SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V11I8P114

Volume 11 Issue 8, 122-133, August 2024
© 2024 Seventh Sense Research Group®

Original Article

Optimizing Thermal Management in Electric Battery Packs through Heat Pipe-Based Systems and Aluminum Sleeve Integration

Satish Patil[1], Prajitsen Damle[2], Pawan Meshram[3], Nilesh Salunke[4]

[1,2]Department of Mechanical Engineering SSBT's College of Engineering, Jalgaon.
[3]Department of Oil Technology, University Institute of Chemical Technology, KBC North Maharashtra
[1,4]Department of Mechanical Engineering, SVKM's Institute of Technology, Dhule.

[1]Corresponding Author : patilsatish02@outlook.com

Received: 19 June 2024 Revised: 27 July 2024 Accepted: 18 August 2024 Published: 31 August 2024

Abstract *- The study aimed to investigate the performance of the battery thermal management when conducting a performance analysis of the BTMS, and the consequence of heat pipes on the maximum temperature of the battery cells was examined utilizing the ANSYS Fluent 2024R1 commercial CFD Package. Several important findings arose from detailed CFD analysis done in this project: Firstly, it was clear that the ability of cylindrical heat pipes to improve performance increased in line with the quantity of heat produced by the battery cells. This increase was attributed to its other part, heat pipes, through which it justified attaining the requisite temperature for phase change according to the working norm of heat pipes. In particular, the minimum temperature is attained with the use of a 30W battery system using a heat pipe with a star shape. On the other hand, the highest temperature was found during the heat generation of 80W without the heat pipe system, irrespective of the working fluid flow rate. Finally, the study emphasized the greatest need for utilising heat pipe thermal management systems where and when feasible, most significantly in battery systems that generate approximately 80W heat. The absence of such systems could result in an overheating state and all the consequent hazards to the battery shell and the system. Cylindrical heat pipes are adaptive in releasing heat as the production of heat from batteries increases. From the results obtained, it was evident that the high-power LHCP systems where heat pipe integration is not incorporated and the system generated high heat are at higher temperatures; those without heat pipe integration and low heat generation are at lower temperatures, suggesting that heat pipe thermal management is necessary in case of high heat generation for safety and reliability. In addition to the previous finding, these results provide conclusive support that the heat pipe-based TMS is vital for sustaining other critical temperature profiles needed for the electric vehicle battery pack for longest-running functionality as well as to arrest catastrophes.*

Keywords *- Battery thermal management, Cylindrical battery, Heat pipe, Thermal performance, CFD.*

1. Introduction

This need for new themes of energy is hence emerging more and more because of the energy suck globally and also the consciousness of people about the protection of the environment. Now, HEVs and EVs are presented as mandatory ingredients of this shift toward renewable power [1-3]. The concept of these vehicles rests in Lithium-Ion-based Batteries, also abbreviated as LIBs, and some of the features include the following: high-density energy, long cyclability, recyclability, and low radiance. However, its performance increases with the temperature, making LIBs highly delicate to the temperature at which they are operated. COFs are highly sensitive. Thus, it is desirable to control the working temperature between 20 – 40 °C, and the variation of temperature across the charge and discharge cycle should not exceed 5 °C [4]. Operating at this range inflicts incremental damage not only on the capacity of the battery but also increases the tendency of an unsafe event known as Thermal runaway [5]. Therefore, a need to integrate a high-performing Battery Thermal Management System or BTMS to manage thermal conditionality in the wake as well as the battery pack. Battery thermal management technologies might be classified by the type of coolant used on the specific technology, as shown in Figure [7]. They are liquid cooling, air cooling [6], heat pipe cooling [8], PCM cooling [7] and a combination of the mentioned coolants. Among these methods, it becomes clear that air cooling is the cheapest method when it comes to costs and is also easy to adopt [9]. However, it has a low convective heat transfer coefficient, which is sometimes an issue when cooling functional battery packs [10]. Conversely, liquid cooling is said to be superior to the rest because of the enhanced heat transfer coefficient of the fluid and its relative heat capacity, which is suited for the thermal regulation of batteries [11]. However, many of the liquid cooling methods tend to place the coolant channel in between the ‘’gap’’ in the battery [12], and this enhances the likelihood of leaking the coolant, which is very dangerous as it can lead to shorts in the battery. By using PCM, it is thus possible to improve the heat capacity of the system and increase the temperature of the battery pack [13]. However, cooling is relatively poor here because PCM is a material of low thermal conductivity. Additionally, PCM has problems with volumetric change during phase transitions; this is a problem with regard to the applicability of PCM in automobile battery packs. The material has great elasticity, a very small weight and a high effective coefficient of thermal conductivity. For those reasons, heat pipes can be regarded as one of the most promising uses in automobile BTMS [14].

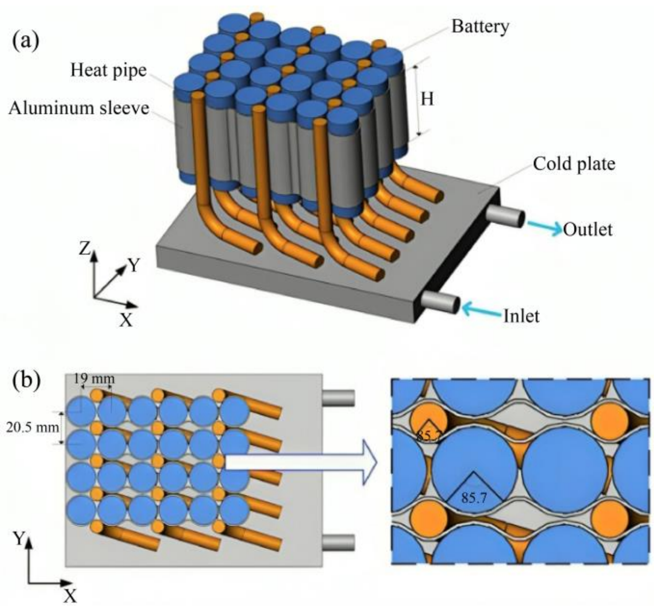

Fig. 1 Geometric representation of the heat management system and battery pack: a) BTMS summary b) BTMS top view [15]

In Figure 1, there are two diagrams, the BTMS and Battery Pack, as well as the BTMS summary that shows the key parts and general design for achieving the desired thermal management and the BTMS top view, which provides a bird-eye view of the location and spatial organization of the parts of the BTMS within the Battery Pack.

In case there is just a small temperature variance, the heat pipes transfer a large quantity of heat in a short time with efficiency since the working fluid inside the loops changes phase. In addition, for it to operate, there is no need for pump power, as will be explained later in this paper. Further, heat pipes are slightly slower in degradation and do not require much servicing at all, which is quite suitable for the automotive industry [16]. Ye et al. [17] also managed to advance the cooling capability of a system based on a heat pipe in which the condenser section had copper fins added to it. Compared to the Oscillating heat pipe of Qu et al. [17], the cooling efficacy rate of PCM was high.

