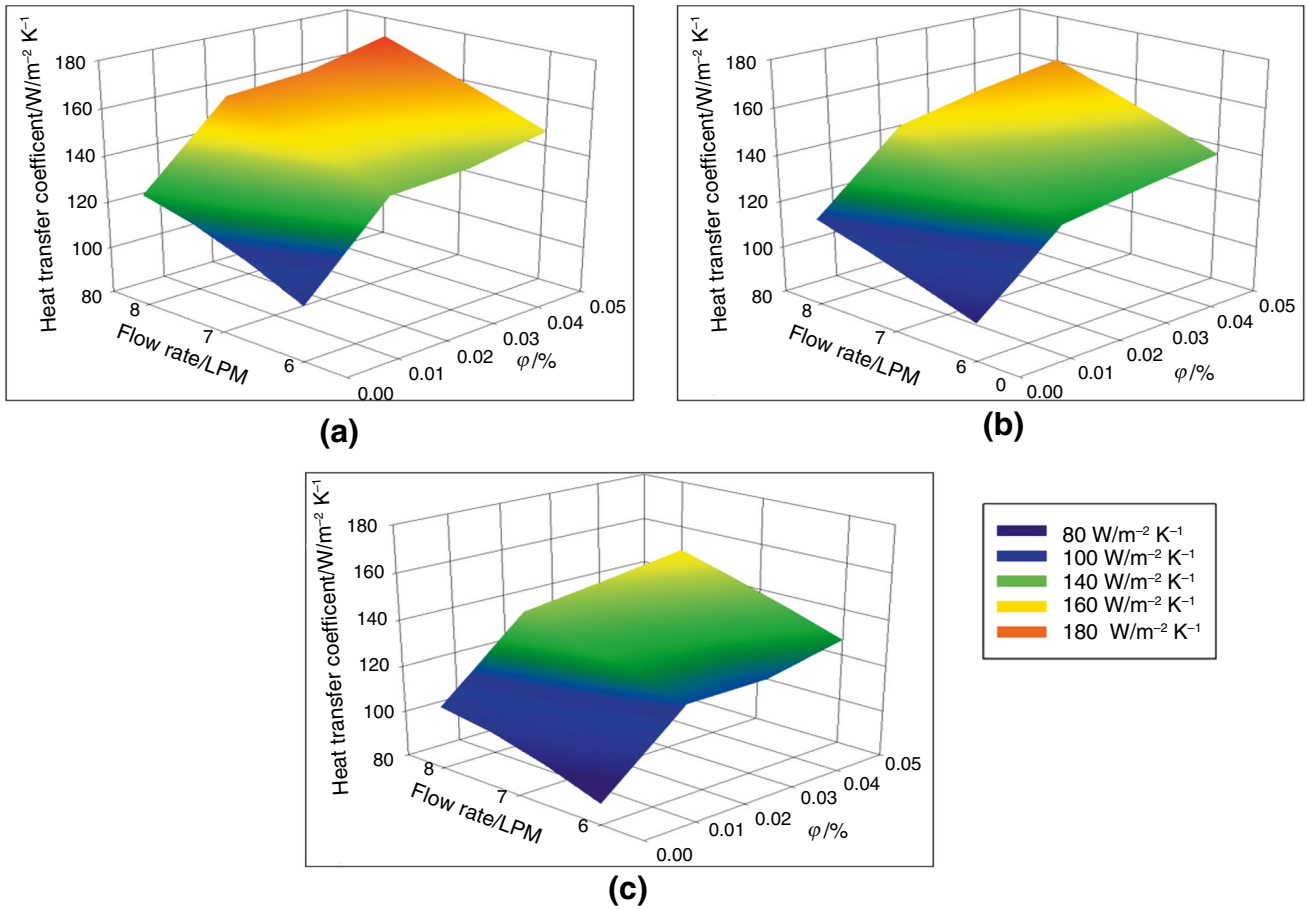


Fig. 11 Effects of flow rate and nanofluid volume concentration on the heat transfer coefficient at a discharge rate of 1 C **a** 10 °C, **b** 15 °C, and **c** 20 °C

is given in Figs. 13–16. When Figs. 13–16 are examined, it is seen that the newly developed hybrid nanofluid provides more effective cooling than pure water and reduces the battery surface temperature more than pure water in all cases. This is due to the thermal conductivity of the hybrid nanofluid being higher than that of pure water and removing more heat from the battery surface [28, 33]. The lowest battery temperatures obtained at 15 °C coolant inlet temperature, 1C discharge rate, and 8 LPM flow rate were 18.1 °C and 16.9 °C for pure water and nanofluid with 0.05% volume concentration, respectively. These values correspond to a cooling improvement of approximately 6.6% using the hybrid nanofluid compared to the base fluid. It was determined that under the conditions where the highest battery temperatures were obtained (20 °C, 5 C, 6 LPM), the hybrid nanofluid reduced the battery temperature by 3.8 °C, improving it by 10.4% compared to pure water. Increasing the volume concentration of the hybrid nanofluid also reduced the battery surface temperature. Considering that the recommended operating temperature for Li-ion batteries is between 15 and 35 °C, experiments conducted with a 5 C discharge rate and a 20 °C fluid temperature show that battery temperatures exceed the upper temperature limit when pure water is used. Such a situation did not occur in experiments using hybrid nanofluid. These findings indicate that the newly developed hybrid nanofluid can be used safely in battery cooling systems. From Figs. 13–16, it is seen that the temperature of the battery surface increases with the rise in discharge rate under all operating conditions. At high discharge rates, irreversible heat dominates and polarization significantly increases, leading to higher heat generation rates [60, 61]. At a fluid inlet temperature of 15 °C, it is observed that the temperature variation trends are generally similar for all discharge rates. Temperature generally experiences a linear decrease in the first stage, where internal resistance is low and cooling systems are more effective. It then reaches a turning point to rise sharply as internal resistance increases and cooling becomes less effective [28, 62]. At 20 °C fluid inlet temperature, the temperature variation trend for low discharge rates (1 C and 3 C) was similar to that at 15 °C. At the highest discharge rate (5 C), the battery temperature increases linearly without any decrease, unlike

