Battery thermal management system using nano enhanced phase change materials

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Abstract. Electric vehicles are being developed as a crucial tool in the fight against global warming and car pollution. As a result, battery heat management is critical for optimal operation in all climates in electric vehicles (EVs) and hybrid electric vehicles (HEVs). Extreme or higher temperatures may cause the battery’s maximum voltage to drop and its durability to deteriorate. An effective battery cooling system is required for the safe operation of electric vehicles throughout their lifecycle. The current work involves the simulation of a battery thermal management system that employs nano-enhanced phase change materials (NEPCM). Ansys Fluent is used to conduct the numerical analysis. To test the thermal performance, paraffin wax is used as the base fluid, into which various combinations of nanoparticles such as Copper Oxide, Copper, and Multi Walled Carbon Tube (MWCNT) are disseminated. The parametric study is carried out by altering the battery temperature and nanoparticle volume fraction. The findings show that at large particle volume fractions, the battery system's heat transmission properties are greatly improved. The findings of this study will aid in the identification of optimal NEPCMs with increased thermal performance.

1. Introduction

During the previous three decades, the automobile sector has witnessed extremely rapid expansion. Based on the type of vehicle, rates of growth ranged from 9 to 18 percent. Two-wheelers, for instance, rose at a rate of roughly 10% per year, whereas passenger vehicles grew at a rate of 13% to 18% per year. India is currently the world’s third-largest producer of motor cars. Almost every international automaker has a plant in India, including Suzuki, Honda, Hyundai, Ford, Toyota, Volvo, and others [1]. India’s rapid urbanization has resulted in a tremendous surge in the number of automobiles on the road, as well as their emissions. Motor vehicle emissions are a mixture of pollutants that have the potential to cause significant health consequences such as carcinogenicity, mutagenicity, cardiovascular mortality, and worsening the health of vulnerable persons such as asthmatics, children, and the elderly [2]. According to a research published by the International Council on Clean Transportation, 3,85,000 deaths occurred unexpectedly 2015 due to air pollution caused by vehicle exhaust emissions [3]. The likelihood of rapid global temperature rise has necessitated a reduction in the usage of fossil fuels and the emissions that accompany them. India has promised to reduce its GHG emission intensity by 33% to 35% below 2005 levels by 2030. Renewable energy, growing urbanization, data acquisition and analysis, battery chemistry, and energy security have all seen significant advancements. As a result, industrialized economies such as the EU, the United States, and Japan, as well as developing economies like China and India, have all adopted EV policies to reduce carbon emissions while delivering easy and cost-effective transportation [4].

In recent years, electric vehicles (EV) have become more prevalent in the transportation sector. This mode of transportation is anticipated to replace internal combustion engine (ICE) cars in the near future, as the current trend implies [5]. Lithium-ion batteries have a high capacity and operating performance due to their high energy density (up to 705 W/L) and power density (up to 10,000 W/L). Lithium-ion batteries are rechargeable batteries that are used as power sources in a variety of applications. Temperature, as a vital factor, has a substantial impact on lithium-ion battery performance and also limits the use of lithium-ion batteries [6]. Due to electrochemical reactions in the cell, the battery drains
and produces a significant quantity of heat during vehicle operation. An electric vehicle often has several battery modules, each of which is made up of multiple cells with series connection and parallel connection. As a result, heat created in the battery compartment must be evacuated in order to preserve the battery's allowable safe operating temperature [7]. As a result, this system was created to improve battery efficiency, extend battery life, and safeguard charge and discharge health. A good thermal management system in an electric car should keep the battery pack temperature consistent throughout the vehicle and within the specified temperature range. It was mentioned that under cold and hot temperature conditions, the battery thermal management system should provide active heating and cooling [8].

