Numerical Investigation on the Thermal Control of Lithium Batteries for Electric Cars Using Metal Foams and Phase Change Materials

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Abstract. Electric cars, in addition to representing an ecological solution for the serious problems of climate pollution due to the use of fossil fuels, can also represent a turning point in terms of renewal for the world economy with a product that in a short future will become a standard in all the advanced economies of the globe. One of the main problems of electric cars is given by the thermal control of their batteries, since, below and above a certain temperature range and also with the use of the air conditioning, they abruptly decrease the autonomy of the vehicle, creating inconvenience to the owners of such cars. The thermal control of lithium batteries for electric cars must therefore take into account both the problems of thermal increase due to the functioning of the battery itself, and the climatic conditions outside the vehicle which impact, if above a certain range, negatively on the performance of the automobile, decreasing both the autonomy and the battery life. In this study, an attempt is made to control both thermal aspects by trying to thermally isolate the battery from the vehicle's external climate and by trying to control the temperature peaks due to the operation of the battery itself. For this purpose, in this study a two-dimensional model is considered to investigate numerically the thermal control of a lithium battery of a commercial electric car. The battery has the size of 8 cm x 31 cm x 67 cm and its capacity is equal to 232 Ah with 5.3 kWh. The thermal control is realized by means one internal layer of copper foam and paraffin, placed around the battery, and a more external paraffin layer. The external surfaces are cooled by an air flow. The governing equations are solved by finite volume method using the commercial code Ansys-Fluent. Different cases are simulated for different thickness of the two layers and air flow velocity. The results, carried out for metal foam with different PPIs and porosities, are given in terms of temperature and liquid fraction fields, heat transfer behaviors such as surface temperature profiles as a function of time and temperature distributions along the external surface of battery for the different cases.

1. Introduction
The severe climatic problems of recent years due largely to fossil fuels have brought the electric car to the fore in recent years. These cars use electric motors, which instead of using fossil fuels, use the electricity stored by batteries as primary energy. The batteries used for this purpose are lithium-ion batteries, which however have several drawbacks, among which the main ones are the thermal problems related to excessive temperatures related to intensive use and recharging, extreme environmental temperatures, poor management of the cooling systems and the thermal runaway phenomenon.

From the study of these problems, it has been shown that in the elaboration of the thermal management system of the battery (TMS), the use of phase change materials (PCM) were very promising because the high latent heat of the PCM it allows to store and release large quantities of heat, allowing the batteries to maintain an almost constant temperature. Lafdi et al. [1] carried out an experimental
study on the heat transfer of a composite PCM in a highly conductive metal foam showed that a larger pore size caused a lower surface temperature due to the higher convective flow. Libeer et al. [2] conducted a study on the effects of using PCM saturated foam on battery TMS by reporting that the use of foam significantly improved the heat transfer rate and that the amount of heat absorbed increases with the reduction of porosity. They also found that the velocity of the liquid PCM increased as the pore size increased and that compared to pure PCM, heat transfer by conduction was found to increase with the addition of foam in the PCM. Li et al. [3], studied a process to refine the thermal management system of lithium ion batteries (BTMS) using phase change materials (PCM). They set themselves the goal of minimizing the mass of PCM. They then implemented a cylindrical BTMS with PCM to demonstrate the proposed optimization method. The results they obtained show that the proposed optimization system is efficient for optimizing the BTMS with the PCM, providing guidelines for engineers to conduct the optimization of the design of similar systems. Ling et al. [4] compared the thermal management capabilities of phase change composites (PCM) from a highly thermally conductive composite. They made a comparison between these systems and the battery pack without the PCM to determine a suitable material to improve the low temperature performance of lithium ion cells. The results they obtained report that the low thermal conductivity of the silica composite causes a greater temperature change on the battery pack than in the PCM-free case, this determines an irregular voltage distribution and, consequently, an early end of the charge and download. Despite this, the highly conductive composite PCM at 60% by weight can reduce the temperature variation between the cells helping to reduce the voltage differences.

Landini et al. [5] have determined that the optimal temperature range for lithium batteries is 25-30 °C, while 25-40 °C is the typical temperature range for the correct operation of lithium batteries. They have determined that there is no better model of TMS than the others, so among the possible types, such as air cooling, liquid cooling, boiling and PCM, the latter has more advantages to obtain an ideal isotherm. Chen et al. [6] determined that solid-liquid PCMs allow for the storage of large amounts of heat in a difficult operating environment and that the addition of carbon materials and metals can significantly improve the thermal conductivity and strength of PCMs.

