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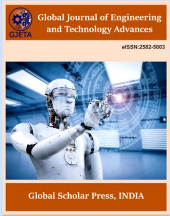

(Research Article)

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Enhancing heat transfer efficiency in li-ion battery packs for EV powertrain through nanofluid cooling

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Abstract

LIB (Lithium-ion) batteries play a crucial role in electric vehicles and are considered the most sustainable energy storage solution for modern electric transportation. These batteries serve various purposes, including supplying power for electronic devices like laptops and cell phones. However, managing battery temperature poses a significant challenge in design, particularly due to excessive heat generation during charging and discharging processes. Insufficient heat transfer between closely packed cells can compromise Li-ion cell performance and even lead to safety hazards such as explosions. Hence, the aim of this study is to enhance heat transfer and cooling processes across the battery pack of electric vehicles. A comprehensive investigation was conducted on the impact of water-copper (II) oxide nanofluid flow at varying speeds on temperature distribution within the battery pack. The adoption of copper (II) oxide nanofluid as a coolant resulted in improved thermal efficiency. This research centres on designing a Li-ion battery pack utilizing water copper (II) oxide nanofluid to enhance heat transfer and cooling efficiency throughout the battery pack.

Keywords: Battery Thermal Management System; Lithium-Ion Batteries; Copper (II)Oxide; Nanofluid; Air; Electric Vehicle; Internal Combustion Engine; Battery Pack

1. Introduction

Currently, there's a global urgency to find sustainable alternatives to fossil fuels like oil and gas, with electric vehicles emerging as a key solution to reduce environmental harm caused by transportation. The recent conflict between Russia and Ukraine has disrupted global oil and gas supplies, intensifying the demand for electric vehicles. In response, the UK plans to phase out traditional gasoline and diesel vehicles by 2030 and promote electric vehicle adoption through regulations mandating the installation of charging points in new constructions. This move is expected to significantly boost the demand for electric vehicles, compelling car manufacturers of all sizes to transition towards electric vehicle production.

In electric vehicle design, batteries serve as the primary energy storage system, with modern technology offering increased durability, particularly in cold climates. Lithium-ion batteries dominate the market due to their versatility

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and widespread use in various electronic devices. The design and configuration of these batteries depend on the manufacturer's specifications, with considerations for power, torque, and pack arrangement.

Batteries not only enable greener transportation but also contribute to combating climate change and reducing reliance on fossil fuels. However, temperature control is crucial for lithium-ion battery safety and performance, as inadequate heat dissipation can lead to overheating and potential damage. Therefore, ongoing research aims to improve heat transfer processes within battery packs to enhance safety and efficiency.

2. Literature Review

The lithium-ion battery pack consists of rechargeable cells, with graphite commonly used at the negative terminal consists of an electrode, while the positive terminal contains a tightly compressed lithium compound. In contrast to batteries such as lithium-iron phosphate cells (LFP cells), lithium-ion batteries offer superior energy storage, absence of memory effect, and minimal self-discharge (Wu et al. 2019). Their popularity in electric vehicles stems from their capacity to consistently generate energy and power density. However, due to the flammable electrolytes they contain, improper charging or damage could lead to explosions and flames, posing a safety risk to life and property. Therefore, enhancing the design of lithium-ion battery packs and improving heat transfer to dissipate heat generated during operation is crucial. Design considerations such as the computational fluid dynamics model, battery pack configuration, and thermal performance were taken into account by Widyantara et al. (2021). Stiffeners and Plexiglas were added to withstand static and dynamic loads from the electric structure. Energy from the battery was transferred to other electronic components via the conductor plate. The Battery Management System (BMS) was housed in an enclosure, which may include an active or inactive cushion (Wahid et al. 2021).

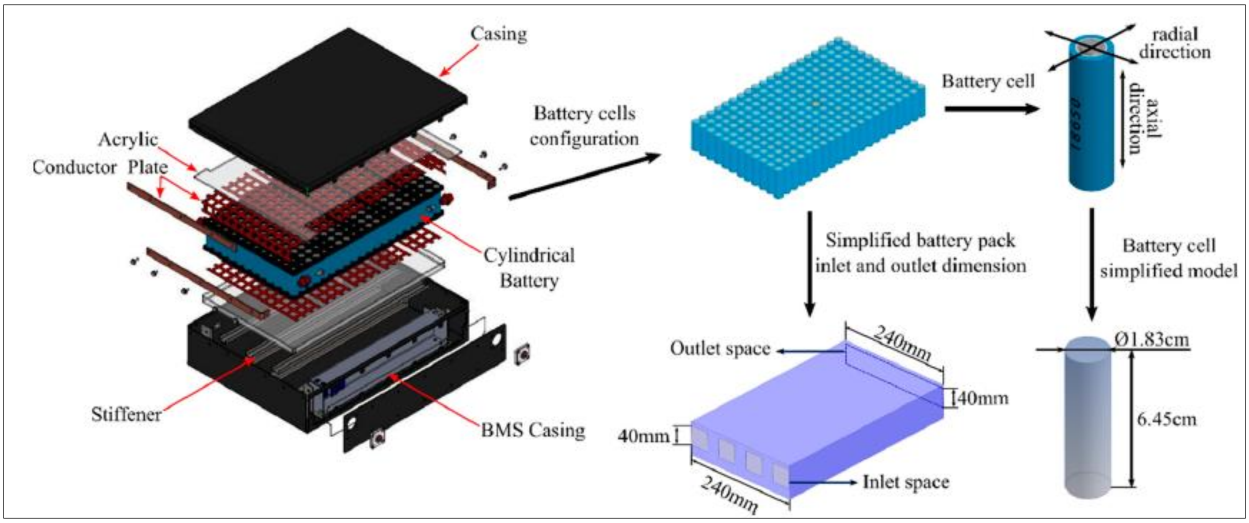


Figure 1 Configuration of Lithium-ion battery pack (Widyantara et al. 2021)

The airflow inlet and outlet were positioned on opposite sides of the battery housing to optimize temperature distribution within the pack through forced convection facilitated by a cooling fan. The details regarding the 240-cell cylindrical battery pack made of lithium nickel manganese cobalt oxide (NMC) are detailed in Table 1, with the choice of 240 cylindrical cells being influenced by their common usage in electric vehicle batteries. The battery pack was simplified for modelling purposes, retaining components susceptible to heat sources to ensure an accurate result. The initial design completely made it challenging to adjust airflow within the battery housing with the aid of Ansys Discovery Live program, potentially leading to errors and prolonged simulation times. Lithium-ion Battery consist of separator, anode, cathode, and current collector layers.