The authors of the present article, Zhao et al., performed experimental works earlier based on the thermal study of ultra-slim heat pipe-BTM systems of lithium-ion batteries [18]. Collecting various cooling processes involved, such as air cooling, water spry, and ambient cooling. Of most interest, they demonstrate how those clients could achieve the best thermal results where wet cooling designs are to be used in conjunction with heat pipes. This goes a long way in supporting the assertion that it is plausible to use a package of cooling methods to optimize the possibilities of BTMS in the field of regulation of temperatures of batteries.

Heatsink with heat pipes that resemble them so that they can fit into the prismatic shape of the batteries is the latest liquid cooling approach pioneered by Liang et al. [19].

Wang et al. [20] put forward a method in which heat pipe is integrated into aluminium cooling plates to enhance the contact area of prismatic batteries in the future. However, due to the constraints implied by the contact area, which is accessible to cooling, prismatic battery packs still need to include heat pipe cooling strategies [21]. This underlines the need for the development of ad hoc cooling solutions to fit the design and thermal control of prismatic battery forms.

Venting is another complexity in cooling design in cylindrical batteries since these packagers have curved surface geometry. Regarding this, other methods apart from heat pipe cooling techniques have been contemplated to augment the contact area. Rao et al. [22] proved the concept of using curved, surfaced aluminum blocks to offer more contact surface area between the cylindrical batteries and the cooling water. Similarly, a new generation of heat exchangers, which has been designed by Bohacek et al. [23], comprises polymeric hollow fibers that achieve the maximum possible coil around cylindrical batteries. Nevertheless, the cooling methods of the heat pipes in the cylindrical battery pack seemed to have been neglected in the previous research works, even though the advancements in electronics have been enhanced in a manifold fashion. This is why there is a need to conduct more studies on the cylindrical battery arrangement to evaluate the heat pipe cooling strategy by efficiency and applicability.

This system includes a cold plate as well as aluminium sleeves, which are placed in wave patterns so that there may be an increased number of contacts between heat pipes and batteries. As in this recommended BTMS, the condenser of the heat pipe can be positioned just over the outer surface of the cold plate in such a manner that the evaporator can be accommodated in the available space within the battery pack. It is also easy to eliminate any leaks because the cold plate is situated in the lower layer of the battery. It is also possible to use a sintered porous material in which the pore size is small, porosity is high, permeability is considerably improved, and capillary action takes place [24]. Besides, since we enhanced the cooling capability through the heat pipe principle that has an anti-gravity feature, the use of a wick that is made from sinter copper powder enhances the absorption feature. To be more specific, all of the advances mentioned above can enhance the dependability and effectiveness of thermal management systems. In the next section, a numerical analysis in terms of numbers regarding the thermal performance of BTMS is made based on some factors. The intended purpose of this venture is thus the development of a new heat pipes thermal control system optimized for cylindrical battery packs.

Experimental tests conducted by Wu et al. in [25], as shown in Figure 2 below, established that there was a significant improvement in the cooling of battery systems. In other experiments, Rao et al. [26] also examined other thermal tests of prismatic-shaped batteries cooled with heat pipes. Among the conclusions mentioned above, they have presented that at the production rate of thermal being below 50W, the battery cell temperature was only 50°C. At the production rate being regulated below 30W, the fluctuations in temperature were only 5°C. These investigations could also be continued in the direction of investigating how these heat pipes affect the temperature circulation of the battery cells or packs. Moreover, additional studies have to be completed to find suitable heat pipes or to design sufficient ones for the highest temperature level of the battery cell. At the moment, the performance of the heat pipe technology does inadequately illustrate the role of material with phase change in thermoregulation problems. The justification for this research arises from the question of whether there are effective and straightforward ways of examining the capability of heat pipes. For the analysis of the present work, a prismatic battery cell with integrated heat pipes was assumed to be discharged at a constant current. The temporary thermal behaviour of the heat pipe other than what has been discussed in this paper can be simulated using a method known as the thermal network [27]. In this paper, the battery cell that will be focused on is the ePLB C020 type, which has a 20 Ah capacity. All the present simulations were made using the geometric and electrochemical parameters which were available in the earlier data [28]. The second purpose of this work is to demonstrate that it is possible to get rid of heat at a considerably higher rate using the appropriate kind of heat pipe than with the help of active cooling. For safety in designing this BMS, the system simulation was done at the highest discharge rating of 5C, where 5C is a current draw of 100A.

However, some of the remarks include the observation that there is little literature on these technologies and that the heat pipes that are particularly applied to cylindrical battery packs have limited information on them. It must be noted that although many research articles are available on prismatic batteries, the faces of the cylindrical cells curved tapering in cross-section and the related problems, such as the need to increase contact surface area, were not considered very much. Moreover, while prior studies have concentrated on basic cooling techniques, few studies have been made on how engineers could better employ the heat pipes in the cylindrical battery structure. To this end, the present study proposes a novel BTMS employing heat pipes for a cylindrical cell battery pack. This system consists of a cold plate and aluminum sleeves, and these parts are wavy-shaped to allow pipes and batteries to have better contact with each other. Therefore, it is suggested that the internal temperature of the BTMS not be raised and that proper heat dissipation be applied so that a higher duration and efficacy of cylindrical battery packs can be achieved.

2. Methodology

The methodology employed in this study aimed to optimize thermal management in electric battery packs through the integration of heat pipe-based systems and aluminium sleeves. Mathematical models were built, combining governing equations to describe heat movement within the battery pack and heat pipes. A numerical method was implemented to solve these equations effectively.

Finite Element Analysis (FEA) solution strategies integrated with the commercial ANSYS Fluent software were employed in modelling the battery packs' thermal behaviour with different heat pipe systems integration strategies. The geometry of the components was done with much precision to identify the border zones for the subsequent mesh generation correctly and to achieve the required level of discretization of the features of flow and boundary conditions. Using CFD, different conditions of heat generation rates, working fluid flow rates, and heat pipe arrangement to battery pack temperature were compared. The main conclusions reported on the beneficial effect of the application of heat pipes for battery cooling, especially for systems with higher thermal loads, which reduce the threat of thermal failure and augment safety. Lastly, the study outlined the optimum approaches for the design of thermal systems for EV battery pack. It highlighted that heat pipe solution bears the importance of operating temperature regulation and safeguarding against thermal issue-related risks.

Figure 2 displays a flow chart that gives an impression of how a Computational Fluid Dynamics (CFD) simulation is conducted from the preprocessing step that involves defining geometry and generating a grid for discretisation. It follows the immediate definitions of the physical properties and boundary conditions of the Fluent setup, followed by simulation and postprocessing for result analysis. Validation confirms the correctness. Case data analysis requires changes, analysis, and re-run of the simulation before conclusions are reached.