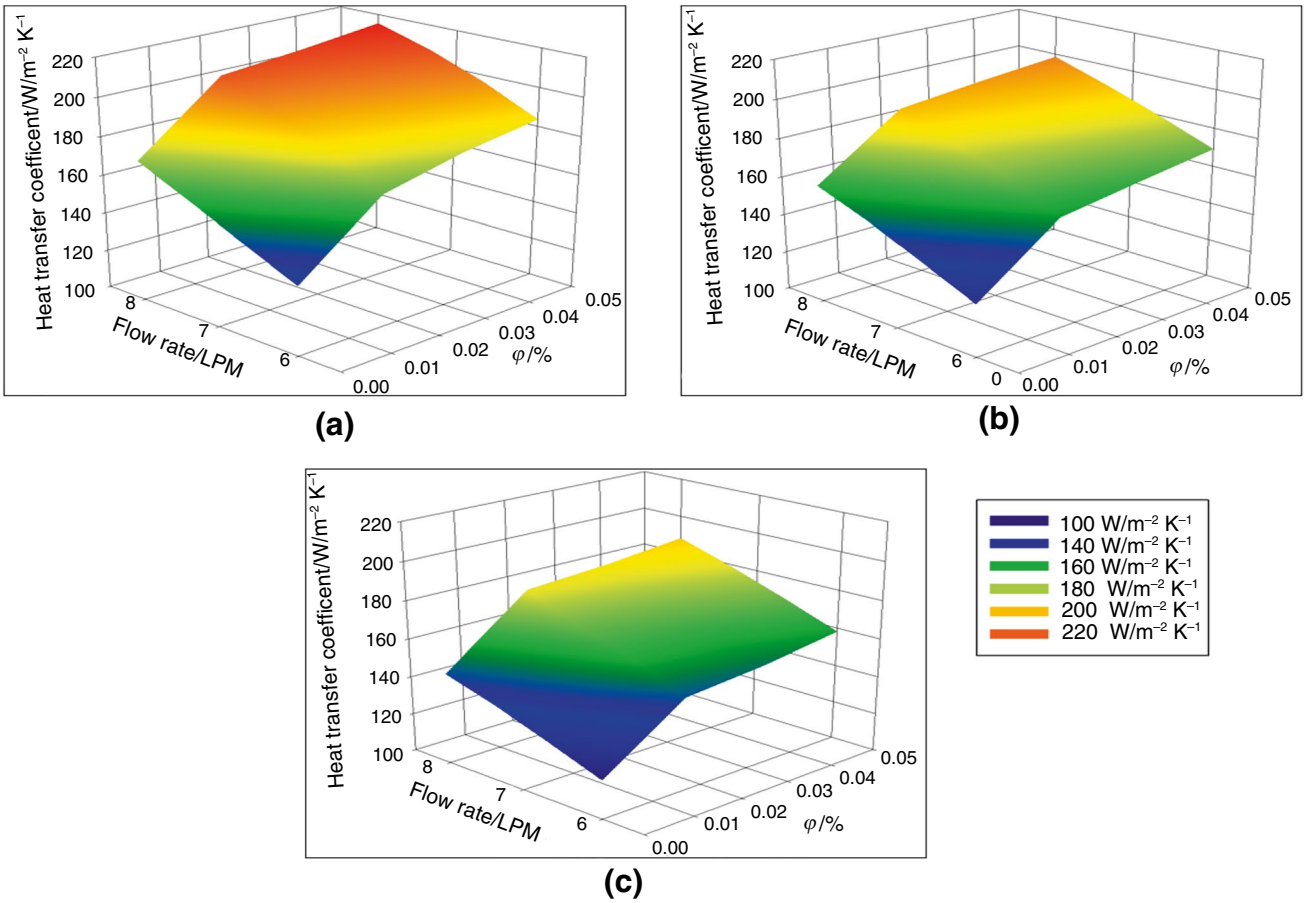


Fig. 12 Effects of flow rate and nanofluid volume concentration on the heat transfer coefficient at a discharge rate of 5 C **a** 10 °C, **b** 15 °C, and **c** 20 °C

the others. The reason for this situation is that heat generation is high under these conditions and cooling is insufficient due to the high coolant inlet temperature. If Fig. 8, which shows the rates of heat generation in the battery, is examined, it is seen that the heat generation remains relatively constant at the beginning for all discharge rates, but in the later period, the heat generation enhances rapidly due to the increase in internal resistance. This supports the results of the temperature variation trend obtained in the present study and explained in detail above. In addition, it was found that the battery temperature decreased as the coolant volume flow rate increased under the same inlet temperature conditions, and the battery temperatures enhanced as the coolant inlet temperature increased.

Within the scope of the study, average battery temperatures were examined under natural convection conditions as well as liquid cooling, and the comparison of the results with the coolants used in liquid cooling is given in Fig. 17. When Fig. 17 is examined, it is seen that as a result of the natural convection experiment with air, the battery surface temperature does not exceed the recommended upper operating temperature limit (35 °C) for Li-ion batteries only at a discharge rate of 1 C and that cooling by natural convection is not sufficient for the battery at discharge rates higher than 1 C. In addition, the highest and lowest battery surface temperatures for all cases were obtained under natural convection air cooling and nanofluid conditions with 0.05% concentration, respectively. Air exhibited the worst cooling performance due to its relatively low heat transfer coefficient, while the hybrid nanofluid exhibited the best cooling performance [17]. For 5 C discharge rate, the maximum battery temperatures achieved with 0.05% concentration nanofluid, pure water, and air are 32.8 °C, 36.6 °C, and 59.8 °C, respectively. Since lithium-ion batteries are highly sensitive to operating temperature, even small temperature changes can lead to capacity reduction, accelerated aging, thermal runaway, and safety hazards [22, 24]. Cetkin [63] stated that every 1 °C increase in temperature between 30 and 40 °C reduces the battery cell's lifespan by two months. Therefore, reducing the discharge temperature from 36.6 to 32.8 °C with hybrid nanofluid compared to pure water at a discharge rate of 5 C can be considered significant for BTMS