A thorough investigation was conducted to determine the best BTMS for the particular battery pack. In general, BTMS is divided into three categories based on the medium of cooling: air, liquid, phase change material (PCM) cooling, and a combination of the three [9]. The use of phase change materials (PCMs) in BTMS is becoming more common. The temperature of a battery pack could be kept within the typical working limit for a long period without requiring any external energy by employing PCMs to absorb heat. By integrating with fillers such as extended graphite (EG) and metallic foam for their high thermal conductivity or coordinating with fins, PCMs might considerably improve the heat dissipation efficiency of BTMS [10]. During phase transition, phase changing materials (PCM) can accumulate and release a large amount of energy, resulting in temperature changes. This allows PCMs to be used as the foundation for thermal accumulators that store thermal energy at high temperatures and release it at lower temperatures below the phase transition point. The use of PCMs in building technology and other sectors is hampered by the fact that most PCMs have a low thermal conductivity coefficient, which causes the reaction of relevant thermal accumulators to be excessively slow, limiting the applications of such devices. This disadvantage can be solved by doping a PCM with high thermal conduction coefficient [11]. The use of nanoparticles (dia <50 nm) in materials synthesis, biotechnology, deep space exploration, microfluidic device design, emission control, and energy efficiency promises to offer up a plethora of new technical options [12]. The impact of distinct nanoparticles with varied properties on the morphology of the solid-liquid interface and the developing concentration during solidification has been documented (i.e., different nanoparticles resulted in different dendritic topologies during solidification) [13]. Organic PCM has a low thermal conductivity, which results in a slow rate of thermal storage and release. Highly conducting elements are commonly added to phase change materials to improve effective thermal conductivity. It was discovered that introducing expanded graphite into the wax matrix enhanced the heat conductivity of paraffin wax [14]. Similar investigations are carried out in the following literatures [15-19].

As a result of our extensive literature review, we have decided to investigate three different nanoparticles: copper, copper oxide, and multi-walled carbon nanotubes doped into paraffin wax in a cylindrical arrangement. The cylindrical body with various nePCM is put to the test and compared to one another. The temperature and velocity contours are plotted to analyze the results. The findings of this investigation will be important in determining the optimal nePCM.

2. Methodology
The model that we have designed for this study comprises of an unsteady state flow of nano enhanced phase change materials enclosed in an enclosure. The base fluid taken here is paraffin wax with different nano particles suspended in it. The three different nano particles taken for the study here are Copper, Copper Oxide and Multi Walled Carbon Nano Tubes.

2.1. Governing Equations
The governing equations for the nanofluid as a continuous medium with thermal equilibrium between the base fluid and solid nanoparticles are:

Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0$$  (1)
X-momentum equation:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{1}{\rho_{nePCM}} \left( - \frac{\partial p}{\partial x} + \mu_{nePCM} \nabla^2 u + (\rho \beta)_{nePCM} g_x (T - T_{ref}) \right)
\]  

Y-momentum equation:

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = \frac{1}{\rho_{nePCM}} \left( - \frac{\partial p}{\partial y} + \mu_{nePCM} \nabla^2 v + (\rho \beta)_{nePCM} g_y (T - T_{ref}) \right)
\]

Energy equation:

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\partial}{\partial x} \left[ \left( k_{nePCM} + k_d \right) \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \left( k_{nePCM} + k_d \right) \frac{\partial T}{\partial y} \right]
\]

2.2. Properties of Nano Enhanced Phase Change Materials

PCMs are heat-absorbing and heat-emitting materials that ingest and emit a considerable amount of heat when a substance solidifies or melts. The Phase transition materials’ thermal conductivity, which might be enhanced by the addition of nanoparticles, has a significant impact on heat transfer in terms of absorption and release of heat. Nanoparticles of metal and metal oxides, graphene, and carbon nanotubes can be added to PCM to create nano-enhanced PCM (nePCM). Due to the addition of nanoparticles, there is an increase in viscosity, density and latent heat capacity of the PCM. The effect of the latter must be weighed against that of increased thermal conductivity. The variant of PCM used in this application is determined by the temperature involved. Table 1 represents the properties of paraffin wax which is taken as the PCM.

| Properties         | Paraffin wax |
|--------------------|--------------|
| Density (\(\rho\)) (kg/m³) | 805          |
| Specific heat (\(c_p\)) (J/kg.K) | 2379         |
| Heat transfer coefficient (k) (W/(m²K)) | 0.2          |
| Viscosity (\(\mu\)) (kg/m.s) | 4.1 x 10⁻³   |

Table 2 represents the properties of nano particles that are doped in the PCM.

| Properties:                  | Cu  | CuO  | MWCNT |
|------------------------------|-----|------|-------|
| Density (\(\rho\)) (kg/m³)  | 8940| 6315 | 1600  |
| Specific heat (\(c_p\)) (J/kg.K) | 376.812 | 531 | 796   |
| Heat transfer coefficient (k) (W/(m²K)) | 398 | 32.9 | 3000  |

Equations (5) to (10) are used to compute the thermophysical characteristics of nano-enhanced phase change materials:

Density (\(\rho\)):

\[
\rho_{nePCM} = (1 - \phi) \rho_{PCM} + \phi \rho_{np}
\]  

(5)
Specific heat \((c_p)\):

\[
C_{P_{nepCM}} = \frac{(1-\phi)(\rho C_p)_{PCM} + \phi (\rho C_p)_{np}}{\rho_{nepCM}}
\]  