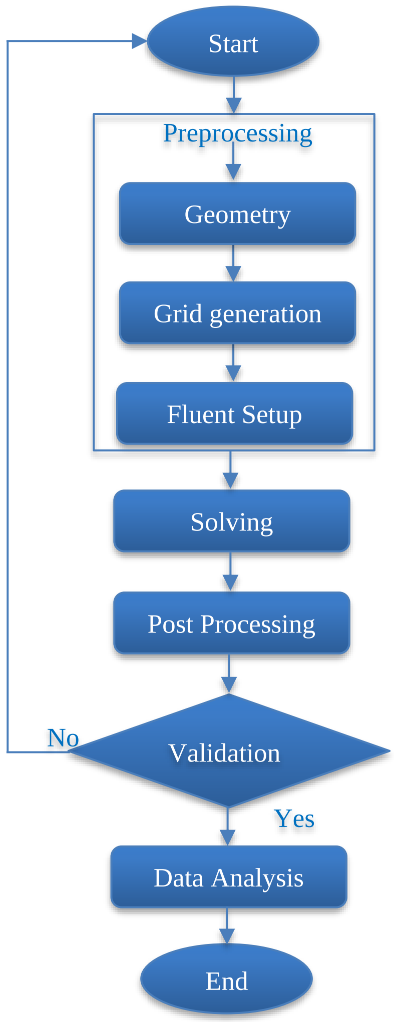

Fig. 2 CFD flow chart

The procedure that was used in simulating and modelling the thermal system of batteries using CFD in ANSYS Fluent is as follows. These are the initiation phases in which the simulation project is carried out with the aim of designing one to enhance the thermal performance of a battery pack that consists of heat pipes and several other TMS components. The objective of this next step, known as preprocessing, is to identify input conditions that apply universally, such as materials, boundary conditions, initial conditions, etc. The subsequent step is the geometry step, which defines the physical characteristics of the model, as well as the size and location of the battery cells and heat pipes. Just like in any other computational simulation, data acquisition and preparation for analysis stand out as very critical steps in any practical simulation. This is the process of obtaining all the input data necessary for the study, such as material properties, constraints, control parameters, and battery pack settings. Thermal management analysis may contain properties of battery cells, like heat generation rates, specific heat and thermal conductivity, properties of the cooling fluids and heat pipes, etc.

Pre-processing also consists of arranging this data in a way that the simulation software will be able to work with it. Such tasks could include preparing pro-CAD models of the system, transformation of geometrically described details into the model comprising meshes, assignment of boundary conditions, and source terms. Pre-processing is always vital in any simulation since an erroneous input would go a long way in distorting the results of the simulation. Proper pre-processing ensures that the subsequent modelling and analysis reflect the real-world behaviour of the system as closely as possible. The process of grid generation requires a mesh, which partitions the geometry into smaller subordinate units to obtain finite solutions to the governing laws of fluid dynamics and heat transfer. The type of mesh used in the simulation determines the degree of accuracy and the amount of time required in the computation.

In the Fluent Setup phase, particular settings that detail physical models, solvers, and convergence are adjusted to guide the simulation to conform to physics. The thermal management of battery systems is inherently a multi-physics problem involving the interaction of various physical phenomena like fluid dynamics, heat transfer, and, in some cases, phase change. Multi-physics modelling refers to the simulation of these interrelated phenomena in a coupled manner.

In this study, ANSYS Fluent is likely used to model heat transfer within battery cells, heat dissipation through heat pipes, and the flow of coolant or working fluid within the system. Multi-physics modelling is essential because the efficacy of a Thermal Management System (TMS) cannot be fully understood by analyzing heat transfer alone. For example, the effectiveness of a heat pipe depends not only on its thermal properties but also on the fluid flow conditions surrounding it. Accurately capturing these interactions in the model is key to designing an efficient TMS. These factors are all incorporated in the simulations in a more or less integrated way, which allows for a more global assessment of the system.

The solving phase is the computation phase where solutions to one or many factors, such as temperature, pressure, fluid flow, and so on, are gained, and the result generated by the ANN can be visualised and analysed. Moreover, after the validation step, the feasibility of the outputs concerning the simulation in the course of the experimentation with the results is checked with the help of experiment or prototype data. If an inconsistency exists, then new phases which could have been defined in the previous steps, namely, alteration of the geometric or the grid density, can be done. After validation, the work described in the papers mentioned above entails analysing the outcome of the analysis for thermal performance on the wall structure and looking for ways to improve it. The fifth and last stage of AEMT is the documentation of the results and discoveries made during the simulation.

In such a way, the steps to define the problem areas regarding the improvement of the heat management of batteries and to define the optimal designs have become much more systematic. Below is the TMS design, which is the end product of this research. In this phase, the opportunities derived from the data collection and the multiphysics modelling are employed to enhance the thermal management system for the battery pack. Therefore, TMS design includes the decision to arrange heat pipes, cooling plates, and aluminium sleeves to control heat within battery cells.

Sometimes, specific arrangements of TMS in some sections could mean that some parameters are to be varied in simulation to check how it would respond. The objective is to regulate the battery cell temperatures while the battery is active with the intent of efficiency and safety. Besides eliminating the risks of heating and thermal explosion, a good TMS design enhances the durability and capacity of the battery. This is a cyclic design; thus, each try involves potential guidelines for enhancing the system until the best design solution.

2.1. Geometry

The geometrical configuration of the battery back, which is in the airflow domain, was modelled using commercial software known as ANSYS Space Claim 2023R2 3D modeling.

This is evident in the two cases shown in Figure 3 (a-b), where the solid and fluid domains are depicted with different colours and in 3D. The model without a heat pipe can see the heat diffusion trend of the entire system and the heat distribution of the solid/liquid area of the system.

The simple cylindrical heat pipe model shows how the heat pipe changes the thermal condition and provides for heat transfer. That is why this particular comparison is aimed at exposing how it impacts the overall thermal management within the system. The geometrical properties of heat pipes are reported in Table 1, in general, for all types of heat pipes.