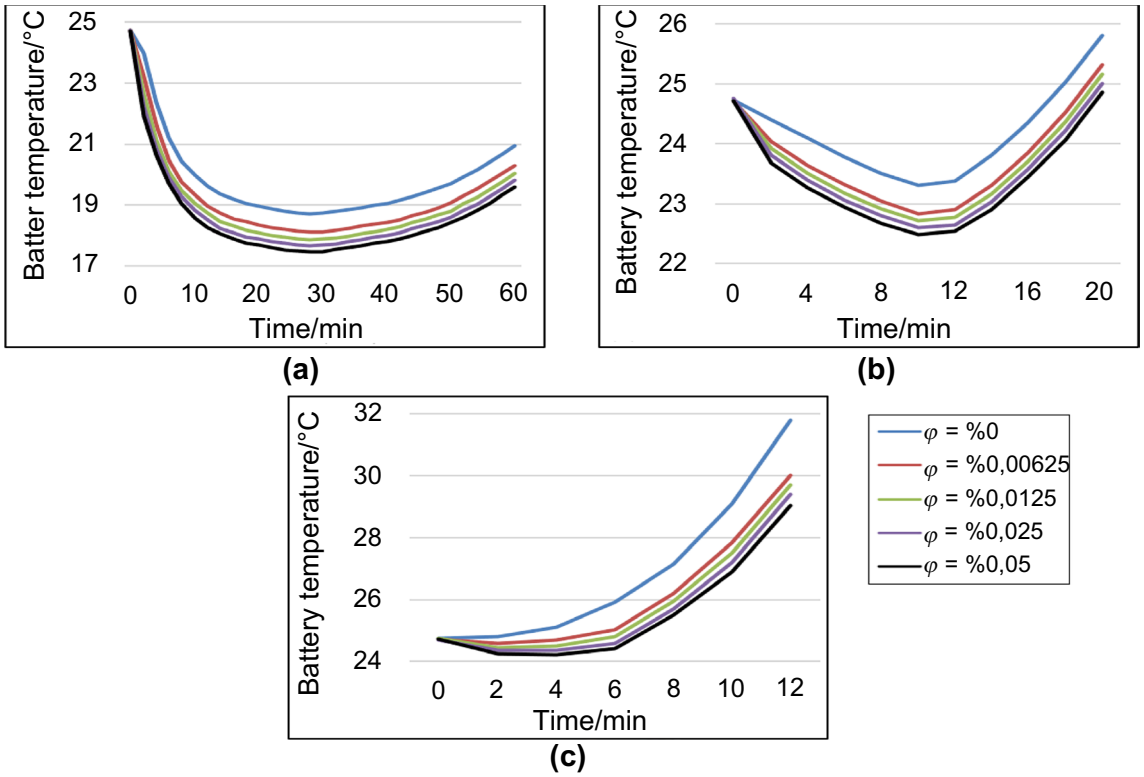


Fig. 13 Variation in battery temperature with time at 6 LPM flow rate and 15 °C coolant inlet temperature **a** 1 C, **b** 3 C, and **c** 5 C

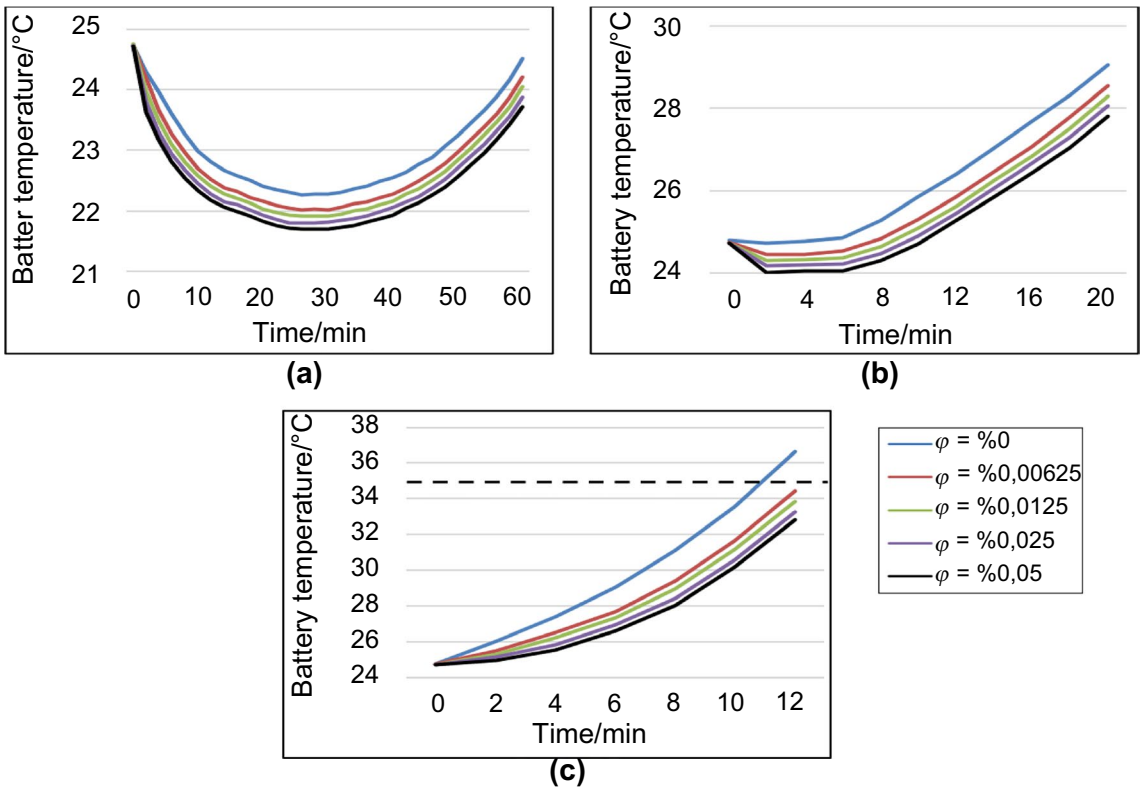


Fig. 14 Variation in battery temperature with time at 6 LPM flow rate and 20 °C coolant inlet temperature **a** 1 C, **b** 3 C, and **c** 5 C

