Computational fluid dynamics and thermal analysis of a lithium-ion battery with different cooling system for electric vehicles

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Abstract. Lithium-ion batteries are the main bases available for electric vehicles and hybrid electric vehicles, because of clean energy transportation as compared to other power sources developed by traditional I.C Engines. In order to get high discharging Lithium-ion batteries battery condition, there is a significant temperature difference should be maintained in between battery temperature and appropriate local temperature. In this paper presents the model designed with different type of heat pipe shapes modeling in CREO parametric software and analyzes the heat pipe with different mass flow inlets (30& 50L/min) thermal analysis done in ANSYS to determine the temperature distribution and heat flux for two types of phase change materials (RT50 & Li Fe PO₄). Also, Computational Fluid Dynamics analysis (CFD) is to calculate pressure (pa), velocity (m/s), heat transfer coefficient (w/m²k), mass flow rate (kg/sec) and heat transfer rate (w) for the different designs of heat pipe and different mass flow inlets. It has been observed that in thermal analysis the heat flux value is more for lithium ion phosphate phase change material (Li Fe PO₄) than RT50 phase change material at U-bend heat pipes. Similarly in CFD analysis observed that mass flow rate (kg/sec), heat transfer rate (w), heat transfer coefficient (w/m²k) values are increases by increasing the mass flow inlets and heat transfer rate more at straight type heat pipes as compared to bend type.

Keywords: Lithium-Ion Battery, Cooling System, Computational Fluid Dynamics, Thermal Analysis.

1. Introduction
Lithium-particle battery (LIB) has gotten significant considerations for footing utilizes because of the higher vitality thickness, efficient power capacities, decreases the voltage and minimizes the nuclear mass contrasted with advanced battery innovations [1]. Basically, Lithium-particle battery (LIB) incorporates various parts i.e electrolyte, separator, anode and cathode are taken into work, as indicated by useful inclusion removal process. The Lithium-particle battery cells are designed in different shapes of structures [2]. Yutaohuo et.al [3] has directed a test in design and advancement of electrical vehicle to outline an execution of electric vehicle innovation taking things down a notch. Here we saw how to
plan an electric vehicle with less cost and have learned about different parts that is required to structure an electric vehicle. It shows that electrical battery worked vehicle is more appropriate than other vehicle on the grounds that the expense of the power is low and furthermore upkeep cost is less. Liwufan et.al [4] have studied the manufacture of fitted a dynamo in the bike which is in contact with the back wheel, its results shows that creates the free energy bicycle and a less expensive. Fanhe.X.Li et.al [5] has studied on the subject of renewable energy sources is useful for continuous electric vehicles (EVs) battery charging is limit within portable. This paper introduces and considers on sustainable power source use, by incorporating sun oriented and wind vitality for constant electric vehicle battery charging limit in portability. Here, the force for electric vehicle is created from sun based cells and wind turbine and it is sustained to the battery for charging the inverter. Hong.G.S et.al [6] led an examination on Electric vehicle which depends on the idea of charging the batteries of an electric vehicle when it is moving. When all is said in done the vitality stockpiling limit of the battery utilized in electric vehicle is low contrast with the customary energizes utilized in present day cars. Consequently they have discovered a technique to revive the battery utilizing inexhaustible asset. Anthony.J et.al [7] studied the warm exhibition of modified electric vehicle battery packs and modules, Also observed along these lines, to get the gauge of the warm presentation, the warmth move standards and limited component investigation programming have been utilized. Based on the exhaustive literature no author has been to study the comparative of thermal and CFD analysis is performed on the different models of a Lithium-Ion battery (straight type and bend type), various cooling systems for electric vehicles using a different phase-change materials (RT50 & Li Fe PO4), and its heat pipes carrying different mass flow rates at 30 and 50 lit/min. As a result of, heat transfer rate (w), mass flow rate(kg/sec), heat transfer coefficient values(w/m²k) and heat flux (w/m²) value is more for lithium ion phosphate phase change material (Li Fe PO4) than the RT50 phase change material at U-bend heat pipes.