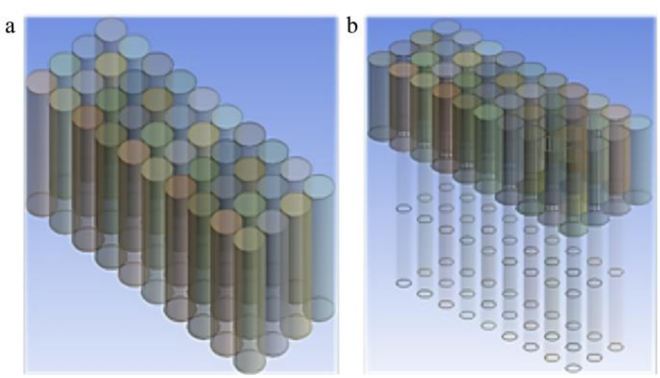

Fig. 3 (a) 3D model of the solid and fluid domains for no heat pipe and (b) Cylindrical heat pipe cases

Table 1. The heat pipe's overall dimensions

The length of the evaporator section	65mm
The length of the insulator section	65mm
The length of the condenser section's	65mm
The heat pipe's cylindrical outside diameter	7.72mm
The heat pipe's cylindrical interior diameter	6.72mm

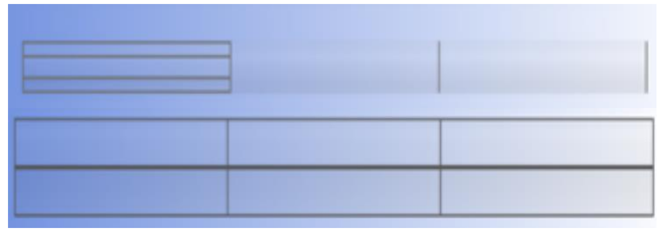

Fig. 4 2D model of both heat pipes

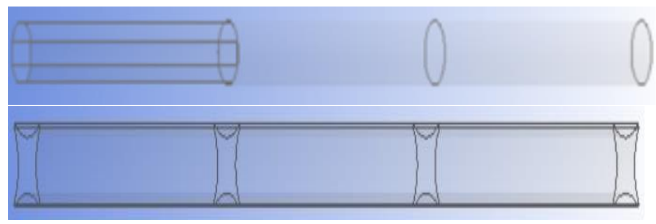

Fig. 5 3D model for both heat pipes

Figure 4 displays the detailed two-dimensional models of two distinct heat pipes, emphasizing geometric features like length, diameter, and internal structure essential for evaluating thermal conductivity and efficiency in heat dissipation. In contrast, Figure 5 represents the comprehensive three-dimensional representations of these heat pipes, illustrating their physical dimensions and spatial placement within the system, which is crucial for assessing integration and effectiveness in managing thermal loads. These diagrams provide a comprehensive understanding of heat pipe design, performance, and application in thermal management systems.

2.2. Meshing

For the study's meshing, ANSYS Meshing 2023R2 was employed, whereby the flow and solid domain were discretised into 670, 907 cells or elements and 175,761 nodes. Further refinement near the cell was done under capture proximity to best correlate with the transitional sensitivity of the solid-to-fluid domain at a low computational cost.

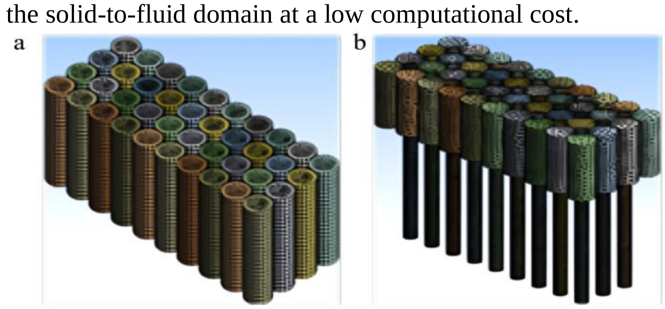

Fig. 6 (a) The grid generation for no heat pipe and (b)Cylindrical heat pipe cases

Figures 6 (a-b) visually define a situation with and a situation without a cylindrical heat pipe and how the computational grids are created. Grid generation is paramount to the correct prediction of fluid flow and heat transfer in Computational Fluid Dynamics (CFD). When comparing these grids, an understanding can be drawn of the impact of the heat pipe in modifying the accuracy and resolution of the simulator in depicting the thermal characteristics of the system. The following step is to assign boundary conditions to these border zones that have been created from the classification of cells.

This involves the identification of distinct boundary areas referring to inlet, outlet and wall areas and the specification of adequate boundary values for the particular areas. In this way, by clearly determining these boundary zones and by defining the conditions that are proper for each of them, the computational model can perform simulations that are close to the physical reality of the studied system. This is even assuming their corresponding boundary conditions are set correctly, and it takes much effort to ensure that boundary conditions are exact for highly accurate results in computational simulations, as used in most engineering and scientific studies.

Figure 7 shows the particular zones that define thermal management systems as critical. They show where water flows in and out, black lines delimiting zones for thermal isolation, and areas where heat transfer is allowed at the condenser wall. The boundary markings are crucial for CFD simulations and thermal analysis as they designate fundamental parameters necessary for modelling fluid flow, heat transfer, and, as a whole, further enhancement of the system's performance.

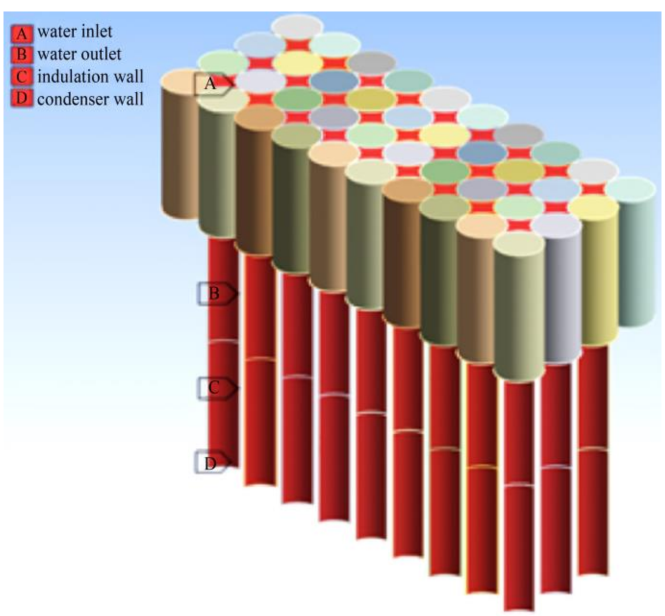

Fig. 7 Named selected boundary zones

2.3. Mathematical Modelling

The forced turbulent flow and air stream heat transfer in the conditions of ambient were modelled using the continuity, momentum, and energy equations.

Continuity equation**,**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \quad (1)$$

Momentum equation**,**

$$\frac{\partial}{\partial t}(\rho V) + \nabla \cdot (\rho V V) = -\nabla P + \nabla \bar{\bar{\tau}} + \rho \mathbb{g} \quad (2)$$

Energy equation,

$$\nabla \cdot \left(\rho \vec{v} C_p T\right) = \nabla \cdot (\lambda \nabla T) \quad (3)$$

2.4. Boundary Conditions and Assumptions

The nonlinear, simplified coupled partial differential conservation equations that govern fluid flow are subject to the following boundary conditions in addition to the assumptions made primarily because of geometric restrictions, input and outlet circumstances, etc.

- Symmetric wall boundary condition was applied to the surrounding fluid wall.
- Unsteady, forced turbulent convection flow was assumed.
- On the duct wall, the usual no-slip conditions were imposed.
- At the enclosure inlet section, uniform axial velocity Vin of 4 m/s and temperature Tin of 298.15K were applied.
- 30W, 45W, 60W, 80W heat generation was applied to the entire battery pack for each simulation.

The code for the computational fluid dynamics problem was solved using Fluent. The control volume approach was used to solve the system of governing equations.