The cylindrical cell structure shown in Figure 2 did not significantly affect the thermal performance of the battery (Wu et al. 2019). Therefore, the parameters listed in Table 1 were utilized to represent the entire battery. Figure 1 depicted a detailed view of the battery housing, comprising 240 cells enclosed in a rectangular housing. Each cell was depicted as a cylindrical shape with a diameter of 18.3 mm and a height of 64.5 mm. There existed a 1 mm deviation between the 240 cylinders and the box on every surface. Proximity and cell mass play a crucial role in enhancing energy density in electric vehicles, and this close arrangement was implemented to ensure a high-density and compact form of the planned battery pack (Wahid et al. 2021). The space between adjacent cells was 1.7 mm, with a centre-to-centre distance of 20 mm. The pack was designed to function as a fluid, with an inlet on one side and an outlet on the other. Some hybrid electric vehicles utilize anywhere from 120 Li-ion cells to over 240 cells, depending on the manufacturer's decision to boost energy storage capacity. Tesla employs 2170 cells with an energy capacity of 5000mAH in the Tesla Model 3/Y Long-Range battery packs (Evannex, 2022). Xiongbin et al. (2020) conducted a thermal analysis and optimization of a 20-cell, air-cooled lithium-ion battery pack. In their study, 20 cells with each voltage of 3.6 volts were chosen for simulation in COMSOL software due to computational efficiency. Each cell had a height of 65.15 mm and a radius of 12.925 mm. The spacing between cells was set at 2.55 mm, as increasing the distance between heat-generating cells enhances the flow of cooling fluid, thereby significantly impacting exchange of heat within the Li-ion battery housing (Julia et al. 2022).

Table 1 The lithium-ion cell properties (Rao et al. 2017 & Jiaqiang et al. 2018).

Properties	Spec
Capacity	2.6 Ah
Voltage	3.6 V
Cell unit mass	0.0475 kg
thermal conductivity (axial direction)	37.6 W/mK
thermal conductivity (radial direction)	0.2 W/Mk
Specific capacity	1200 J/kgK
Diameter of cell	18.3 mm
length of cell	64.5 mm

2.1. Lithium-Ion BTMS (Battery Thermal Management System)

Temperature plays a crucial role in battery performance, as highlighted by Xu et al. (2019). Effectively controlling battery heating, as emphasized by Wang et al. (2015), presents a notable challenge. Thus, the adoption of an efficient battery thermal management system (BTMS), as advocated by Jilte et al. (2019), is vital for maintaining optimal temperature levels during operation. Top of Form

Excessive heat production or inadequate dissipation can cause the battery to overheat, potentially leading to the detachment of active materials on the electrodes and accelerating the degradation of the electrolyte, ultimately causing harm to the battery pack (Weng et al. 2019). These irreversible changes can result in permanent damage to the batteries. Excessive heat presents safety concerns, including the risk of battery short circuits that may harm internal parts and potentially initiate a fire or explosion (Wang et al., 2020). If not managed properly, the issues with one battery can impact the entire battery pack, worsening thermal runaway and making the pack difficult to control. Thus, the development of a reliable Battery Thermal Management System (BTMS) for electric vehicles is essential (Liu et al., 2014). Effective thermal management improves battery pack performance (Gachot et al. 2012).

(a)Prismatic shape (b) pouch shape (c) cylindrical shape

Figure 2 Lithium-Ion battery geometry form (Xiongbin, et al. 2020)

The three Lithium-Ion battery geometric configurations are illustrated in Figure 2. Customizing the prismatic battery allows meeting customers' requests, making it suitable for nearly all electric vehicles. Establishing a universal standard for prismatic batteries is challenging due to their adaptability, resulting in variations in size, nominal voltage, and other characteristics. Pouch batteries are produced and packed using superposition. Soft-pack batteries, however, lack consistency and require more advanced control and monitoring systems. The cylindrical battery has undergone extensive research, leading to a high level of standardization and ease of producing a uniform industry standard. The cylindrical battery offers inherent advantages in heat dissipation, creating a good heat dissipation space when packed together.

2.2. Design, simulation, and testing of EV battery pack

A crucial component in Electric Vehicle is the propulsion battery, which converts excess mechanical energy into electrical energy. However, continuous recharging and discharging of the battery cause its temperature to rise, potentially beyond its optimal operating range if not adequately cooled. This overheating diminishes the battery's energy storage and transmission capabilities, shortening its lifespan. To ensure the battery functions properly throughout its intended lifespan, maintaining a consistent and suitable temperature is essential.

In vehicles like the Tesla, Renault etc, their battery housing is typically located in the rear compartment. Johnson Electric tackled cooling challenges by introducing a secondary blower system that channels air-conditioned cabin into the trunk. However, achieving adequate air return from the rear to the front HVAC module poses difficulties due to the dual heat load system. Consequently, the vehicle operates with two opposing airflow circuits dictated by pressure differentials. Designing an efficient HVAC system becomes crucial to minimize airflow demands for the battery pack and optimize air return to the front AC system, particularly in recirculation mode. This strategy reduces negative pressure from battery fan operation and lowers noise levels by operating the fans at reduced speeds. Considering the numerous direct sound transmission paths for rear passengers, noise reduction becomes pivotal for overall comfort. Pesaran (2001) highlighted the importance of addressing challenges related to hybrid electric vehicle battery thermal cooling early in the design process.