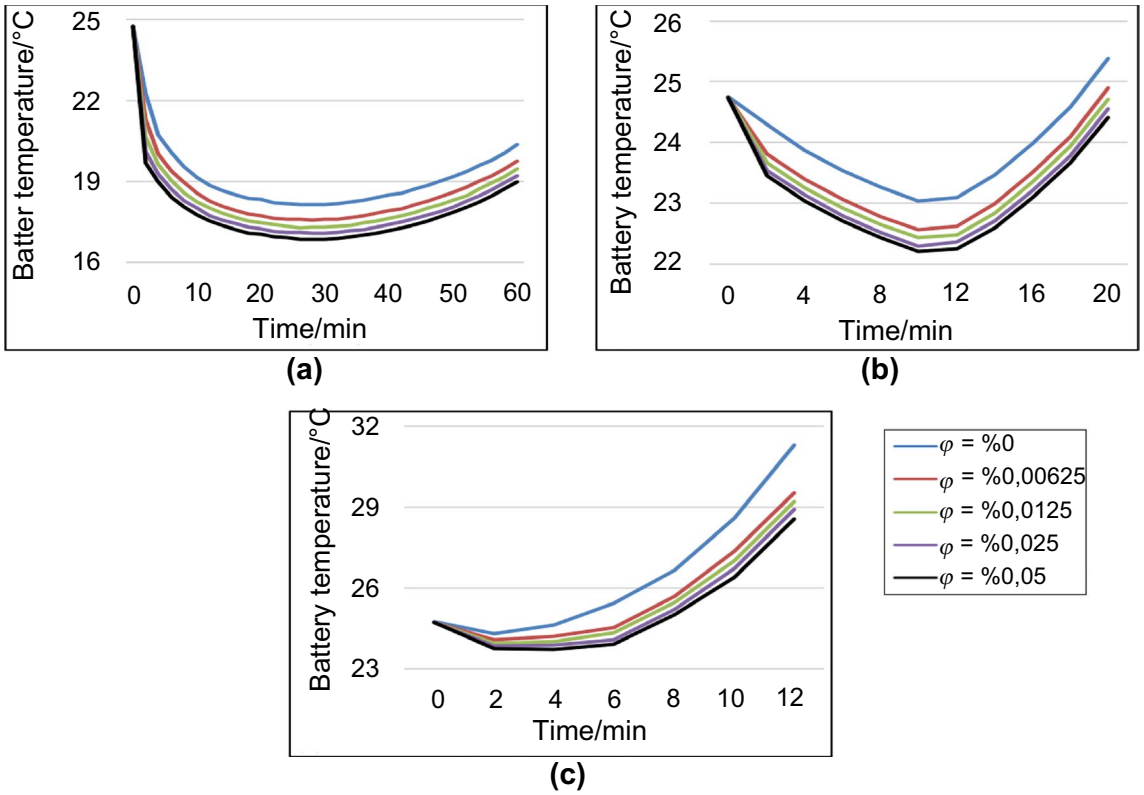


Fig. 15 Variation in battery temperature with time at 8 LPM flow rate and 15 °C coolant inlet temperature **a** 1 C, **b** 3 C, and **c** 5 C

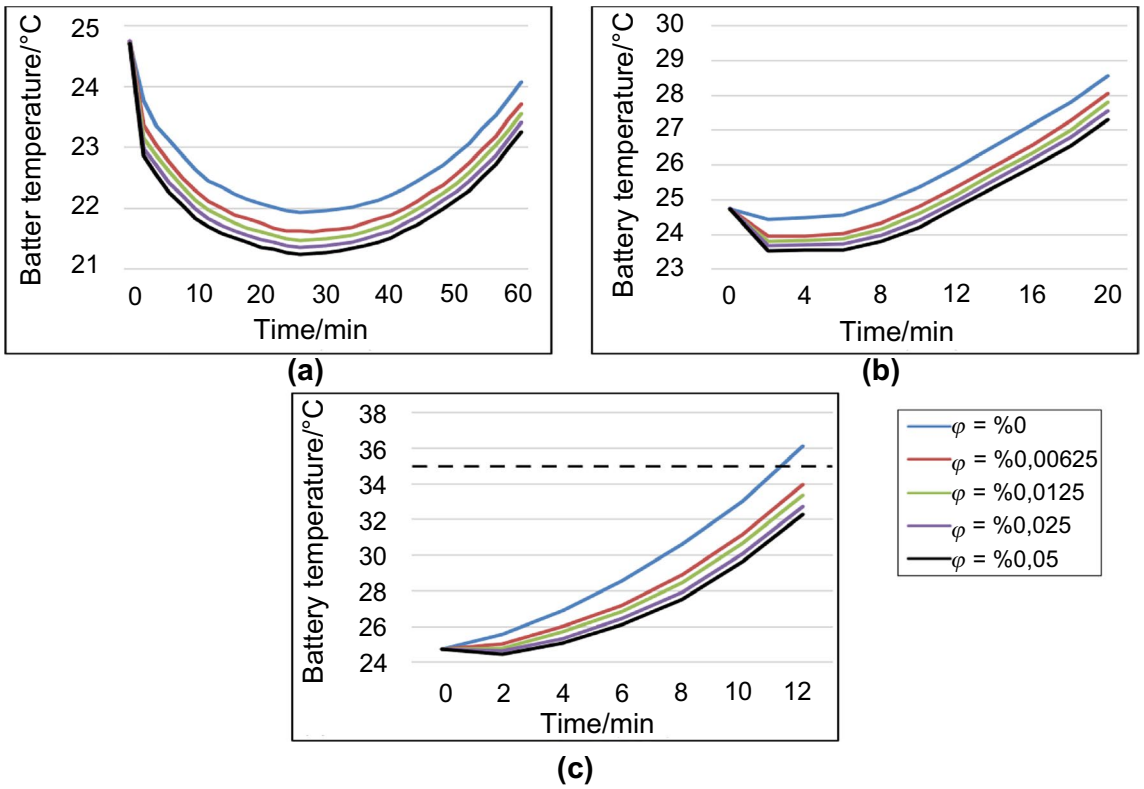


Fig. 16 Variation in battery temperature with time at 8 LPM flow rate and 20 °C coolant inlet temperature **a** 1 C, **b** 3 C, and **c** 5 C