2. Modeling of different cold plate of heat pipes
The various types of heat pipes are required for thermal and Computational Fluid Dynamic (CFD) analysis of a lithium-ion battery (LIB) cooling system for electric vehicles (EVs) and its containing different material of heat pipes are modeled (Straight heat pipes & Bend type heat Pipes) in CATIA V5 as shown in Fig.1

![Figure 1](image.png)

Figure 1. Various cold plate designs (a) Straight Type (b) Bend Type
They are light in weight, have phenomenal erosion obstruction and the capacity to withstand outrageous temperatures [8]. The itemized mechanical properties of chosen materials are in Table 1

| Table 1. Material properties of the heat pipes |
|---------------------------------------------|
| **Type of the part** | **Density (kg/m³)** | **Specific heat (j/kg·°C)** | **Thermal conductivity (w/m·°C⁻¹)** |
|----------------------|---------------------|-----------------------------|-------------------------------------|
| Copper               | 8910                | 380                         | 390                                 |
| Graphite             | 1340                | 1427                        | 1342                                |
| Electrolyte          | 1370                | 1370                        | 0.52                                |
| Material                  | LiCoO₂ | Al | PCM RT50 | PCM LiFePO₄ |
|---------------------------|--------|----|----------|-------------|
| Aluminium                 | 897    | 897| 2000     | 2800        |
| Separator                 | 1532   | 1532| 0.3      | 0.35        |
| Cooling fans              | 2719   | 871 | 202.4    |             |
| Heat pipes                | 2920   | 126.8| 11940    |             |
| Battery outer case        | 2688   | 905 | 1        |             |
| Phase change materials    | 753    | 2000| 0.2      |             |
| Phase change materials    | 853    | 2800| 0.35     |             |

3. Computational Tools
3.1 Thermal analysis of cooling plate’s designs
The vital role of the conceptual advancement of thermal management is designed based on a cooling response of a lithium ion battery and its solicitations. A liquid cooling system is one of the maximum appropriate methods for significant lithium battery package stimulating and discharged at sophisticated heat transfer coefficient rate and in maximum temperature atmosphere conditions [9]. So, its advancement of thermal management system is essential for maintaining and controlling the electric car battery pack temperature. Also, in addition with both LIB and LPB have the more internal resistance energy transportation their performance and its life of the battery in electric car can be affected by the operating temperature [10].

3.2 Different cold plate designs
The various cold plate modeling’s are represented in Fig. 2(a), (b), (c) and (d) have the dimensions of 150 mm ×26 mm ×230 mm. From Figure 2(a) considered by five traditional cooling straits is equally distributed lengthwise breadth of cold design flat-plates. The input connection straits are located at central in order to get extra flow rates at central of the cold- plate design. The output connection strait is placed at interior of the bottom to improve the hot liquid system. From Figure 2(b) contains first make cold strait having an input and output ends on the left and right hand sides of the design cold plate respectively. From Figure 2(c) considered by four-straight cooling straits, where the overall flow rate is divided homogenously into the different lines. From Figure 2(d) containing same specific characteristics more than Fig.2 (b), conversely in-between helping with flowing design is prescribed straight.

![Figure 2. Dissimilar designs of cold plates for thermal analysis](image-url)
3.3 Mesh Generation and CFD Methodology
In this model, the physical geometry, mesh and boundary conditions of the problem are well-defined. This defined problem described in terms of the fluid behaviour, material behaviour at the boundaries of the defined meshed problem as shown in Fig.3(a) and Fig.3(b) and Fig.4(a) and Fig.4(b). For thermal and CFD analysis, i.e. initial conditions are defined and their simulations results compare with the analytical equations are solved iteratively as a thermal and CFD analytical equations.

3.4 Mathematical modeling and Analytical equations
3.4.1 Problem Definition. The battery stacks utilized for electric vehicles incorporate numerous battery units associated in arrangement and its every battery unit is shaped by various cells the frequently connected in arrangement; and each unit cell carry various deposits (layers) comprising two slight deposits of graphite attached on a copper foil, 2-layers of LiCoO$_2$ attached on an aluminum oil, an electrolyte deposit among the cathodes, and a partition among the adjoining cells. Thickness, design and warm are the actual properties of layers are appeared as shown in Table1. The electrochemical responses are

\[
\begin{align*}
\text{Anode: } & \text{LiC}_6 \rightarrow \text{C}_6 + \text{Li}^+ + e^- \quad \text{(1)} \\
\text{Anode: } & \text{CoO}_2 + \text{Li}^+ + e^- \rightarrow \text{LiCoO}_2 \quad \text{(2)} \\
\text{Overall: } & \text{CoO}_2 + \text{LiC}_6 + \text{LiCoO}_2 + \text{C}_6 \quad \text{(3)}
\end{align*}
\]

From the above equations (1) to (3), the electrochemical reactions will be during a discharging process.