2.3. Water-Al2O3 nanofluids cooled battery thermal management system

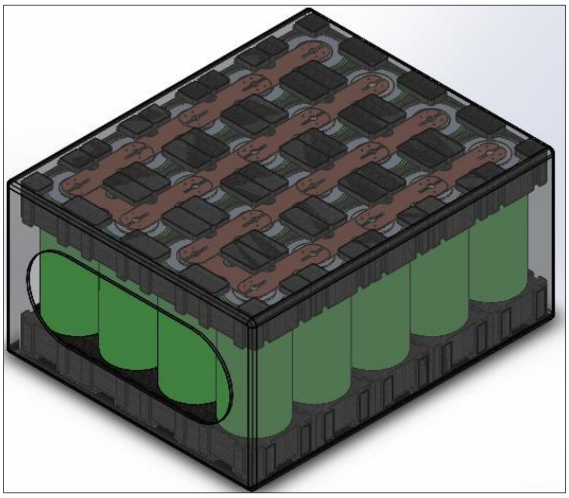
Using air for BTMS (battery thermal management systems), especially during high discharge rates, may not be the optimal choice (Rao and Wang, 2011). While forced convection air conditioning can mitigate temperature rises in the cell, cooling becomes challenging when temperatures exceed 66 degrees Celsius, preventing the cell from reaching temperatures below 52 degrees (Nelson et al., 2002). Air cooling proves inadequate under severe battery operating conditions, such as higher ambient temperatures (>40°C) or increased discharge rates (Sabbah et al., 2008). In contrast, alternative cooling mediums like mineral oil, water, dielectric fluid, and ethylene glycol offer more efficient heat dissipation than air cooling (Nelson et al., 2002). Unlike air-based systems, which are unaffected by their location within the vehicle, liquid cooling systems typically add weight and cost (Pendergast et al., 2011).

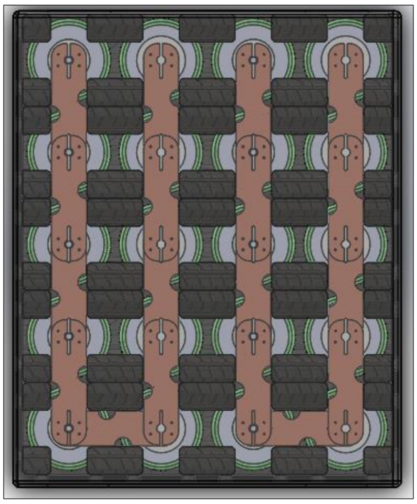
Studies comparing liquid cooling mediums like silicone transformer fluid to air cooling reveal the former's superior heat dispersal capabilities (Nelson et al., 2002). Researchers suggest increasing channel width in liquid-cooled systems to reduce average channel temperature and employing oblique mini-channels for higher heat transfer coefficients (Giuliano et al., 2012; Jarrett and Kim, 2011; Jin et al., 2014). Investigation into prismatic batteries suggests adjusting cooling measures based on ambient temperature, with liquid cooling proving most effective under normal conditions (Huo et al., 2015; Zhao et al., 2015).

Efforts to enhance heat transfer in liquid-cooled systems include utilizing nanofluids, suspensions of nanoparticles in base fluids. Early studies by Choi et al. (2001) demonstrated the potential for nanofluids to enhance thermal conductivity, with subsequent research confirming their efficacy (Duangthongsuk and Wongwises, 2010; Mondal et al., 2017; Sefidan et al., 2017; Tran et al., 2017; Rani et al., 2017; Li et al., 2015; Hung et al., 2013). These studies explore various nanoparticle types and their effectiveness in improving battery cooling performance.

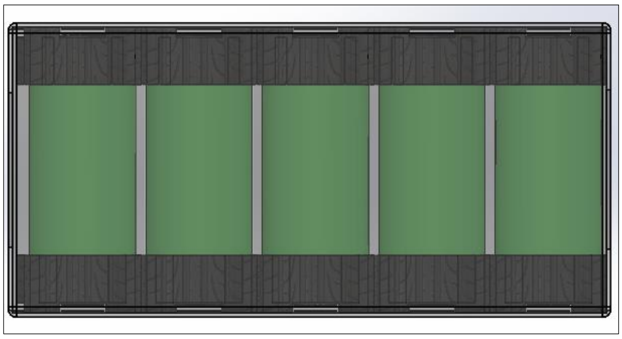
3. Methodology

The 3D model design, depicted in figures 3, illustrates the battery pack configuration. It comprises 20 lithium-ion batteries arranged in a five-row, four-column layout. The battery pack holders, totalling 40, are divided with 20 positioned at the bottom and 20 at the top. Additionally, there are 36 Nickel strips, with 18 connected at the top and 18 at the bottom. The battery pack case, rectangular in shape, was uniquely designed and assembled using inventor assembly features like mating.





(a) Isometric view of battery pack **(b) Top view of Lithium-Ion battery pack**



Side view of Lithium-Ion battery pack

Figure 3 Battery pack assembly

3.1. Boundary Conditions

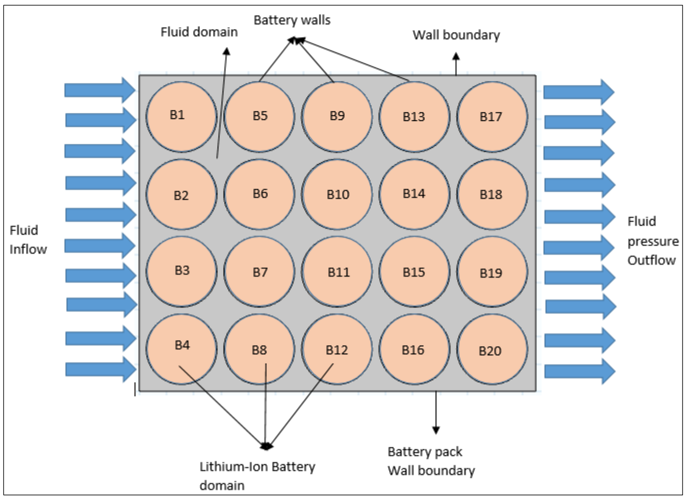


Figure 4 boundary condition of battery pack

The battery pack comprises four S5P Lithium-Ion cells connected by nickel strips. To analyse its behaviour, a 2D model was created, illustrating boundary layers and computational areas. These boundaries were selected to meet mathematical requirements, with labels corresponding to those in Figure 4. The pack's sidewalls, also known as x-axis no-slip boundaries, were depicted. The outlet boundary defines the pressure outlet, while the inlet boundary sets the temperature and velocity of incoming flow. Within the computational simulation, the physical structure includes the Lithium-Ion battery domain (B1-B20), serving as the heat source. For the flow simulation in COMSOL Multiphysics, the following assumptions are made:

- All flow for air and nanofluid is assumed to be laminar.
- The computational domain's geometry is restricted to two dimensions (2D).
- Heat loss to the surroundings from the battery pack enclosure is neglected due to insulation.
- The nanofluid flow within the battery pack enclosure is treated as incompressible.
- Heat transfer within the Lithium battery material is not accounted for.
- The nanofluid is assumed to be homogeneous and possess constant properties throughout.