Safdari et al. [7] analyzed three different battery thermal management models (BTMS) with PCM as passive material and active air cooling. Thermal management was assessed with different charging and discharging speeds. They obtained that the use of latent heat is optimal and that, for fast charging and discharging situations, the rectangular shape is better. Buonomo et al. [8], have understood that the PCM has the ability to delay the achievement of the critical temperature for the battery until liquefaction. The metal foam acts as a thermal carrier by uniformly distributing the thermal energy in the PCM allowing to avoid that the PCM, given its low thermal conductivity, behaves like a thermal insulator.

The use of PCM in metal foam has allowed to reduce the evolution of the battery temperature over time, allowing an extension of the operation especially in the presence of high loads. In this research work, a type of passive electronic cooling system for the lithium ion battery has been developed. A PCM element with metal foams that use the enthalpy porosity process has been realized numerically. Numerical simulations were conducted with the use of Ansys-Fluent software. The results obtained are reported as a function of the average temperature reached and the melting time obtained.

2. Governing equations and physical domain
The physical domain of the system consists of two zones, in which in the first there is the lithium battery in which a generation thermal source in order to simulate the heat dissipation of the battery has been applied, while in the second zone they have been used, based to the type of analysis, the air, the copper foams, the PCM of paraffin RT42 that melts in a range of temperatures around 42 °C [9] and the copper foams filled by the PCM. The material that characterizes this type of batteries is lithium and the operating temperature should generally remain below 45 °C (318K) [10].

The PCM has the function of lowering the temperature when a heat peak occurs during high battery loads. Metal foam has the function of extracting heat from the PCM.

Figure 1 shows the 2D sketch of the system whose dimensions are 100 mm x 310 mm. Details on the material used and the properties of copper foams [11] are given in Table 1 and Table 2.
Figure 1. Physical Domain

Table 1. Properties of materials.

| Thermal Properties          | Paraffin RT42 | Lithium | Aluminum | Copper | Air   |
|-----------------------------|---------------|---------|----------|--------|-------|
| Density [Kg/m3]             | 820           | 534     | 2719     | 8978   | 1.225 |
| Specific Heat [J/Kg K]      | 2000          | 3560    | 871      | 381    | 1006.4|
| Thermal Conductivity [W/m K] | 0.2           | 85      | 202.4    | 387.6  | 0.0242|
| Dynamic Viscosity [Kg/m s]  | 0.02          | -       | -        | -      | 1.789e-5|
| Thermal expansion coefficient [1/K] | 0.0001     | -       | -        | -      | 0.00333|
| Melting Heat [J/Kg]         | 165000        | -       | -        | -      | -     |
| Solidus Temperature [K]     | 311.15        | -       | -        | -      | -     |
| Liquidus Temperature [K]    | 316.15        | -       | -        | -      | -     |

Table 2. Properties of copper foams [11].

|                              | Cu-20-6.7    | Cu-40-6.6 |
|------------------------------|--------------|-----------|
| Number of pores per inch, PPI (in⁻¹) | 20           | 40        |
| Relative density, ρR (%)      | 6.7          | 6.6       |
| Porosity, ε (–)              | 0.933        | 0.934     |
| Fiber thickness, t (mm)       | 0.292        | 0.262     |
| Fiber length, l (mm)          | 1.236        | 1.109     |
| Surface are per unit of volume, a_sv (m²m⁻³) | 1148    | 1635     |
| Permeability, K (m²) × 10⁷   | 0.41         | 0.44      |
| Inertia coefficient f         | 0.039        | 0.060     |
| Drag coefficient C (m⁻¹)      | 193          | 286       |

The melting phenomenon of the PCM can be modelled with the enthalpy-porosity method [12], in which the solid-liquid interface is not explicitly traced but the method defines a mixed solid-liquid region that is described as a “pseudo” porous zone where the porosity is the liquid fraction. The most important parameter of the enthalpy-porosity method is the liquid fraction, indicated with Greek letter
\[ \beta = 0 \quad \text{for} \quad T < T_{\text{solidus}} \]
\[ \beta = \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} \quad \text{for} \quad T_{\text{solidus}} < T < T_{\text{liquidus}} \]
\[ \beta = 1 \quad \text{for} \quad T > T_{\text{liquidus}} \] 