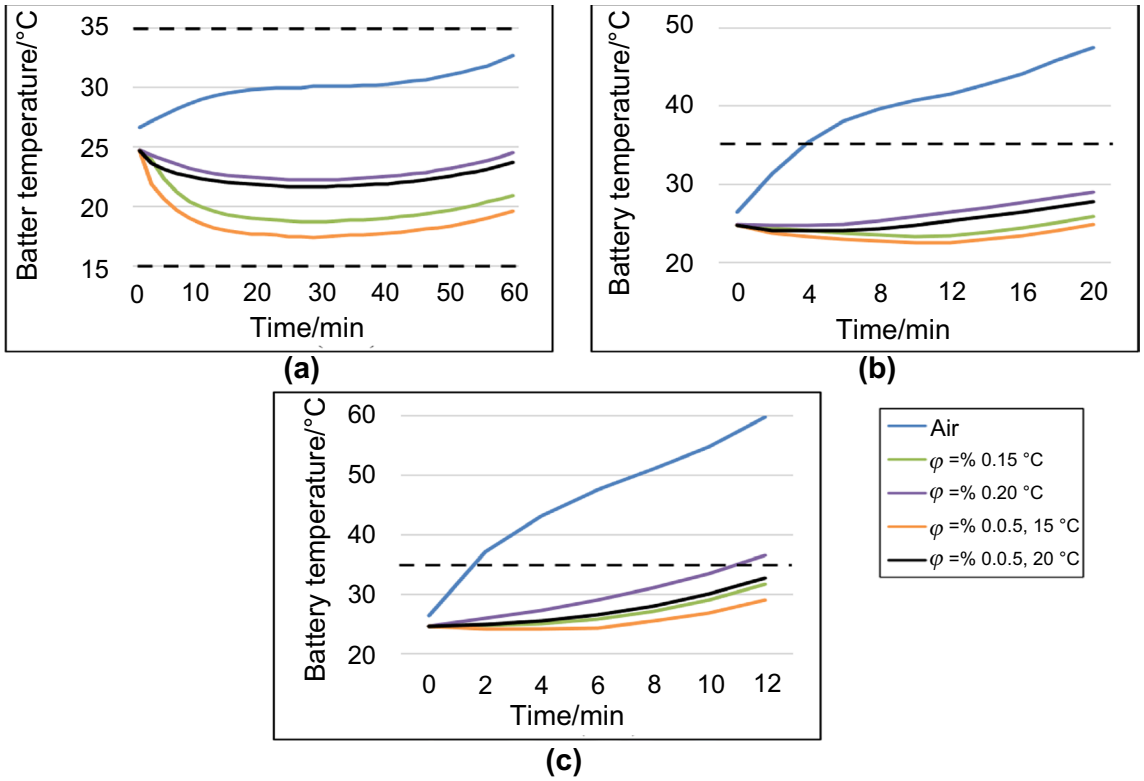


Fig. 17 Variation in battery temperature with time at different coolant conditions **a** 1 C, **b** 3 C, and **c** 5 C

applications. Furthermore, previous studies [10, 11, 22, 24] have reported that maintaining the battery temperature within the recommended operating temperature range can significantly improve cycle life and thermal stability. In this context, the observed temperature decrease demonstrates that the hybrid nanofluid can effectively suppress excessive heat generation under high discharge scenarios in practical applications.

Surface temperature uniformity of Li-ion batteries is considered an important criterion for battery thermal management systems [59]. In general, for optimum battery performance, it is recommended that the maximum temperature difference between areas on the battery surface be below 5 °C. Within the scope of the study, nine different points on the battery surface were measured, and the maximum temperature differences on the battery surface for different operating conditions are given in Table 6. When Table 6 is examined, it is seen that the highest temperature differences are obtained with pure water, and the hybrid nanofluid reduces the temperature difference compared to pure water. It can be said that the temperature distribution on the battery surface is more uniform and the maximum temperature difference is kept within the safe range when the hybrid nanofluid is used instead of pure water. Compared to pure water, the maximum reduction in temperature difference with hybrid nanofluid was obtained as 32.8% at a discharge rate of 5 C. This improvement can be attributed to the enhanced thermal conductivity and convective heat transfer capability of the hybrid nanofluid. The increased convective heat transfer with the hybrid nanofluid compared to pure water results in more efficient heat removal from the battery surface, minimizing temperature gradients that can lead to thermal stress and uneven aging of battery cells and achieving a more homogeneous temperature distribution on the battery surface [24, 27, 28]. Li et al. [64] stated that a 3 °C temperature gradient on the battery surface accelerates battery degradation by 300%. Therefore, achieving a more homogeneous temperature distribution increases the overall lifespan and reliability of the battery, which is critical in practical electric vehicle applications. There are studies in the literature reporting that the use of nanofluids reduces the temperature difference [27, 28, 32, 38]. In addition, the

enhancement in nanoparticle volume concentration and flow rate positively affected the maximum temperature difference on the battery surface. As the discharge rate increased, the maximum temperature difference also increased.