3.2. Nano fluid Flow specification

The flow region is defined by mass flow rate ($\dot{m}$) as:

$$\rho_{nf} V A_I = \rho_{nf} v (N_T S_T L). \quad \text{..........Equation 1}$$

$$\dot{m} = \rho_{nf} V_{max} (2A_D). \quad \text{..........} \quad \text{Equation 2}$$

the Reynolds number can be analysed as:

$$Re = \frac{\rho_{nf} V_{max} D}{\mu_{nf}} = \frac{V_{max} D}{v_{nf}}. \quad \text{...........} \quad \text{Equation 3}$$

The mean Nusselt number on the walls of the batteries can be approximated using the provided formula (Ahmed et al., 2017). The Nusselt number (Nu) illustrates the relationship between heat transfer within the fluid by convection and heat transfer occurring at the boundary walls of both the battery housing by conduction whille the 20 cells are immersed in the fluid:

$$Nu = \frac{1}{L} \int \left(- \frac{k_{nf}}{k_f} \frac{\partial T}{\partial y} \right) dx. \quad \text{..................} \quad \text{Equation 4}$$

The nanofluid's effective density is defined as:

$$\rho_{nf} = (1 - \emptyset) \rho_f + \emptyset \rho_{sp}. \quad \text{..................Equation 5}$$

where $\emptyset$ is the volume fraction of nanoparticles. In this research a volume fraction of 2% was considered.

The thermal diffusivity:

$$\propto_{nf} = \frac{k_{nf}}{(\rho c_{sp})_{nf}}. \quad \text{..................Equation 6}$$

where $(\rho c_{sp})_{nf}$ is the heat capacitance.

Equation 3.14 can be used to calculate the effective thermal capacitance.

$$(\rho c_{sp})_{nf} = (1 - \emptyset)(\rho c_{sp})_f + \emptyset (\rho c_{sp})_{sp} \quad \text{..................Equation 7}$$

The thermal expansion coefficient of the nanofluid can also be calculated using

$$(p\beta)_{nf} = (1 - \emptyset)(p\beta)_f + \emptyset (p\beta)_{sp}. \quad \text{..................Equation 8}$$

where μ_{nf} is the effective dynamic viscosity which can be calculated below:

$$\mu_{nf} = \frac{\mu_f}{(1 - \emptyset)^{2.5}}. \quad \text{..................Equation 9}$$

Mahdy & ElShehabey (2021) and Olamide et al. (2022), the thermal conductivity of the nanofluid k_{nf} can be derieved as:

$$k_{nf} = k_f \left[\frac{(k_{sp}+2k_f)+2\emptyset(k_f+2k_{sp})}{(k_{sp}+2k_f)-\emptyset(k_f+2k_{sp})}\right]. \quad \text{..................Equation 10}$$

where k_{sp} and k_f are the thermal conductivity of nanoparticles and base fluid respectively.

Equations 11 to 14, along with the specified boundary conditions, will be influenced by the properties of the nano-particle fluid outlined in Equations 6 to 16. Equation 11 to 14 constitutes the mathematical framework for the battery assembly model, encompassing continuity in both x & y direction, momentum, and energy equations to describe the system's physical behaviours (Olamide et al. 2022):

continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \quad \text{..................Equation 11}$$

x- momentum:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho_{nf}}\left(-\frac{\partial p}{\partial x} + \mu_{nf}\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right]\right). \quad \text{..................Equation 12}$$

y- momentum:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho_{nf}}\left(-\frac{\partial p}{\partial y} + \mu_{nf}\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right]\right). \quad \text{..................Equation 13}$$

Energy:

$$u\frac{\partial(\rho_{nf}T)}{\partial x} = \frac{\mu_{nf}}{pr_{nf}}\frac{\partial}{\partial x}\left[\frac{\partial T}{\partial x}\right]. \quad \text{..................Equation 14}$$

3.3. Heat Dissipation Model for Lithium batteries

The Heat Dissipation Model for Lithium batteries considers four primary sources of heat production during operation: chemical reaction heat (RH), side reaction heat (SRH), joule heat (JH), and polarization heat (PH). Equation 15 outlines the calculation for total thermal generation.

$$P_{TH} = P_{CR} + P_{SRH} + P_{JH} + P_{PH} \quad \text{..................Equation 15}$$

PTH represents the total heat power, with PCR representing the power related to chemical reaction (CR), PSRH representing side reaction heat (SRH), PJH representing joule heat (JH), and PPH representing polarization heat (PH). CR refers to the heat released by chemical reactions within the electrodes during both charge and discharge processes. During the charge process of a Li-Ion battery (LIB), energy is absorbed, contributing to a decrease in ambient temperature, while heat is produced during discharge (Ismial et al., 2013). JH accounts for the work of current on internal resistance (IR), which can be determined using Joule's law, as demonstrated in Equation 16:

$$P_{JH} = I^2 R_\Omega \quad \text{.................. Equation 16}$$

where R_Ω is IR, and I refers to the current on R_Ω. Typically, polarization takes place at I. R R_p, and the heating power is calculated by Joule's law, as shown in Equation 17,

$$P_{po} = I^2 R_p \quad \text{..................Equation 17}$$

$$\frac{d\emptyset}{dt} = C_m M \frac{dT}{dt} \quad \text{..................Equation 18}$$

The battery's Specific Heat Capacity (SHC), which is its ability to absorb heat, is directly linked to the heat it generates, leading to a temperature increase. This SHC is determined using the principle of conservation of energy (COE), where the heat generated by the battery corresponds to its stored heat in an environment insulated from external heat exchange (adiabatic). Consequently, an increase in heat storage within the battery will result in a rise in its temperature. The SHC of the battery can be evaluated by observing the temperature increase over a defined period, as described in equation 18. Chen et al. (2019) conducted the relevant experimental procedures.

$$P_{TH} = -IT\frac{dE}{dT} + I(E-U)$$ ………………Equation 19

Here, P represents the power generating heat, I stand for the current within the circuit, T denotes the current temperature of the battery, E represents the battery's open circuit voltage, and U signifies the battery's average terminal voltage (Xiongbin et al. 2020).