\( T \) is the local temperature of the cell, \( T_{\text{liquidus}} \) is the temperature upper which the domain is completely liquid and \( T_{\text{solidus}} \) is the temperature below which it is completely solid. The solid part of the mixed zone is modelled by adding a source term in the momentum equation. The metal foam is modelled with the Brinkman-extended Darcy-Forchheimer model because it behaves like a porous media; The gravitational acceleration is along the y-axis and the Boussinesq approximation is considered in order to take into account the buoyancy force due to natural convection. The thermal interaction between the metal foam and the flows is modelled with the LTE assumption, where a unique local Temperature function between the porous media and the fluid flow is defined. The governing equation are the following:

**-Battery**

\[
(\rho c)_{\text{Lit}} \frac{\partial T_{\text{Lit}}}{\partial t} = k_{\text{Lit}} \left( \frac{\partial^2 T_{\text{Lit}}}{\partial x^2} + \frac{\partial^2 T_{\text{Lit}}}{\partial y^2} \right) + u^m
\]  

(2)

**-PCM**

\[
\frac{\partial u_{\text{pcm}}}{\partial x} + \frac{\partial v_{\text{pcm}}}{\partial y} = 0
\]  

(3)

\[
\frac{\rho_{\text{pcm}}}{\epsilon} \left( \frac{\partial u_{\text{pcm}}}{\partial t} + u_{\text{pcm}} \frac{\partial u_{\text{pcm}}}{\partial x} + v_{\text{pcm}} \frac{\partial u_{\text{pcm}}}{\partial y} \right) = -\frac{\partial p_{\text{pcm}}}{\partial x} + \frac{\mu_{\text{pcm}}}{\epsilon} \left( \frac{\partial^2 u_{\text{pcm}}}{\partial x^2} + \frac{\partial^2 u_{\text{pcm}}}{\partial y^2} \right) + S_x
\]  

(4)

\[
\frac{\rho_{\text{pcm}}}{\epsilon} \left( \frac{\partial v_{\text{pcm}}}{\partial t} + u_{\text{pcm}} \frac{\partial v_{\text{pcm}}}{\partial x} + v_{\text{pcm}} \frac{\partial v_{\text{pcm}}}{\partial y} \right) = -\frac{\partial p_{\text{pcm}}}{\partial y} + \frac{\mu_{\text{pcm}}}{\epsilon} \left( \frac{\partial^2 v_{\text{pcm}}}{\partial x^2} + \frac{\partial^2 v_{\text{pcm}}}{\partial y^2} \right) + S_y
\]  

(5)

\[
\left[ (1-\epsilon)(\rho c)_{\text{mf}} + \epsilon (\rho c)_{\text{pcm}} \right] \left( \frac{\partial T_{\text{pcm}}}{\partial t} + u_{\text{pcm}} \frac{\partial T_{\text{pcm}}}{\partial x} + v_{\text{pcm}} \frac{\partial T_{\text{pcm}}}{\partial y} \right) =
\]

\[
k_{\text{eff,pcm}} \left( \frac{\partial^2 T_{\text{pcm}}}{\partial x^2} + \frac{\partial^2 T_{\text{pcm}}}{\partial y^2} \right) - \epsilon \rho_{\text{pcm}} H_{\text{L}} \frac{\partial \beta}{\partial t}
\]  

(6)

**-Air**

\[
\frac{\partial u_{\text{air}}}{\partial x} + \frac{\partial v_{\text{air}}}{\partial y} = 0
\]  

(7)
\[
\frac{\rho_{\text{air}}}{\varepsilon} \left( \frac{\partial u_{\text{air}}}{\partial t} + u_{\text{air}} \frac{\partial u_{\text{air}}}{\partial x} + v_{\text{air}} \frac{\partial u_{\text{air}}}{\partial y} \right) = -\frac{\partial p_{\text{air}}}{\partial x} + \frac{u_{\text{air}}}{\varepsilon} \left( \frac{\partial^2 u_{\text{air}}}{\partial x^2} + \frac{\partial^2 u_{\text{air}}}{\partial y^2} \right) \tag{8}
\]

\[
\frac{\rho_{\text{air}}}{\varepsilon} \left( \frac{\partial v_{\text{air}}}{\partial t} + u_{\text{air}} \frac{\partial v_{\text{air}}}{\partial x} + v_{\text{air}} \frac{\partial v_{\text{air}}}{\partial y} \right) = -\frac{\partial p_{\text{air}}}{\partial y} + \frac{u_{\text{air}}}{\varepsilon} \left( \frac{\partial^2 v_{\text{air}}}{\partial x^2} + \frac{\partial^2 v_{\text{air}}}{\partial y^2} \right) + S_{\text{air}} \tag{9}
\]

\[
(1-\varepsilon)(\rho c)_m + \varepsilon(\rho c)_{\text{air}} \left( \frac{\partial T_{\text{air}}}{\partial t} + u_{\text{air}} \frac{\partial T_{\text{air}}}{\partial x} + v_{\text{air}} \frac{\partial T_{\text{air}}}{\partial y} \right) = k_{\text{eff,air}} \left( \frac{\partial^2 T_{\text{air}}}{\partial x^2} + \frac{\partial^2 T_{\text{air}}}{\partial y^2} \right) \tag{10}
\]

About the boundary conditions there is a pressure outlet edge at the top of the domain while the other edges are adiabatic. The heat generation rate simulates a typical power dissipation of a battery equal to 5.3 KW.