Pressure drop (Δ*P*)

Pressure drops across the cold plates are critical to minimizing the energy consumed for pumping. The pressure drop is related to the thermophysical properties, flow rate, and geometry of the heat exchanger [65]. A high pressure drop can negatively affect battery performance [9]. Figure 18 illustrates the pressure drops (ΔP) measured across the cold plate in experiments conducted under different operating conditions. Examining Fig. 18 reveals that in all cases, an increase in the coolant flow rate enhances the pressure drop. It is known that the pressure drop is directly proportional to the square of the fluid velocity. According to the values under pure water and 10 °C fluid inlet temperature conditions, a 41.6% increase in pressure drop occurred by increasing the volume flow rate from 6 to 8 LPM. This pressure drop, which increases with flow rate, also leads to an increase in the power required for pumping [11]. While higher flow rates can improve battery cooling performance, the resulting increase in power consumption may reduce the overall energy efficiency of the system [12]. Therefore, for practical BTMS systems, the balance between thermal performance and hydraulic losses must be considered, and an optimum flow rate should be selected. However, it can be seen that the pressure drop difference according to the coolant inlet temperature is at negligible levels. The reason for this is that the fluid density changes very little in this temperature range [59]. In all cases studied, both the addition of nanoparticles to pure water and increasing nanoparticle volume concentration were found to enhance the pressure drop. Based on the values at 10 °C coolant inlet temperature conditions, it was determined that the pressure drop increased by 24.7% and 17.8% at the lowest (6 LPM) and highest (8 LPM) flow rates, respectively, compared to pure water, with the use of nanofluid with a concentration of 0.05%. The maximum increase in pressure drop compared to pure water with hybrid nanofluid was obtained as 25.8%. Although the use of nanofluids results in an increase in pressure drop compared to pure water, the pressure drop can be considered within an acceptable range given the thermal improvement achieved. In practical BTMS applications, since maintaining the battery within a safe temperature range is critical for safety, cycle life, and performance, a moderate increase in pumping power can be considered acceptable relative to the significant increase in thermal improvement [26, 32, 66]. Increases in pressure drop are due to the fact that the hybrid nanofluid has higher density and viscosity compared to pure water due to the suspended ZnO–Al_2O_3 nanoparticles, thus having more friction during flow within the channel, i.e., high flow resistance. In addition, the flow pattern, dispersion, fluctuation, Brownian motion, and migration of suspended ZnO–Al_2O_3 nanoparticles also play an important role in the pressure drop of nanofluids [51, 65].

Performance evaluation criteria (PEC)

Nanofluids used due to their superior thermophysical properties compared to the base fluid increase the thermal performance while also increasing the pressure drop and the corresponding pump power. Therefore, it is necessary to evaluate these two criteria together. That is, it should be examined whether the increase in thermal performance dominates the increase in pressure drop. Performance evaluation coefficient (PEC) is a tool for evaluating thermal–hydraulic performance and is calculated by Eq. 10. Figure 19 illustrates the variation in the PEC for different temperatures according to the nanofluid volume concentration and flow rate. Examining Fig. 19 reveals that the PEC consistently exceeds 1 in all scenarios. Performance evaluation coefficient above 1 means that the use of hybrid nanofluid is advantageous in terms of thermal–hydraulic performance [67]. In other words, when hybrid nanofluid is used, the percentage increase in heat transfer is dominant over the percentage increase in pressure drop compared to the case when pure water is used. The highest PEC was obtained as 1.15 at 8 LPM flow rate and 0.05% volume concentration conditions. The obtained PEC value demonstrates that the newly developed hybrid nanofluid can provide a beneficial thermal improvement relative to a practically acceptable hydraulic loss. Furthermore, it can be said that the relatively low nanoparticle concentration used in the present study helps to limit the increase in viscosity, pumping power, and preparation complexity.

The thermal performance enhancement observed in the present study is not only attributed to the addition of nanoparticles into the base fluid but also to the synergistic interaction between Al_2O_3 and ZnO nanoparticles. The combined effect of these nanoparticles may improve energy transport mechanisms within the fluid, leading to enhanced cooling performance compared to conventional fluids and mononanofluids [44]. In terms of heat transfer coefficient, previous studies reported enhancements of 25% for Al_2O_3-water

Table 6 Maximum temperature differences on the battery surface at different operating conditions

Discharge rate	Coolant inlet temp./°C	Flow rate/ LPM	Maximum temperature difference/°C		
			ω = %0	ω = %0,00625	ω = %0,05
1 C	10	6	5.2	4.4	3.6
		8	4.8	4.1	3.4
3 C	10	6	5.6	4.5	3.8
		8	5	4.3	3.5
5 C	10	6	5.8	4.6	3.9
		8	5.1	4.4	3.6

[42] and 21% for ZnO-water [68], whereas the present Al_2O_3–ZnO-water hybrid nanofluid achieved 42% enhancement. Therefore, the observed thermal enhancement can be attributed to both nanoparticle addition and the synergistic hybrid effect between Al_2O_3 and ZnO nanoparticles.

A comparison between the findings of the present study and those reported in previous hybrid nanofluid studies is presented in Table 7. The comparison indicates that the Al_2O_3–ZnO-water hybrid nanofluid employed in the present study provides enhanced cooling performance and heat transfer characteristics compared to several hybrid nanofluids reported in the literature.

Battery voltage

The electronic load device recorded the voltage change during the battery discharge process, which Fig. 20 presents based on time. While the battery has a voltage of approximately 3.6 V when fully charged, the discharge process is terminated at 2 V, which is the discharge cutoff voltage of the battery. When Fig. 20 is examined, it is seen that the voltage value decreases over time for all discharge rates, and this decrease enhances especially toward the end of the discharge process. In addition, with the increase in discharge rate, both the voltage value and discharge time decreased. While the battery discharge took 60 min for 1 C, this period was 12 min for 5 C. As the discharge rate increases, the battery voltage value decreases more due to the increase in ohmic, activation, and mass transfer losses [72].

Increasing the discharge rate leads to an increase in the rate of heat generation and temperature in the battery, primarily due to Joule heating [72]. High heat generation places more demanding thermal loads on the cooling system used in the BTMS, making the efficiency and reliability of the cooling system even more critical. In the present study, the newly developed hybrid nanofluid was able to maintain the battery temperature within a safe range by providing enhanced heat transfer capability even under challenging operating conditions such as a 5 C discharge rate, demonstrating its potential to contribute to the operational safety of the battery.

Conclusions

In this study, experimental analysis of the use of hybrid nanofluid in thermal management of pouch-type Li-ion battery was carried out. Pure water and Al_2O_3-ZnO-water hybrid nanofluid at different volume concentrations were used as coolants. Cooling performances for all fluids at different operating parameters were examined, and the findings are listed below.