From equation 19, the first $IT\frac{dE}{dT}$ on the right side of equation is the formula to calculate the power of RH, which equals the P_{TH} in equation 21. The second item refers to summary of JH and PH and it shows the voltage attribution. The voltage drops $(E - U)$ in the open circuit voltage and terminal voltage are attributed to internal DC resistance and their relationship is denoted by equation 21 below.

$$I(E-U) = I^2(R_\Omega + R_p)$$ ………………Equation 20

$(R_\Omega + R_p)$ make up the internal DC resistance, which was expressed by R. The heat production was expressed by equation 21:

$$P_{TH} = -IT\frac{dE}{dT} + I^2R$$ ……………… Equation 21

3.4 Setting up a heat transfer simulation for a 2D battery pack using COMSOL Multiphysics

The design pattern was extracted from Inventor design software and transferred to COMSOL in the Model Builder interface. Figure 5 displays the uniform geometry of the 20 batteries. The lithium-ion battery specifications sourced from the COMSOL library, utilized for simulation, are outlined in Table 2.

Table 2 Positive, Li-ion Battery properties

Properties	**Value**
Electrical conductivity	100[S/m]
Electric conductivity symmetry	3
Density	4650[kg/m^3]
Temperature difference	max(393.15, min(T, 223.15))
Specific Heat capacity	922.4
Thermal conductivity	141.2
Dynamic viscosity	1
Reference concentration	23000[mol/m^3]

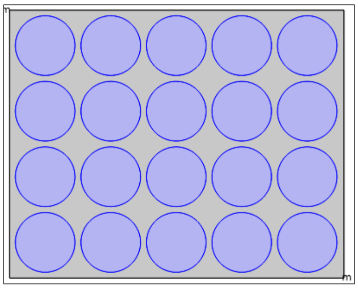


Figure 5 Positive, Li-ion Battery

Table 3 CuO nanofluid properties

nanofluid properties	Value	Unit
Density	1013.924	kg/m^3
Heat capacity at constant pressure	4106.16	J/(kg·K)
Dynamic viscosity	0.00100803	Pa·s
Thermal conductivity	0.607212675	W/(m·K)

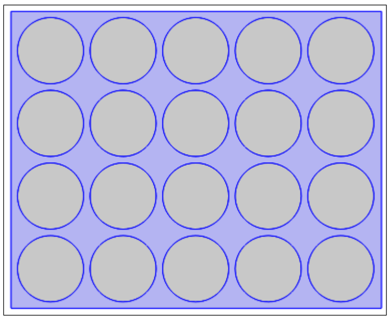


Figure 6 CuO fluid domain

The focus of this study is on designing, analysing, and simulating a lithium battery. The 3D model comprises twenty standard cylindrical lithium cells, along with additional components such as nickel strips, battery clips, and a battery case. These cells, known as 4S5P batteries, are arranged in four series circuits and five parallel circuits, totaling twenty cells, chosen for computational simplicity in Comsol Multiphysics. This configuration mirrors that used by Xiongbin et al. (2020) in their research on heat transfer agents in electric vehicle battery packs. The goal here is to prototype an electric vehicle battery pack, optimizing heat dissipation from the cells. Nickel strips connect the batteries in parallel, allowing for both parallel and series configurations due to their high conductivity and resistance to corrosion. Battery clips firmly secure individual cells within the battery enclosure, with oval shape opening at both ends, enabling the flow of air or fluids like air or nanofluid around the contained cells.

4. Methodology

4.1. Grid Test Sensitivity

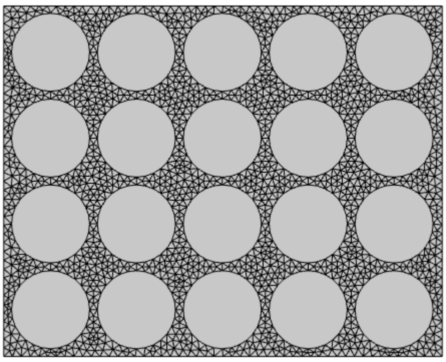


Figure 7 Fluid flow domain mesh

The process of achieving accurate simulation results for lithium-ion battery packs. It involves discretizing governing equations such as continuity equation, momentum equation, and energy equation across the flow domain using Comsol Multiphysics 5.6. A two-dimensional model with a triangular mesh comprising 2634 elements is constructed to simulate coolant circulation and heat transfer phenomena within the battery pack. The mesh is further subdivided into solid and liquid domains to enhance result precision. Additionally, an analytical thermal model is developed to assess heat generation from electrochemical reactions, with its parameters used as boundary conditions for Computational Fluid Dynamics (CFD) simulations to evaluate cooling behaviour. This approach aims to improve the quality of simulation results.