(6)

Thermal Conductivity \((k)\):

\[
k_{nepcm} = \frac{(k_{np}+2k_{PCM}-2k_{PCM}-k_{np})\phi}{k_{np}+2k_{PCM}+2(k_{PCM}-k_{np})\phi} k_{PCM} + 5 \times 10^4 \beta \rho_{PCM} C_{PCM} \phi \sqrt{\frac{k_B T}{\rho_{np} d_{np}}} f(T, \phi)
\]  

(7)

Where,

\[
\beta = 8.4407(100\phi)^{-1.07304} 
\]  

(8)

\[
f(T, \phi) = (3.917 \times 10^{-3} + 2.8217 \times 10^{-2} \phi) \frac{T}{T_0} - 3.0669 \times 10^{-2} \phi - 3.91123 \times 10^{-3}
\]  

(9)

\(k_B\) - Boltzmann constant = 1.381 \times 10^{-23} \text{ J/K}

\(T_0 = 273\ \text{K}\)

Dynamic viscosity \((\mu)\):

\[
\mu_{nepCM} = (0.983e^{22.85\phi}) \mu_{PCM}
\]  

(10)

Where \(\phi\) denotes the volume fraction of nanoparticles. The subscripts \(\text{nePCM}, \text{PCM},\) and \(\text{np}\) signify nano-enhanced PCM, PCM (paraffin wax), and nano particles (Cu, CuO, MWCNT) respectively. Table 3 represents the properties of nano enhanced phase change materials.

### Table 3. Properties of nano enhanced Phase Change Materials (nePCM)

| Nano particle | Concentration \((\phi)\) | Density \((\rho)\) \(\text{(kg/m}^3\) | Specific heat \((c_p)\) \(\text{(J/kg. K)}\) | Heat transfer Coefficient \((k)\) \(\text{(W/m}^2\text{K)}\) | Viscosity \((\mu)\) \(\text{(kg/m. s)}\) |
|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Cu            | 0.02            | 967.7           | 2009.05         | 0.2216          | 6.365 \times 10^{-3} |
|               | 0.04            | 1130.4          | 1745.61         | 0.2389          | 10.05 \times 10^{-3} |
|               | 0.06            | 1293.1          | 1548.45         | 0.258           | 15.87 \times 10^{-3} |
|               | 0.02            | 820.9           | 2317.29         | 0.2277          | 6.365 \times 10^{-3} |
| MWCT          | 0.04            | 836.8           | 2257.9          | 0.2488          | 10.05 \times 10^{-3} |
|               | 0.06            | 852.7           | 2200.78         | 0.26407         | 15.87 \times 10^{-3} |
|               | 0.02            | 915.2           | 2124.435        | 0.2163          | 6.365 \times 10^{-3} |
| CuO           | 0.04            | 1025.4          | 1923.755        | 0.2341          | 10.05 \times 10^{-3} |
|               | 0.06            | 1135.6          | 1762.40331      | 0.25343         | 15.87 \times 10^{-3} |

2.3. Modelling and Simulation

The modelling is done using Ansys. The simulation was carried out using fluent module in Ansys Software as shown in Figure 1, which is used for the numerical simulation modelled as three-dimensional incompressible flow.
Figure 1. Ansys Fluent Module

Figure 2 depicts the battery module placed in an enclosure which was designed as a cylindrical component of 15 mm diameter and was extruded for a height of 50 mm and then an enclosure was made around it using design modeller window in Ansys Software.

Figure 2. Battery enclosed in a 3D enclosure

Figure 3 and figure 4 portrays the meshing of enclosure and cylindrical component with default elemental size.

Figure 3. Meshing of the enclosure
Figure 4. Meshing of the cylindrical component

The meshed component was simulated in Ansys fluent in transient heat conduction and at a temperature of 333 K by applying essential boundary conditions. After the initialization of all these necessary values, the simulation was performed. After the simulation, the surface heat transfer coefficients were collected from the reports for each combination. The temperature, velocity and pressure contour plots were obtained by using Ansys CFD post.

3. Results and Discussions:
The numerical investigation of the modelling of a Battery Thermal Management System (BTMS) employing nano enhanced Phase Change Materials (nePCM) was performed using Ansys Fluent. The contour plots are obtained using Ansys CFD Post.