2.5. Finite Volume Method

This methodology utilizes control volumes to apply conservation principles or physical laws expressed by the governing equations over discrete volumes. By partitioning the domain into finite control volumes, the finite volume method facilitates the accurate representation of fluxes and changes within the system. It is a widely used technique for solving a diverse range of differential equations encountered in various scientific and engineering applications.

The employed grid schemes are staggered ones, and entirely scalar quantities are determined at the center points of the control volumes, while all the velocity apparatuses are determined at the midpoints of the control volumes. They were discretized in terms of time using second-order upwind techniques. The [SIMPLE] technique was applied to connect pressure and velocity. In each case, the residual terms turned out to be less than 10 to the power -6.

2.6. Numerical Procedure

The flow domain is divided using a computational grid generator into discrete control volumes. 2023R2 ANSYS meshing.

Within the framework of a second-order upwind method, discrete variables, or "unknowns," including velocities, conserved scalars, temperature, and pressure, are formulated by integrating the governing equations over each control volume. This step, known as discretization, is pivotal in numerical simulations. Employing a second-order upwind technique enhances precision at cell faces by extrapolating a Taylor series expansion from the cell-centered solution around the cell centroid. One of the most direct ways of understanding the discretization process is using a scalar quantity transit stable conservation equation represented by φ.

$$\oint \rho\varphi\vec{v}\cdot d\vec{A} = \oint \Gamma_\varphi \nabla\varphi \cdot d\vec{A} + \int_V S_\varphi dV \quad (4)$$

Which includes density ρ, velocity vector $\vec{v}$ $\vec{v} = v_r\hat{r} + v_x\hat{k}$, and for surface area $\vec{A}$, is a vector. Furthermore, it comprises a diffusion coefficientΓ_φ, and source per unit volumeS_φ. A gradient of φ is calculated as $\nabla\varphi = (\frac{\partial\varphi_r}{\partial r} + \frac{\varphi_r}{r})\hat{r} + \frac{\partial\varphi_x}{\partial x}\hat{k}$. The integration is implemented for every control cell or volume within the computational area, resulting in,

$$\sum_f^{N_{faces}} \rho_f\vec{v}_f\varphi_f \cdot \vec{A}_f = \sum_f^{N_{faces}} \Gamma_\varphi \nabla\varphi_f \cdot \vec{A}_f + S_\varphi V \quad (5)$$

Here, the terms $\rho_f\vec{v}_f\varphi_f$ represent the rate of mass that passes through the face, while N_faces stands for the number of faces that surround a particular cell. $\vec{A}_f$ is an area of the face $\vec{A}_f = A_r\hat{r} + A_z\hat{k}$, $\nabla\varphi_f$ is a gradient of φ at the face, V is the cell volume, and φ_f is the value of φ convected through the face f. The face value φ_f in second-order unwinding is calculated with the equation given below :

$$\varphi_f = \varphi + \nabla\varphi.\vec{r} \quad (6)$$

Where ∇φ in the upriver cell is represented by the displacement vector $\vec{r}$ from the centroid to the face centroid of the upstream cell, φ is the cell-centered value and its gradient.

The gradient ∇φ at the cell center c0 is intended using the method using Least Squares Cell is confined by a slope limiter or standard gradient to prevent the occurrence of false oscillations in the flow with solution field around shocks, discontinuities, or rapidly altering local flow field changes.

$$(\Delta\varphi_r)_{c0} = \sum_{i=i}^{n} W^r io \cdot (\varphi_{ci} - \varphi_{c0}) \quad (7)$$

$$(\Delta\varphi_x)_{c0} = \sum_{i=i}^{n} W^x io \cdot (\varphi_{ci} - \varphi_{c0}) \quad (8)$$

A coupled algorithm is used to perform the linearization, which brings together the pressure correction equation and pressure with momentum equations. This facilitates the transformation of the discretized equations into a linear equation system. Subsequently, this system is iteratively solved to gain a converged numerical solution. The pressure-based solver then utilizes the resulting solution to update the values of dependent variables. It is worth noting that the discretized equation exhibits nonlinearity concerning variables at the cell center and neighbouring cells due to the presence of an unknown scalar variable, denoted as φ. Once linearized, the equation takes the following form:

$$a_p\varphi = \sum_{nb} a_{nb}\varphi_{nb} + b \quad (9)$$

Where neighbour cells nb are comprised of linearized coefficients a_p and a_nb for φ and φ_nb.

If analogous equations are used for each cell, an algebraic equation set will contain a ROW sparse coefficient matrix. The velocity field is defined from the solutions of the momentum equations. In this work, an iterative procedure is adopted with the convergence criterion defined in a way that the residuals are less than 10-6 in all the simulations conducted. Substituting and fixing convergence requirements maintain the stability of the convergence solution. For stability, the default values of under-relaxation factors are unchanged in all the simulations performed in this study.

3. Results and Discussion

The numerical method utilized in this study, primarily rooted in the Finite Control Volume technique, has proven highly effective in addressing the governing equations with the system while adhering to appropriate boundary conditions.

Figure 8 shows the sequential process within ANSYS Workbench for conducting simulations across multiple scenarios. It covers geometry creation or import, mesh generation, boundary condition setup, simulation execution, and post-processing for analysis and optimization of thermal and fluid dynamics performance.

Fig. 8 ANSYS workbench workflow for simulations of all the cases

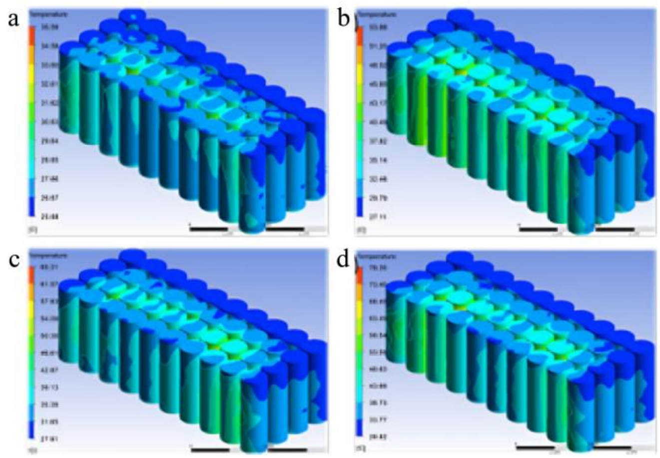

Fig. 9 Temperature contour of battery cells with no heat pipe at (a) 30W, (b) 45W, (c) 60W, and (d) 80W Heat generation rates

3.1. Temperature Contour

For each of the heat generation cases, the temperature is maximum at the middle cell of the 3rd row, counting from the inlet side. This is mainly because airflow is restricted through the pack, and sweeping the heat produced from the battery is challenging for the middle ones.