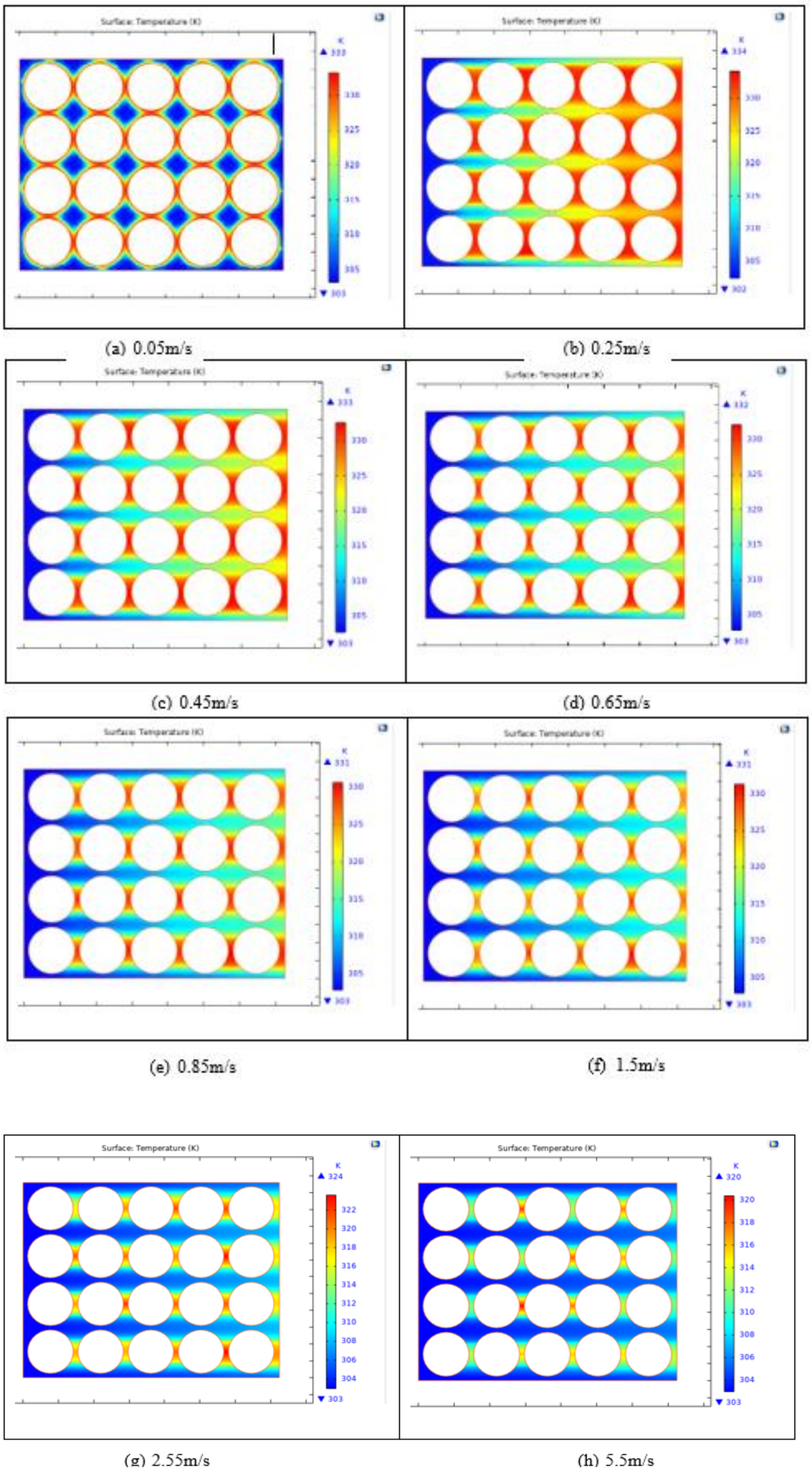
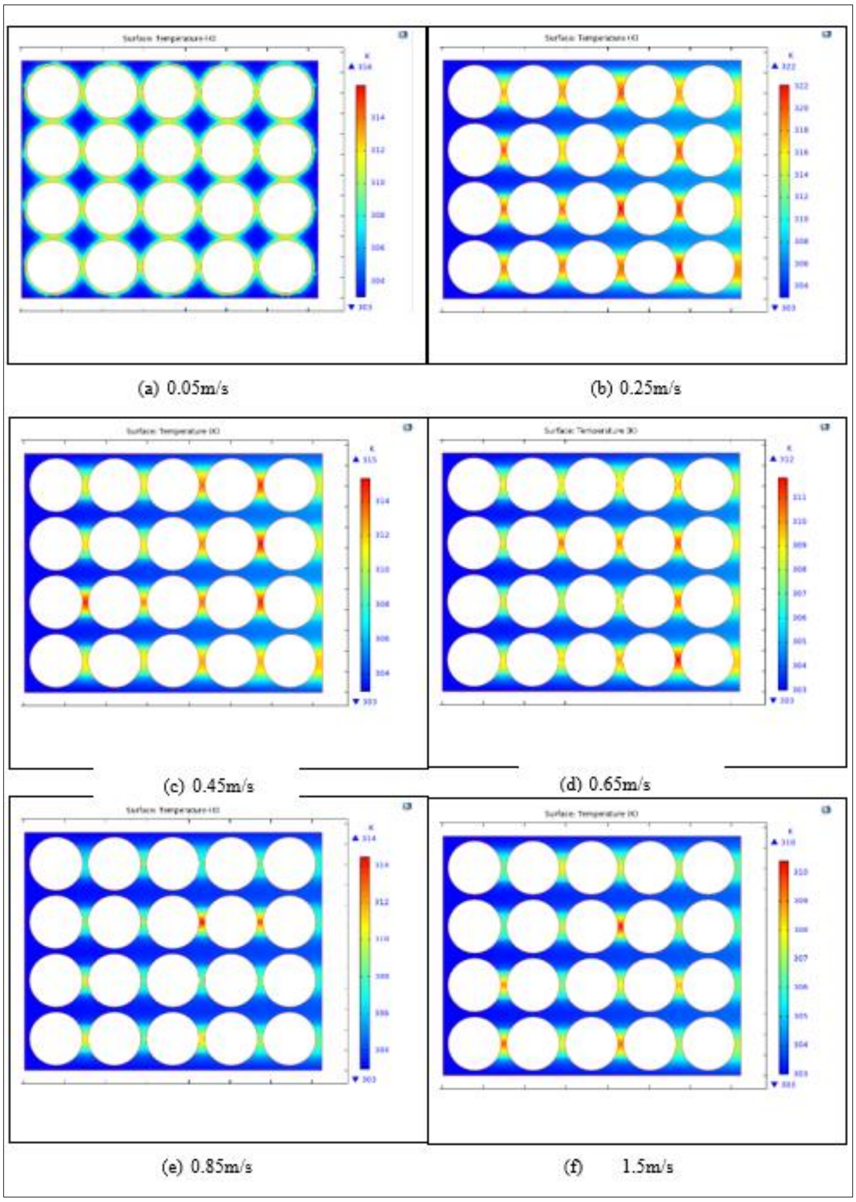


Figure 8 heat transfer in lithium-ion cell packs using air flow at various velocities