(1) The heat transfer rate from the battery surface is directly proportional to the discharge rate, nanofluid volume concentration, and flow rate and inversely proportional to the coolant inlet temperature. The newly developed hybrid nanofluid has enhanced the heat transfer rate from the battery surface by up to 42.5% compared to pure water.
(2) Compared to pure water, the use of nanofluid and the increase in nanofluid concentration enhanced the heat transfer coefficient. The highest increase in heat transfer coefficient achieved with hybrid nanofluid compared to pure water is 42.1%. The heat transfer coefficient changes in direct proportion to the volume flow rate.
(3) While the battery surface temperature decreased with increasing volume flow rate and nanofluid volume concentration, it enhanced with increasing discharge rate and coolant inlet temperature. The hybrid nanofluid showed more effective cooling performance than pure water and reduced the battery surface temperature more than pure water in all cases. Compared to pure water, the hybrid nanofluid resulted in a maximum average battery surface temperature reduction of 3.8 °C. While the battery temperature exceeded the upper temperature limit in some cases using pure water, the upper temperature limit was not exceeded in any case using hybrid nanofluid.
(4) The maximum temperature difference on the battery surface was reduced by 32.8% using a hybrid nanofluid, keeping it within a safe range compared to pure water,

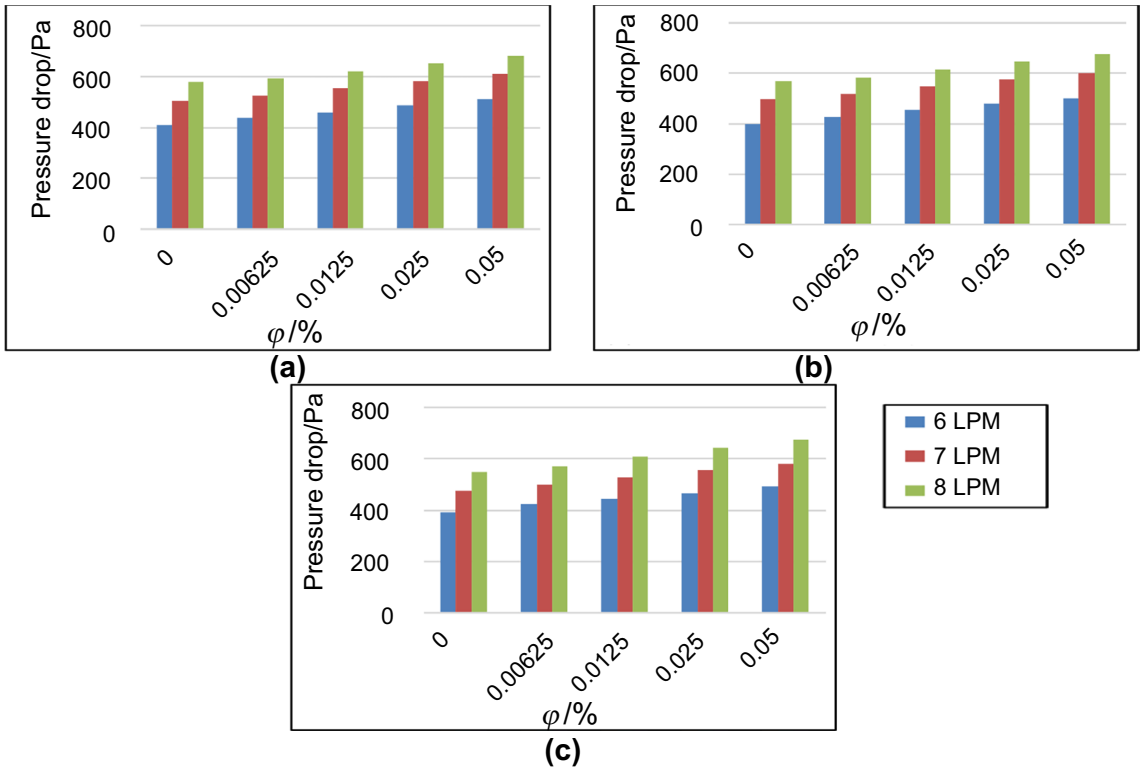


Fig. 18 Variation in pressure drop with nanofluid volume concentration and flow rate **a** 10 °C, **b** 15 °C, and **c** 20 °C