In the equations, \( \rho \) and \( c \) are respectively the density and the specific heat, \( u' \) is the heat generation rate inside the battery; \( u \) and \( v \) are respectively the \( x \) and \( y \) direction velocity, \( \varepsilon \) the porosity of the metal foam, \( p \) the relative pressure, \( \mu \) the dynamic viscosity of PCM or air, \( S \) the source term, \( V \) is the velocity vector of the PCM in the liquid phase or air and \( t \) is the time. The subscripts \( \text{Lit, pcm} \) and \( \text{air} \), referred respectively to the battery, the phase change material and the air. About the local temperature, the LTE approach is used and therefore the temperature foam in the PCM domain is equal to the temperature of the PCM and the same assumption is set in the air domain. The source terms in the PCM momentum equations are:

\[
S_x = \left( \frac{1-\beta^2}{\beta^3 + 0.001} \right) A_{\text{mush}} + \frac{\mu_{\text{pcm}}}{K} + \frac{C_F}{\sqrt{K}} \rho_{\text{pcm}} |\vec{V}_{\text{pcm}}| v_{\text{pcm}} \tag{11}
\]

\[
S_y = \left( \frac{1-\beta^2}{\beta^3 + 0.001} \right) A_{\text{mush}} + \frac{\mu_{\text{pcm}}}{K} + \frac{C_F}{\sqrt{K}} \rho_{\text{pcm}} |\vec{V}_{\text{pcm}}| v_{\text{pcm}} + \rho_{\text{pcm}} \beta \rho_{\text{pcm}} g \gamma_{\text{pcm}} \left( T_{\text{pcm}} - T_0 \right) \tag{12}
\]

The first term is the Kozeny–Carman term that models the presence of the solid part of the PCM during the melting. \( A_{\text{mush}} \) is the mushy zone constant which takes into account the damping of the velocity during the solidification [8]. Its value is set to \( 10^4 \) kg/(m\(^3\)s). The second term is the Darcy term where \( K \) is the permeability of the porous media and the third term is the Forchheimer term, where \( C_F \) is inertial drag factor. The details of equation 12 are found in [13].

The last term is the Boussinesq approximation where \( g \) the gravity acceleration module, \( \gamma_{\text{pcm}} \) is the PCM thermal expansion coefficient and \( T_0 \) is the operating temperature, set to 310K. \( k_{\text{eff}} \) is the effective thermal conductivity calculated by [14]:

\[
k_{\text{eff,pcm}} = (1-\varepsilon)k_{mf} + \varepsilon k_{pcm}
\]

\[
k_{\text{eff,air}} = (1-\varepsilon)k_{mf} + \varepsilon k_{air} \tag{13}
\]

3. Numerical model

The government equations were solved using the finite volume method using Ansys Fluent software [15]. A transient mode with a time step measurement of 1 s was activated. The phenomenon related to velocity - pressure coupled fields has been solved with the SIMPLE algorithm elaborated by Patankar [16]. A second-order upwind scheme is used to treat convective terms in both momentum and energy equations and a second-order central difference scheme is used for the discretization of diffusive terms.
The PRESTO pressure offset option was used for the discretization scheme for the pressure equation. A transient mode with a step of 0.1 s has been enabled. Convergence errors for the continuity and momentum equation were set to $10^{-5}$ and the energy equation was assumed to be $10^{-8}$. For the independent solution of the mesh a research has been carried out realizing five different grids, which are: 5x4, 10x5, 20x8, 40x15, 80x30 and the percentage error on the average temperature inside the copper foam $\varepsilon=0.933$ at 40 PPI filled by the PCM from which it has been decided to use the 40x15 because the calculation costs are satisfactory with precision (Table 3).

| Grid     | Time (s) | Average Temperature (K) | %error |
|----------|---------|-------------------------|--------|
| 5x4      | 500     | 355.80                  | 0.0759 |
| 10x5     | 500     | 355.76                  | 0.0646 |
| 20x8     | 500     | 355.70                  | 0.0478 |
| 40x15    | 500     | 355.53                  | 0      |
| 80x30    | 500     | 355.53                  | -      |

4. Results and Discussions

The simulations were carried out using initially only air, then copper foams with porosity $\varepsilon = 0.933$ with 20 PPI (Pores per Inch) and $\varepsilon = 0.934$ with 40 PPI, only RT42 PCM and filled copper foam by PCM. The simulations were carried out with $h = 0, 20, 50, 100, 150, 200$ (W / m$^2$K) and concerned the analysis of the average temperature of the top layer of the battery, of the top layer of the domain (Figure 3) and the liquid fraction $\beta$ (Figure 2).