Figures 9 (a-d) illustrate the temperature variations in battery cells without a heat pipe across varying heat generation rates (30W, 45W, 60W, 80W), showing the distribution of heat and temperature gradients on the battery's surface. Higher heat generation rates lead to increased temperatures and more pronounced gradients. Analyzing these distributions is essential for developing effective thermal management solutions to enhance battery performance and prevent overheating in real-world scenarios.

Attaching heat pipes right through the spaces between the battery packs looks to contribute a lot to improving thermal management. For the same heat generation rate, the temperature of the battery cells is lower when heat pipes are attached to them. That is mainly because of the heat sweeping enhancement made by the heat pipes. That can be easily demonstrated by the fact that the middle battery cells are at lower temperatures than the outer ones, in contrast with the battery pack with no heat pipe.

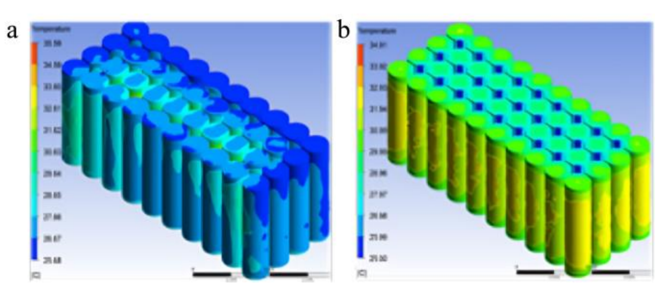

Fig. 10 (a) Temperature contour of battery cells with no heat pipe, (b) Cylindrical heat pipe at 30W heat generation rate

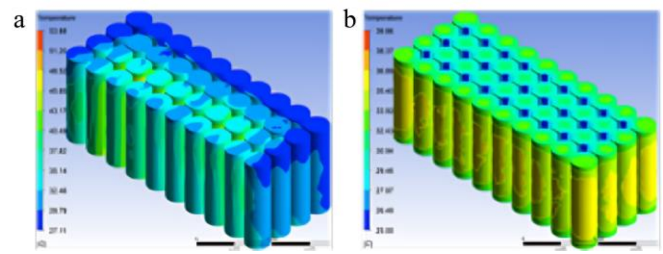

Fig. 11 (a) Temperature contour of battery cells with no heat pipe, (b) Cylindrical heat pipe at 45W heat generation rate

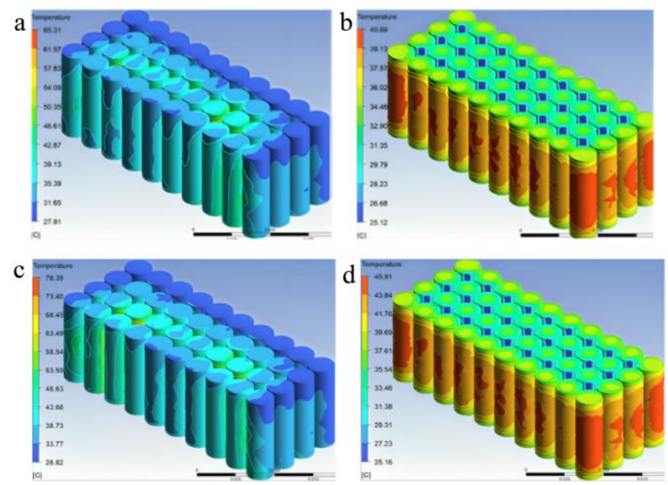

Fig. 12 (a&c) Temperature contour of battery cells with no heat pipe, (b) Cylindrical heat at 60W heat generation rate, (d) Cylindrical heat pipe at 80W heat generation rate

Figures 10 (a-b) show the temperature distributions across battery cells under a 30W heat generation rate, comparing scenarios with no heat pipe and with a cylindrical heat pipe. It visually represents how heat is managed differently in each case, highlighting the potential effectiveness of the cylindrical heat pipe in reducing temperature gradients and enhancing thermal management within the battery cells. Analyzing these contours provides insights into optimizing heat dissipation strategies for improving battery performance and longevity. As the heat generation increases, the heat transfer enhancement gets better, as evidenced by the significant temperature drop in the battery cells with the heat pipes. Figures 11 (a-b) display temperature contours across battery cells under a 45W heat generation rate, comparing scenarios with no heat pipe and with a cylindrical heat pipe. It visually depicts how heat is distributed within the cells, showing differences between the two thermal management approaches. This comparison helps in assessing the efficiency of the cylindrical heat pipe in managing higher heat loads and optimizing thermal performance within the battery cells, which is crucial for enhancing efficiency and lifespan in practical applications.

Figures 12 (a-d) illustrate temperature distributions in battery cells with and without a cylindrical heat pipe, highlighting the potential benefits of cylindrical heat pipes for improved thermal management efficiency. Comparing the temperature distribution for cases of cylindrical heat pipes, battery cells with cylindrical-shaped heat pipes has an increase in temperature. This can be directly attributed to the area of contact between the battery cells and the heat pipes. The cylindrical ones transfer more heat at a given heat generation rate and flow rate of the working fluid.

A max temperature of the battery pack is in the case where battery cells harvest 80W of heat, and there is no heat pipe in the vicinity to take it, which amounts to 78. 35°C and 49. regions, and 35°C, 53°C, respectively according to Table 2.

Table 2. Maximum temperature and change in temperature comparison

Parameters		Max T (°C)	ΔT (°C)
No heat pipe	30 W	35.59	9.91
	45 W	53.88	26.77
	60 W	65.31	37.4
	80 W	78.35	49.53
Cylindrical heat pipe	30 W	34.91	9.91
	45 W	39.86	14.86
	60 W	40.69	15.53
	80 W	45.91	25.75

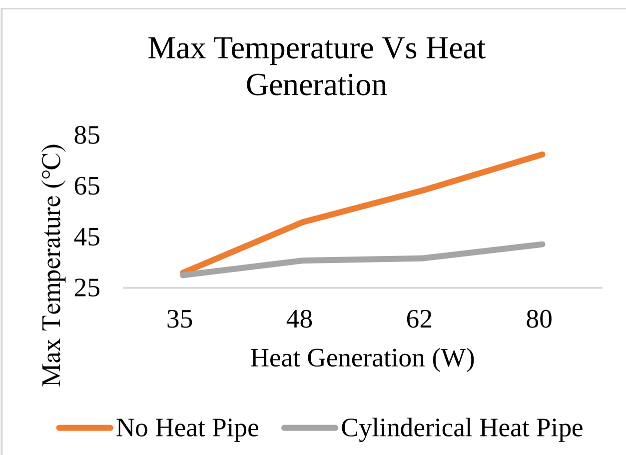

Fig. 13(a) Temperature profile Vs heat generation rate

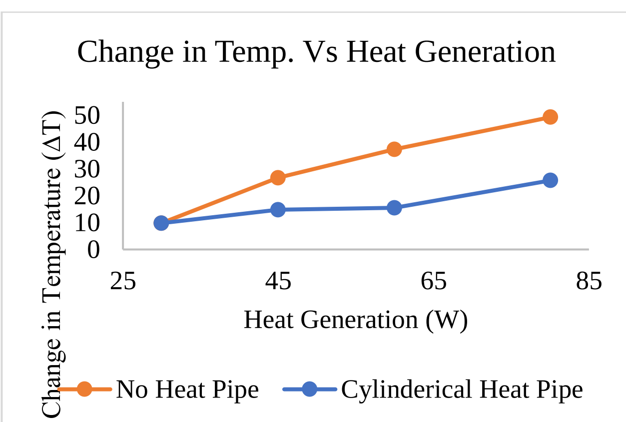

Fig. 13(b) Change in temperature vs heat generation rate

Figure 13 shows that integrating a cylindrical heat pipe in a battery pack setup results in lower temperature rises for the same heat generation rates, indicating more effective thermal management. This signifies the benefit of heat pipe systems in improving cooling efficiency and maintaining optimal operating temperatures for electric battery packs.