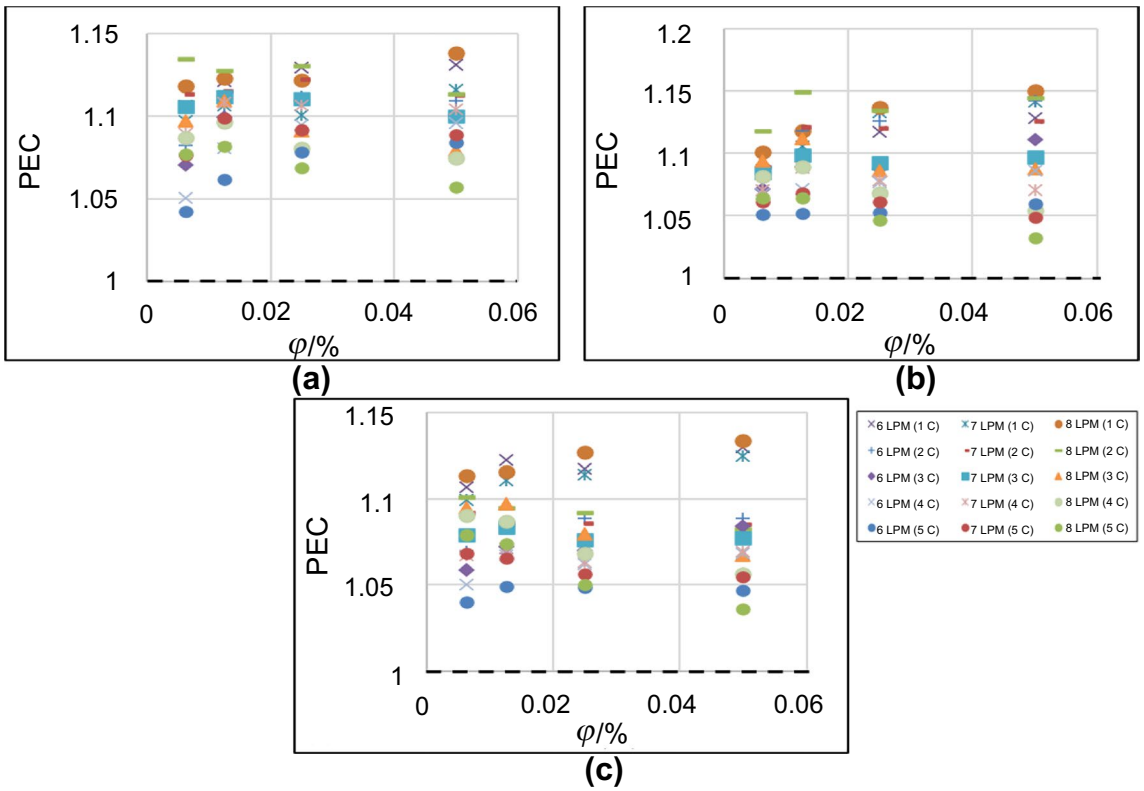


Fig. 19 Variation in performance evaluation criteria at different conditions **a** 10 °C, **b** 15 °C, and **c** 20 °C

Table 7 Comparison of the current study with previous hybrid nanofluid studies

Study	Nanofluid/application	Operating conditions	Evaluation parameter	Comparison with current study findings
Gasmelseed et al. [7]	Fe_3O_4-TiO_2-water Cu-TiO_2-water/BTMS	$\varphi = 0–3\%$ $250 \le Re \le 400$ C-rate: 3 $T_{in} = 25$ °C	Performance evaluation criteria	Fe_3O_4–TiO_2 = > 1.05 Cu–TiO_2 = > less than 1 Current study = > 1.15
Mishra et al. [36]	CNT-Al_2O_3-water/BTMS	$\varphi = 0.1\%$ $V_{in} = 0.02$ m s^{-1} C-rate: 5 $T_{in} = 25$ °C	Average temperature	Max. drop in battery temperature = > 2.7 °C Current study = > 3.8 °C
Selvarajoo et al. [12]	Al_2O_3-GO-water/BTMS	$\varphi = 0–1\%$ $V_{in} = 0.1–0.3$ m s^{-1} C-rate: 0.5–2 $T_{in} = 25$ °C	Average temperature	Decrease in battery temperature = > 7.5% Current study = > 10.4%
Bahiraei et al. [69]	Ag-Graphene-water/Heat sink	$\varphi = 0–0.1\%$ $100 \le Re \le 5\,00$	Heat transfer coefficient	Increase in heat transfer coefficient = > 17% Current study = > 42.1%
Abdul Hamid et al. [70]	TiO_2-SiO_2-water-EG/Liquid cooling	$\varphi = 1\%$ $3000 \le Re \le 24\,000$	Heat transfer coefficient	Max. increase in heat transfer coefficient = > 35.3% Current study = > 42.1%
Bhattad et al. [54]	Al_2O_3-MWCNT-water/Plate heat exchanger	$\varphi = 0–0.03\%$ Flow rate: 2–4 LPM $T_{in} = 15–30$ °C	Heat transfer coefficient	Increase in heat transfer coefficient = > 39.16% Current study = > 42.1%
Selvakumar et al. [71]	Al_2O_3-Cu-water/Heat sink	$\varphi = 0–0.1\%$ Flow rate: 0.79–2.45 LPM	Heat transfer coefficient	Increase in heat transfer coefficient = > 25.2% Current study = > 42.1%

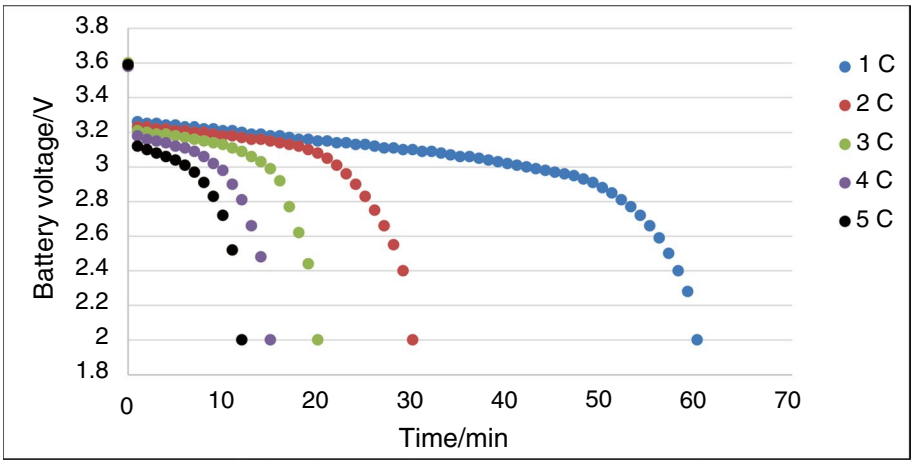


Fig. 20 Variation in battery voltage with time at different discharge rates

and a more homogeneous temperature distribution was achieved on the battery surface.

(5) It was observed that battery cooling by natural convection was sufficient for 1 C discharge rate but not for higher discharge rates.

(6) While the pressure drop increases with the coolant volume flow rate, it is not much affected by the increase in the coolant inlet temperature. Addition of nanoparticles to pure water and increasing nanoparticle volume concentration enhanced the pressure drop. With hybrid nanofluid, a maximum increase of 25.8% in pressure drop was achieved compared to pure water.

(7) Using hybrid nanofluid instead of pure water is more advantageous in terms of thermal–hydraulic performance. The highest value for performance evaluation criteria was obtained 1.15.

(8) Both the battery voltage value and discharge time change inversely proportional to the discharge rate.

In summary, it was concluded that the newly developed hybrid nanofluid is effective for BTMS due to its improved heat transfer properties. While integrating nanofluids into battery thermal management may incur additional initial costs, this investment pays off over time through extended operating

life and increased performance. This study may provide guidance for researchers interested in keeping battery temperatures within safe ranges and improving performance in electric vehicle applications.

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Data availability No datasets were generated or analyzed during the current study.

Declarations

Competing interests 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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