The effectiveness of battery stacks of thermal management is determined by the following equation (4).

\[
\alpha = \frac{\text{Vol.of cooling conduit}}{\text{vol. of battery system}} \quad \text{(4)}
\]

\[
\alpha = \text{density of battery unit}
\]
Cooling efficiency defined as the heat removal rate to the cooling power depletion/consumption

\[ \beta = \frac{\text{heat removal rate}}{\text{cooling power consumption}} \quad -------- (5) \]

Where \( \beta \) represents the higher energy efficiency.

The two important factors are taken for design of lithium batteries stacks i.e. flat plate and bend type. From Fig.5 (a) the flat-design the battery unit contains a no. of battery a stack, the cooling is circulated among the battery stacks. From Fig 5(b) observed that boundaries should be considered on both sides of a stack in x-direction. From Fig.5(c) observed that the corresponding computational domains of the grid and engages for the design of flat plate stack batteries.

![Figure 5(a). Lithium-ion battery stack of flat plate](#)

![Figure 5(b). CFD region for lithium-ion battery](#)

![Figure 5(c). Meshing with grid size of a lithium-ion battery](#)

3.4.2 Conservative calculation.

The mass conservative calculation of the air in conserving system

\[ \frac{\partial \rho_a}{\partial t} + \nabla \cdot (\rho_a \vec{v}) = 0 \quad ----- (6) \]

Where \( \rho_a \) = density of air (kg/m\(^3\)), \( \vec{v} \) = velocity vector air

The characterization calculation momentum of system of air

\[ \frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p \quad ---- (7) \]

Where \( p \) = pressure of a fluid

The energy conservation calculation for air

\[ \frac{\partial}{\partial t} (\rho_a c_{pa} T_a) + \nabla \cdot (\rho_a c_{pa} \vec{v} T_a) = \nabla \cdot (\kappa_a \nabla T_a) \quad ---- (8) \]

Where \( T_a \) is the temperature of air in °C, \( K_a \) is the heat conduct of air in w/m\(^{-1}\)°C\(^{-1}\) and \( C_{pa} \) is the isochoric specific heat transfer of substance i.e. air in j/kg\(^{-1}\)°C\(^{-1}\)

The energy conservation calculation for battery

\[ \frac{\partial}{\partial t} (\rho_b c_{pb} T_b) = \nabla \cdot (\kappa_b \nabla T_b) + S_T \quad ---- (9) \]

Where \( S_T \) = heat generation rate/volume (wm\(^{-3}\)), \( \rho_b \) = average battery density (kg/m\(^3\)), \( C_{pb} \) = specific heat of battery (jkg\(^{-1}\)°C\(^{-1}\)), \( T_b \) = temperature of battery (°C), \( K_b \) = heat transfer conductivity of lithium-ion battery (w/m\(^{-1}\)°C\(^{-1}\)) [jingzhi et.al]
4. Results and Discussion

4.1 CFD analysis of different cold plate designs

The mean Pressure is 8.41e+07Pa relying upon the form map, and the base pressure is 2.56e+06Pa. The general speed of the impeller inside the limit, as per the form map, and the base speed extent outside the limit. The middle speed is 1.61 e+03m/s as indicated by the form plot above and the base speed is 1.61e+02m/s. As found in Table 2, the pressure, velocity and heat transfer coefficient form plot for 30lit/min and 50lit/min is found in Fig 6, to Fig.7. The weight and speed for edge points is high at 50lit/min from these weight and speed forms for different edge points [11].