3.2. Thermal Conductivity of the Heat Pipes

As shown in Figure 14, as the rate of heat generation from the battery cells increases, more water is evaporated. This increase in evaporation results in a transition from liquid water to steam within the heat pipe. Steam, being less dense than liquid water, exhibits lower thermal conductivity. This decrease in thermal conductivity occurs because steam transfers heat differently than liquid water, primarily through a less efficient mode due to its lower density. Therefore, higher heat generation rates can lead to more steam formation, reducing the overall effectiveness of thermal conductivity within the system.

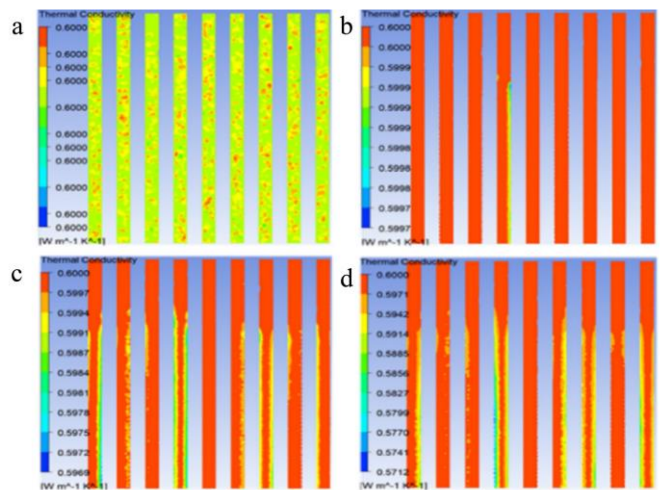

Fig. 14 Thermal conductivity contour of the cylindrical heat pipe at (a) 30W, (b) 45W, (c) 60W, and (d) 80W Heat generation rates

In the current investigation, the use of cylindrical heat pipes for thermal management in battery systems resulted in much better performance than the relevant state-of-the-art literature. The reasons for this success are the natural benefits of Heat Pipe technology, the chosen design improvements, and the large-scale analysis of thermal management systems. Another one of the numerous objectives is the improved effectiveness of cylindrical heat pipes in dealing with heat transfer. Conventional approaches in managing thermal issues involve simple elements like heat sinks or just the use of vents, and this has been proved ineffective, especially when dealing with high heat loads from the new battery systems.

Conversely, the cylindrical heat pipes based on phase change can enhance the thermal performance by transferring heat directly from high-temperature zones to low-temperature zones. This capability enables greater capacity for heat extraction from the battery cells, which lessens overall temperatures as well as temperature differentials. Due to the nature of cylindrical heat pipes, they may provide better handling of heat loads as opposed to conventional approaches that can fail to work effectively under higher levels of heat generation. The other factor that has contributed to better performance is the ability to design the heat pipe system uniquely for this particular research. With heat pipes of specific geometries and configurations, such as the star geometry involved, it is easier to integrate with the spatial and heat distribution requirements of the battery pack. This design optimisation increases the general thermal performance of the thermal management system to distribute heat more uniformly across the battery cells and help avoid hot zones. The specific design or layout of heat pipes minimizes the drawbacks seen in previous research papers where authors employed general heat pipe designs or layouts that could not yield the best performance.

Another key consideration explained by this study involves the use of a comprehensive approach that helps in arriving at better results. The simulations performed using ANSYS Fluent 2024R1 methodology help to evaluate the thermal characteristics of the system under the variation in the heat generation rate and geometry of the heat pipe. This level of grading gives a detailed analysis of the heat flow within the battery system. It ensures that modifications can be made effectively on the location and design of the heat pipe. Unlike those, many existing studies utilize less advanced models or tools that would not be capable of accurately mimicking the thermal transfers and, therefore, may not yield as high efficiency.

Additionally, how the study incorporated the change in heat generation rate gives a broader perspective on the performances of different thermal management systems on the heat pipe system. Focussing on a range of cases, the temperature distributions and the performance figures prove that the heat pipe system is capable of handling high heat loads effectively and reliably. This comprehensive study also provides a sensible approach that differs from certain current methods, where studies may be centred on particular working conditions or settings, thus overlooking the generality of enhanced thermal management systems.

Table 3. Comparison with existing research

Parameters		**Max T (°C)**
Heat Pipe-Based BTMS [29]	30 W	43.82
	40 W	46.59
	50 W	50.96
	60 W	54.38
Cylindrical heat pipe	30 W	34.91
	45 W	39.86
	60 W	40.69
	80 W	45.91

4. Conclusion

The conclusions drawn from the battery thermal management system performance analysis using ANSYS Fluent 2024R1 commercial CFD Package offer valuable insights into the effectiveness of heat pipes and their impact on the final temperature of battery cells.

- As the heat produced by the battery cells increases, the enhancement of the cylindrical heat pipes corresponds. It can, therefore, be explained by the working fluids getting to the right temperature that is needed for phase change, which is done by the operational mechanism of heat pipes. Consequently, if the heat load rises, the heat pipes enhance how heat is removed from the battery cells, thus resulting in better thermal management.
- The study shows that the lowest temperature is obtained in a system with battery cells producing 30W heat and connected to a star-shaped heat pipe system. On the other hand, the highest temperature is observed in conditions where the heat generation is 80W, and no heat pipe system is incorporated, independently of the flow rate of the working fluid provided. This shows how effectively heat pipe systems have helped manage thermal problems and, foremostly, regulate the proper working temperature of the battery cells.
- Here, it is indispensable to mention that the battery system marked with a heat generation rate of 80W must not be used without the heat pipe thermal management system. Lack of such a system has been known to cause overheating, thus exposing the battery to the danger of its shell being damaged or the whole system jamming. This underlines the need to incorporate proper thermal control measures, especially in applications involving high levels of heat generation, for the safety of the battery system.
- On this basis, the following recommendations could be made: The development of heat pipe-based thermal management systems for battery systems, especially those with high heat generation rates, should be given emphasis. Thus, continuous research and development should be conducted to improve heat pipe designs and arrangements and their effectiveness in temperature control of batteries.