Figure 8 presents simulation outcomes depicting the heat transfer dynamics of air-liquid within a lithium-ion battery pack across velocity from 0.05 m/s to 5.5 m/s. At a velocity of 0.05 m/s, the findings reveal a maximum temperature of 333 K, aligning with the optimal operational temperature of Li-ion cells utilized in this investigation. However, at 2.5m/s, the simulation indicates a higher maximum temperature of 334 K attributed to heat generation from the lithium-ion cells, surpassing the intended optimal temperature. Consequently, this speed parameter proves inadequate for sufficiently cooling the battery pack. Upon reducing the speed to 0.45 m/s, the temperature reverts to the optimal operational temperature of 333 K (60°C) for the lithium-ion cells. Subsequently, at velocities of 0.65 m/s and 0.85 m/s, there is a slight temperature decrease from 333 K to 332 K and further to 331 K at 1.5 m/s. As the velocity escalates to 2.55 m/s and 5.5 m/s, the simulation results indicate maximum temperatures of 324 K and 320 K, respectively. Notably, at these velocities, negligible heat transfer occurs at the boundary wall of the 20 cells, rendering air currents with speeds between 0.05 m/s and 1.5 m/s impractical for use in battery thermal management systems. Moreover, the highest temperature achieved for cooling the cell wall at a velocity of 2.55 m/s is 331 K, decreasing further to 327 K at 5.0 m/s. This implies that the most efficient method for thermal management via air cooling involves applying high speeds across the cell wall during both discharging and charging of the lithium-ion battery. These findings indicate that regulating the velocity of the cooling fluid, specifically air in this instance, is crucial for effectively managing the battery pack's temperature. By ensuring that the fluid velocity falls within the optimal range, engineers can prevent overheating and maintain battery cells within their desired temperature thresholds, thereby optimizing the performance and lifespan of electric vehicle batteries.



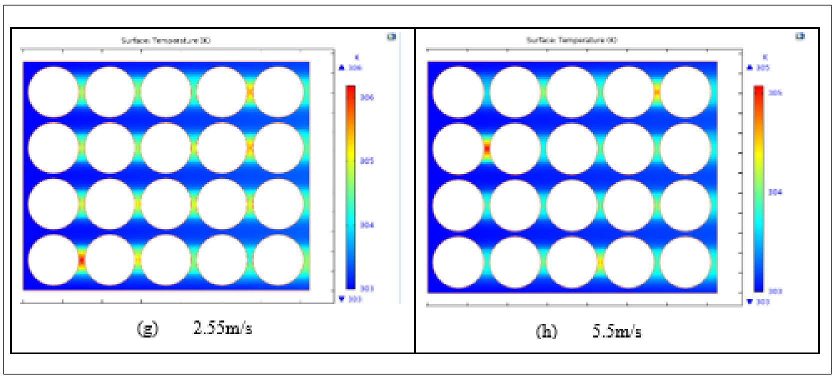


Figure 9 Simulation of heat transfer in lithium-ion cell packs using CuO nanofluid

Figure 9 provides a clear depiction of the behaviour of copper (II)oxide nanofluid functioning as a coolant. The data illustrates temperature fluctuations at various fluid velocities. At velocity of 0.05 m/s, the highest recorded temperature stands at 316 K at the wall boundary of Li-ion battery. With an increase in velocity to 0.25 m/s, the temperature rises further to 322 K. However, at 0.45m/s, there is a decrease in temperature, with the maximum temperature dropping to 315 K. Subsequently, there is a further decrease of 3 K at 0.6 m/s, resulting in a maximum temperature of 312 K on the cell wall. This trend persists with increasing velocity: at 0.85 m/s, 1.05 m/s, 2.55 m/s, and 5.5 m/s, the maximum temperatures decrease to 314 K, 310 K, 306 K, and 305 K, respectively. This observation suggests that as the coolant's velocity increases, the surrounding temperature of the battery pack decreases accordingly. This discovery holds significant implications for the thermal regulation of Li-ion batteries, especially in electric vehicles. Effective cooling plays a crucial role in maintaining optimal battery performance and longevity, as excessive heat can harm battery cells and impact overall vehicle performance. By comprehending how different coolant velocities influence temperature distribution within the battery pack, engineers can optimize thermal management systems to ensure efficient cooling and enhance the reliability and safety of electric vehicle.

Figure 10 focused on comparing and analyzing the heat transfer dynamics of air fluid and copper (II) oxide within the battery pack at various velocities. It highlights the impact of different air velocities on temperature variations within the cells and the effectiveness of air cooling for thermal management. The findings suggest that controlling air velocity is crucial for maintaining optimal temperature and preventing overheating. On the other hand, the behavior of copper (II) oxide nanofluid as a coolant and its effect on temperature variations at different fluid velocities are more effective than the convectional air fluid flow. The two-cooling fluid present various temperature reduction with increasing fluid velocity and emphasizes the significance of effective cooling for preserving battery performance and longevity. However, the copper (II) oxide shows better cooling performance than the convectional air fluid cooling fluid. The high air velocities are necessary for effective cooling of Li-ion battery pack, particularly during the charge and discharge operations. It suggests that optimizing air velocity can prevent overheating and extend battery lifespan in electric vehicles. The use of using copper (II) oxide nanofluid as a coolant can led to significant temperature reduction within battery packs at various velocities. It emphasizes the importance of copper (II) oxide as an efficient cooling system in maintaining battery performance and safety.