![Figure 6](image1.png)

**Figure 6** (a) Pressure (b) velocity and (c) Heat Transfer coefficient of Material- RT50 (Phase Change Material) at mass flow rate at 30 lit/min

![Figure 7](image2.png)

**Figure 7** (a) Pressure (b) velocity and (c) Heat Transfer coefficient of Material- Li Fe Po4 (Phase Change Material) at mass flow rate at 30 lit/min

| Models                  | Flow rate (lit/min) | Pressure (Pa) | Velocity (m/s) | Heat transfer coefficient (w/m²-k) | Mass flow rate (kg/s) | Heat transfer rate(W) |
|-------------------------|---------------------|---------------|----------------|-----------------------------------|-----------------------|-----------------------|
| Design1 (Straight heat pipes) | 30                  | 2.47e+02      | 5.77e-01      | 3.23e+03                          | 8.1002e-05            | 18.507813             |
|                         | 50                  | 5.92e+02      | 9.57e-01      | 4.92e+03                          | 0.0002552             | 58.59375              |
| Design2 (Bend type heat pipes) | 30                  | 2.06e+05      | 8.58e+00      | 3.70e+04                          | 0.0069425             | 1592.7266             |
|                         | 50                  | 3.98e+05      | 1.44e+01      | 5.95e+04                          | 0.008344              | 1913.5                |

4.2 Thermal Analysis of different cold plate designs

In these examination the fit model is imported and afterward we apply limit conditions like weight and speed is applied on inlet for 30lit/min and 50lit/min and apply the materials RT50 (Phase Change Material) and Li Fe Po4 (Phase Change Material) subsequently we compute temperature and Heat flux as shown in Fig 8, to Fig.11 and their values as shown in Table 3. From these figures the minimum and maximum values of temperature and heat flux, values occurs at 30lit/min and 50lit/min as [12] shown in Fig 8 to Fig.11.
Figure 8 (a) Temperature and (b) Heat flux of Material- RT50 (Phase Change Material) at mass flow rate at 30 lit/min

Figure 9 (a) Temperature and (b) Heat flux of Material- Li Fe Po4 (Phase Change Material) at mass flow rate at 30 lit/min

Figure 10 (a) Temperature and (b) Heat flux of Material- RT50 (Phase Change Material) at mass flow rate at 50 lit/min

Figure 11 (a) Temperature and (b) Heat flux of Material- RT50 (Phase Change Material) at mass flow rate at 50 lit/min
Table 3. Thermal analysis results of cold plate designs

| Models               | Flow rate (lit/min) | Material       | Temperature(°C) | Heat flux (w/mm²) |
|----------------------|---------------------|----------------|------------------|------------------|
|                      |                     |                | Min  | Max  |               |                   |
| Design 1 (straight heat pipes) | 30                  | PCM RT50       | 19.213 | 80   | 0.020264      |                   |
|                      |                     | PCM Li Fe PO₄  | 17.838 | 80   | 0.031486      |                   |
|                      |                     | PCM RT50       | 12.928 | 80   | 0.022175      |                   |
|                      |                     | PCM Li Fe PO₄  | 12.922 | 80   | 0.0315        |                   |
| Design 2 (bend type heat pipes) | 30                  | PCM RT50       | 12.961 | 80   | 0.014355      |                   |
|                      |                     | PCM Li Fe PO₄  | 12.913 | 80   | 0.014391      |                   |
|                      |                     | PCM RT50       | 12.007 | 80   | 0.014376      |                   |
|                      |                     | PCM Li Fe PO₄  | 12.91   | 80   | 0.014393      |                   |

Figure 12. Pressure Vs different cold plate designs

Figure 13. Mass flow rate Vs different cold plate designs
5. Conclusion

In thesis the modeling in CREO parametric software and analysis done in ANSYS. The model designed with different type of heat pipe shapes and analyses the heat pipe with different mass flow inlets (30& 50L/min).

A significant improvement obtained from the computational fluid dynamic (CFD) heat transfer rate (w), mass flow rate (kg/sec) and heat transfer coefficient (w/m²k) values are increases by increasing the mass flow inlets and heat transfer rate more at design 2 (box type heat pipes). Similarly, in thermal finite analysis the results of heat-flux values (w/m²) are more significant for lithium ion phosphate phase change material than RT50 phase change material at design 2 (U-bend heat pipes) So it can be concluded the design 2 (U-bend type heat pipes) is better model for Lithium-ion power battery cooling system.

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