Funding Statement

The authors state that no financial supporting bodies have funded this article.

Acknowledgements

All authors contributed during the research and preparation of the manuscript.

References

[1] Guizhou Ren, Guoqing Ma, and Ning Cong, "Review of Electrical Energy Storage System for Vehicular Applications," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 225-236, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[2] Wangyu Liu et al., "Experimental Investigation on Thermal Management of Cylindrical Li-Ion Battery Pack Based on Vapor Chamber Combined with Fin Structure," *Applied Thermal Engineering*, vol. 162, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[3] Jialin Liang et al., "Thermal–Electrochemical Simulation of Electrochemical Characteristics and Temperature Difference for a Battery Module under Two-Stage Fast Charging," *Journal of Energy Storage*, vol. 29, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[4] Zhonghao Rao, and Shuangfeng Wang, "A Review of Power Battery Thermal Energy Management," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 9, pp. 4554-4571, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[5] Chengchao Yuan et al., "Inhibition Effect of Different Interstitial Materials on Thermal Runaway Propagation in the Cylindrical Lithium-Ion Battery Module," *Applied Thermal Engineering*, vol. 153, pp. 39-50, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] Haobing Zhou et al., "Thermal Performance of Cylindrical Lithium-Ion Battery Thermal Management System Based on Air Distribution Pipe," *International Journal of Heat and Mass Transfer*, vol. 131, pp. 984-998, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[7] E. Jiaqiang et al., "Investigation on Thermal Performance and Pressure Loss of the Fluid Cold-Plate Used in Thermal Management System of the Battery Pack," *Applied Thermal Engineering*, vol. 145, pp. 552-568, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[8] Yunhua Gan et al., "Development of Thermal Equivalent Circuit Model of Heat Pipe-Based Thermal Management System for a Battery Module with Cylindrical Cells," *Applied Thermal Engineering*, vol. 164, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[9] Qiqiu Huang et al., "Experimental Investigation of the Thermal Performance of Heat Pipe Assisted Phase Change Material for Battery Thermal Management System," *Applied Thermal Engineering*, vol. 141, pp. 1092-1100, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[10] Dafen Chen et al., "Comparison of Different Cooling Methods for Lithium Ion Battery Cells," *Applied Thermal Engineering*, vol. 94, pp. 846-854, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[11] Yongxin Lai et al., "A Compact and Lightweight Liquid-Cooled Thermal Management Solution for Cylindrical Lithium-Ion Power Battery Pack," *International Journal of Heat and Mass Transfer*, vol. 144, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[12] Wenjiong Cao et al., "Thermal Modeling of Full-Size-Scale Cylindrical Battery Pack Cooled by Channeled Liquid Flow," *International Journal of Heat and Mass Transfer*, vol. 138, pp. 1178-1187, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[13] Z.Y. Jiang, and Z.G. Qu, "Lithium–Ion Battery Thermal Management Using Heat Pipe and Phase Change Material during Discharge–Charge Cycle: A Comprehensive Numerical Study," *Applied Energy*, vol. 242, pp. 378-392, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[14] Zhonghao Rao et al., "Experimental Investigation on Thermal Management of Electric Vehicle Battery with Heat Pipe," *Energy Conversion and Management*, vol. 65, pp. 92-97, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[15] Yunhua Gan et al., "A Numerical Study on the Performance of a Thermal Management System for a Battery Pack with Cylindrical Cells Based on Heat Pipes," *Applied Thermal Engineering*, vol. 179, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[16] Jaewan Kim, Jinwoo Oh, and Hoseong Lee, "Review on Battery Thermal Management System for Electric Vehicles," *Applied Thermal Engineering*, vol. 149, pp. 192-212, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[17] Yonghuang Ye et al., "Numerical Analyses on Optimizing a Heat Pipe Thermal Management System for Lithium-Ion Batteries during Fast Charging," *Applied Thermal Engineering*, vol. 86, pp. 281-291, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[18] Rui Zhao, Junjie Gu, and Jie Liu, "An Experimental Study of Heat Pipe Thermal Management System with Wet Cooling Method for Lithium Ion Batteries," *Journal of Power Sources*, vol. 273, pp. 1089-1097, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[19] Jialin Liang, Yunhua Gan, and Yong Li, "Investigation on the Thermal Performance of a Battery Thermal Management System Using Heat Pipe under Different Ambient Temperatures," *Energy Conversion and Management*, vol. 155, pp. 1-9, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] Q. Wang et al., "Experimental Investigation on EV Battery Cooling and Heating by Heat Pipes," *Applied Thermal Engineering*, vol. 88, pp. 54-60, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[21] Hyuntae Kim et al., "Development of PCM-Based Shell-and-Tube Thermal Energy Storages for Efficient EV Thermal Management," *International Communications in Heat and Mass Transfer*, vol. 154, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[22] Zhonghao Rao et al., "Thermal Performance of Liquid Cooling Based Thermal Management System for Cylindrical Lithium-Ion Battery Module with Variable Contact Surface," *Applied Thermal Engineering*, vol. 123, pp. 1514-1522, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[23] Jan Bohacek, Miroslav Raudensky, and Ebrahim Karimi-Sibaki, "Polymeric Hollow Fibers: Uniform Temperature of Li-Ion Cells in Battery Modules," *Applied Thermal Engineering*, vol. 159, pp. 1-11, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[24] Jinwang Li et al., "Effect of Fabricating Parameters on Properties of Sintered Porous Wicks for Loop Heat Pipe," *Powder Technology*, vol. 204, no. 2-3, pp. 241-248, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[25] Mao-Sung Wu et al., "Heat Dissipation Design for Lithium-Ion Batteries," *Journal of Power Sources*, vol. 109, no. 1, pp. 160-166, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[26] Zhonghao Rao et al., "Experimental Investigation on Thermal Management of Electric Vehicle Battery with Heat Pipe," *Energy Conversion and Management*, vol. 65, pp. 92-97, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[27] Remi Bertossi, "*Modeling of Heat and Mass Transfers in Heat Pipes. Contribution to the Analysis of Interface Phenomena Occurring in Two-Phase Flows*," Free University of Brussels, Poitiers, France, pp. 1-221, 2009. [Google Scholar] [Publisher Link]

[28] Peyman Taheri, and Majid Bahrami, "Temperature Rise in Prismatic Polymer Lithium-Ion Batteries: An Analytic Approach," *SAE International Journal of Passenger Cars-Electronic and Electrical Systems*, vol. 5, no. 1, pp. 164-176, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[29] Hussein Mbulu, Yossapong Laoonual, and Somchai Wongwises, "Experimental Study on the Thermal Performance of a Battery Thermal Management System Using Heat Pipes," *Case Studies in Thermal Engineering*, vol. 26, pp. 1-12, 2021. [CrossRef] [Google Scholar] [Publisher Link]