Temperature contour plot
Figure 5 depicts the temperature contours of paraffin wax dispersed with MWCNT. Battery which is acting as the heat source is centrally located inside the square enclosure. Concentric circle pattern is observed in this case where the temperature decreases as the distance from the battery increases. Temperature in this case is considered as 333K, and nePCM of paraffin wax dispersed with MWCNT which is surrounding the battery source gets heated up which results in difference in density and thermal diffusion of nePCM particles as seen in figure 5.
Velocity contour plot
Figure 6 depicts the velocity contour plot of nePCM consisting paraffin wax dispersed with MWCNT. At initial timeframes, the velocities of the nePCM are maximum near the heat source which is the cylindrical battery. As the transient heat transfer proceeds, these high energy particles propagate towards the wall surfaces. Heat is convected and nano enhanced phase change materials diffuse towards the walls of the enclosure resulting in the green spots as seen in the figure.

![Velocity contour plot](image)

**Figure 6. Velocity contour plot**

Pressure contour plot
Figure 7 portrays the pressure contour plot of nePCM consisting paraffin wax dispersed with MWCNT. Due to the buoyancy effect, pressure is higher at the top and lower at the bottom of the enclosure. Due to the heat generated, the temperature of the molecules rises. As a result of this, the particles absorb this heat and become lighter. Hence a high concentration of molecules is present near the upper portions.

![Pressure contour plot](image)

**Figure 7. Pressure contour plot**

Table 4 shows the surface heat transfer coefficient of different combinations of nePCMs’ obtained after the numerical simulation.
Table 4. Surface Heat Transfer coefficient of nePCMs

| Materials                        | Volume Fraction of nano particles | Surface Heat Transfer Coefficient (W/(m²K)) |
|----------------------------------|-----------------------------------|--------------------------------------------|
| Paraffin wax – Copper            | 0.02                              | 23.8960                                    |
|                                  | 0.04                              | 25.4524                                    |
|                                  | 0.06                              | 27.1100                                    |
|                                  | 0.02                              | 23.4901                                    |
| Paraffin wax – Copper Oxide      | 0.04                              | 25.0531                                    |
|                                  | 0.06                              | 26.7290                                    |
|                                  | 0.02                              | 24.3212                                    |
| Paraffin wax – Multi walled carbon nano tubes | 0.04 | 26.0190 |
|                                  | 0.06                              | 27.2214                                    |

Figure 8 represents the change in the heat transfer coefficient with the volume fraction of Copper. The heat transfer coefficient is discovered to vary linearly with the volume fraction. The heat transfer coefficient increases by 6.5% when the volume fraction is increased from 2% to 4%. Subsequently, a 6.5% increase in coefficient of heat transfer was observed from 4% to 6% of volume fraction.

![Paraffin wax_Copper](image)

**Figure 8.** Change in heat transfer coefficient (W/m²K) with volume fraction of Copper

Figure 9 represents the change in the heat transfer coefficient with the volume fraction of Copper Oxide. The heat transfer coefficient is discovered to vary linearly with the volume fraction. The heat transfer coefficient increases by 6.65% when the volume fraction is increased from 2% to 4%. Subsequently a 6.26% increase in coefficient of heat transfer was observed from 4% to 6% of volume fraction.
Figure 9. Change in heat transfer coefficient (W/m²K) with volume fraction of Copper Oxide

Figure 10 represents change in the heat transfer coefficient with the volume fraction of Multi Walled Carbon Nano Tubes. The heat transfer coefficient is discovered to vary linearly with the volume fraction. The heat transfer coefficient increases by 6.12% when the volume fraction is increased from 2% to 4%. Subsequently a 6.2% increase in coefficient of heat transfer was observed from 4% to 6% of volume fraction.

Figure 10. Change in heat transfer coefficient (W/m²K) with volume fraction of MWCNT

From Figure 11, it can be inferred that the Paraffin Wax – Multi Walled Carbon Nano Tube nePCM has the highest heat transfer coefficient and better cooling characteristics.
4. Conclusions
In this study, the use of nano-enhanced phase change materials in a battery thermal management system to keep the temperature of electric vehicle batteries within safe limits is discussed. It was carried out by testing a cylinder with constant wall temperature in an enclosure. From these results, it is observed that as the volume fraction of nano particles increases, the surface heat transfer coefficient also increases. Three different nanoparticles (Cu, CuO, and MWCNT) were selected and added in different proportions (2%, 4%, and 6%) to the phase change material (paraffin wax). Their thermal characteristics were analysed and plotted using line graphs. Their temperature, velocity and pressure contours were also plotted. The highest heat transfer coefficient of 27.413 W/(m²K) is observed for Paraffin Wax – Multi Walled Carbon Nano Tube with 6% volume fraction has better cooling characteristics and hence maintains the surface of the battery at a lower temperature.

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