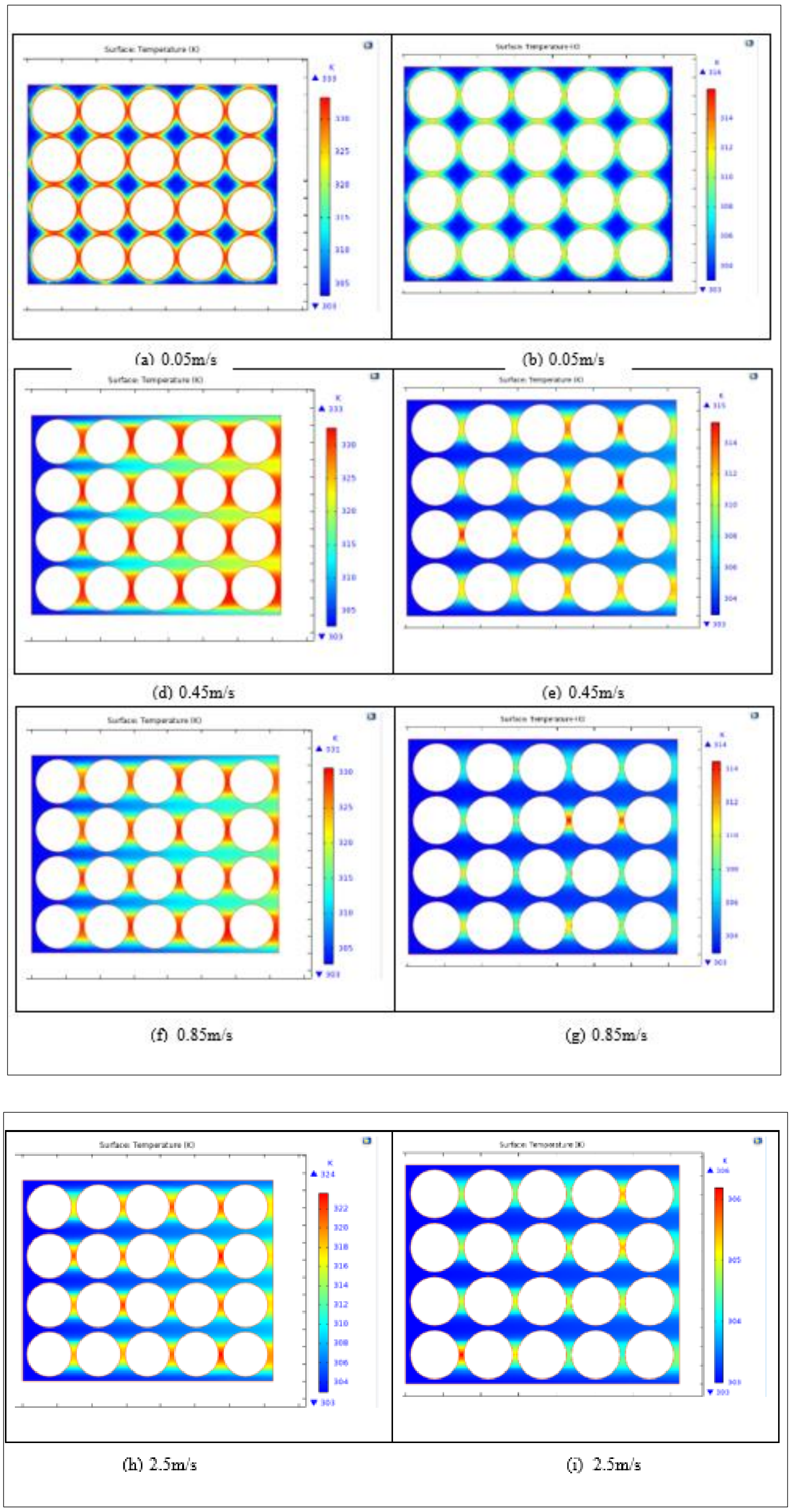


Figure 10 Heat transfer (2D) comparison of convectional cooling fluid with CuO nanofluid

Abbreviations

- AEV: All-electric Vehicle
- PHEV: Plug-in hybrid electric Vehicle
- BMS: Battery Management System
- BTMS: Battery Thermal Management System
- PCMs: Phase Change Materials

- LIBs: Lithium-Ion Batteries
- AC: Air Conditioning
- EV: Electric Vehicle
- LC: Liquid cooling
- HVAC: Heating Ventilation and Air Conditioning
- LBM: Lattice Boltzmann Method
- CFD: Computational Fluid Dynamics
- SOC: State of Charge
- HEV: Hybrid electric vehicle
- ICEV: Internal Combustion Engine Vehicle
- NMC: Nickel Manganese Cobalt-oxide
- SIMPLE:Semi Implicit Method for Pressure Linked Equation
- FVM: Finite Volume Method
- CuO: Copper (II)oxide
- N: Numbers of cylindrical batteries
- LFP: Lithium-iron Phosphate cells

Nomenclature

- F: Skin Fraction
- K: Thermal conductivity
- $\dot{m}$: Mass flow rate
- Pin: Pressure inlet
- Pout: Pressure outlet
- $\dot{Q}$: Total heat transfer over the batteries
- Re: Reynolds number
- Vmax: Maximum velocity
- Nu: Average Nusselt Number

Greek Symbols

- Α: Thermal diffusivity
- Φ: Volume concentration of particles
- ρ: Density
- $p\beta$: Thermal expansion coefficient
- Μ: Dynamic viscosity

Subscripts

- F: Fluid
- Nf: Nano fluid
- sp: Particles

5. Conclusion

The study assumed the behaviour of an incompressible fluid with adjusted thermophysical properties to replicate CuO nanofluid characteristics. The examination focused on how flow velocity affects temperature distribution. The findings can be summarized as follows:

- The analysis showed that incorporating CuO nanoparticles, typical of nanofluids, improved heat transfer.
- Increasing the speed of the cooling fluid was found to enhance the efficiency of thermal management systems for lithium-ion batteries.
- Additionally, utilizing CuO-based nanofluid was shown to enhance lithium-ion batteries or cell packs' effectiveness, resulting in a more compact configuration and better heat transfer performance.

Recommendations

This research offers insights for future investigations into the application of nanofluids in laminar flows within Li-Ion battery packs intended for both hybrid Vehicles and Electric Vehicles (EVs). Subsequent studies can be backed up with experimental work to validate the simulation carried out, while enhancing the volume fraction of CuO nanoparticles to explore their impact on heat transfer efficiency within battery packs. There's significant potential for nanofluids to serve as heat transfer agents for Li-Ion batteries due to their compactness and effectiveness in heat management (cooling). This study underscores CuO nanofluid effectiveness over conventional fluids in terms of thermal transfer characteristics, which could be leveraged to enhance heat control in batteries to prevent damages and sudden explosion.

Study impact to the body of knowledge

It's crucial to emphasize that the utilization of CuO nanofluid has been found beneficial for convective heat transfer applications, particularly in scenarios where there's limited surface area. This discovery enhances efficiency and productivity, making it applicable for both commercial and industrial purposes

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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