The simulation with only air presents similar temperatures in case $h=0$, while as the value of the coefficient $h$ increases the two zones tend to have significant differences in temperature. The case with only PCM results to have even more marked temperature differences than the case with only air, in fact while the top layer of the domain presents very low temperatures, the top layer of the battery is instead affected by extremely higher temperatures. The case that has the closest average temperatures between the two layers and more in tune with the safety parameters of the battery is the case of PCM with copper

![Figure 2](image)

Figure 2. Liquid fraction of PCM with copper foam with $\varepsilon = 0.933$ with 20 PPI and PCM with copper foam $\varepsilon = 0.934$ with 40 PPI
Figure 3. Average temperature on the top layer of the coil and the top of the air domain, the copper foams with $\varepsilon = 0.933$ with 20 PPI and $\varepsilon = 0.934$ with 40 PPI, only the RT42 PCM and the copper foam filled with PCM.

In this case, when the temperature of the battery is approaching the critical temperature, the PCM starts to melt keeping the temperature in the safety range for an acceptable time.

The results obtained show that there are no substantial differences between copper foams with 20 PPI and 40 PPI, but the difference in terms of temperature is given by the increase of the heat transfer coefficient $h$. 

foams. In this case, when the temperature of the battery is approaching the critical temperature, the PCM starts to melt keeping the temperature in the safety range for an acceptable time.
5. Conclusions
According to the results obtained, the cases with only air and foams have the highest average temperatures, while the case with only PCM shows great differences in temperature between the top of the battery and the top of the domain. These differences are dangerous because, although the top of the domain is at low temperatures, the battery has very high and dangerous temperatures. The best average temperature trend was found with the combination of PCM with copper foams, which has subtle differences in temperature between the two layers, keeping the battery for a long time at lower temperatures than the other cases analyzed. The number of pores per inch (PPI) showed no temperature differences between 20 PPI and 40 PPI, while the contribution of the heat exchange coefficient \( h \) was important for obtaining lower average temperatures.

6. Nomenclature

| Symbol | Description |
|--------|-------------|
| \( A_{\text{mush}} \) | Mushy constant [kg/(m\(^3\)s)] |
| \( C_f \) | Inertial drag factor [-] |
| \( c \) | Specific heat [J/kg K] |
| \( d \) | Diameter [m] |
| \( g \) | Gravity acceleration [m/s\(^2\)] |
| \( H_L \) | Latent Heat [J/kg] |
| \( k \) | Thermal conductivity [W/mK] |
| \( K \) | Permeability [m\(^2\)] |
| \( p \) | Relative pressure [Pa] |
| \( S \) | Source term [N/m\(^3\)] |
| \( T \) | Local Temperature [K] |
| \( t \) | Time [s] |
| \( u \) | Heat generation [W/m\(^3\)] |
| \( u \) | Velocity along x direction [m/s] |
| \( V \) | Local velocity module [m/s] |
| \( v \) | Velocity along y direction [m/s] |
| \( x, y \) | Cartesian directions [m] |

**Greek letters**

| Symbol | Description |
|--------|-------------|
| \( \beta \) | Liquid fraction [-] |
| \( \varepsilon \) | Porosity [-] |
| \( \gamma \) | Thermal expansion factor [1/K] |
| \( \mu \) | Dynamic viscosity [Pa s] |
| \( \rho \) | Density [kg/m\(^3\)] |
| \( \omega \) | Pore density – Number of pore per Inch [-] |

**Subscript**

| Symbol | Description |
|--------|-------------|
| \( 0 \) | Operating |
| \( \text{air} \) | Air |
| \( f \) | Fiber |
| \( \text{Liquidus} \) | End melting temperature |
| \( \text{mf} \) | Metal foam |
| \( p \) | Pore |
| \( \text{pcm} \) | Phase change material |
| \( \text{Sil} \) | Battery |
| \( \text{Solidus} \) | Start melting temperature |

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