Thermal Management of Li-ion Battery Packs

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Abstract: A design for the thermal management of the media used for packing Li-ion batteries used in hybrid and electric vehicles has been developed. The design satisfies all thermal and physical issues relating to the battery packs used in vehicles such as operating temperature range and volume, and, should increase battery life cycle and charge and discharge performances. Particular attention was devoted to the thermal management of batteries operating in extreme temperature conditions, that is, from -50ºC to +50°C, with desired operating conditions held between 20°C and 30°C. The method of cooling/heating here could be thought akin to a heat sink approach with heat removed or added using water. This current work is a series of simulations used to give sound indications for the design and assembly of a prototype.

Keywords: Thermal management, Li-ion batteries,

1. Introduction

Temperature affects batteries in five major ways: the operation of the electrochemical system; efficiency and charge acceptance; power and energy produced; safety and reliability; and, life and life-cycle costs. Li-ion batteries are extremely sensitive to low and high temperatures. For example as temperature falls below -10ºC, the performance of Li-ion batteries deteriorates severely [1,2], while at high temperature, these types of batteries are prone to uncontrolled temperature build-up [3].

Hence there is a need for battery and battery pack thermal management. For battery packs it is important to regulate the pack to remain in the desired temperature range for optimum performance and life, and also to reduce uneven distribution of temperature throughout a pack which would lead to reduced performance. Importantly, the attainment of even temperature distributions through the battery pack eliminates potential hazards related to uncontrolled temperature build-up ('thermal runaway'). Of course a battery thermal management system will always include an internal switch which is open if the battery is operated outside of its operating temperature range. This would prevent fire or explosion risk but the battery also becomes temporarily unavailable. A number of works have reported that Li-ion battery calendar life [4] and cycle life [5] degrade quickly if kept or used at high temperature.

A well-designed thermal management system will ensure good battery performance, safety and higher capacity [6]. Many methods have been used, including air, liquid (direct and indirect), insulation, phase-change material, passive (ambient) or active (heaters, air-conditioning), or, a combination of these various approaches. Some ventilation should always be provided for the ventilation of potentially hazardous gases generated by batteries. Thermal management systems using active cooling (forced circulation of air or liquid) have been proposed and simulated for lead-acid batteries in electric vehicle applications [7]. Air convection (natural or forced) quite often is insufficient for effective heat dissipation from batteries under abuse conditions leading often to non-uniform temperature distributions within battery packs [8,9]. Indirect liquid cooling of battery packs (both passive and active) can prove an efficient method for dissipation or addition of heat [10,11]. However, it is desirable to keep the cooling fluid separate from the battery and so for small battery packs, cooling by fluid may not actually be possible. It is known that the desired operating temperature for most Li-ion batteries is 20ºC to 30°C, although ambient temperatures can vary from-50°C to 50°C.

2. Thermal Management System

The aim of a thermal management system is to maintain a battery pack at an optimum average temperature, as dictated by life and performance trade-off. Important is that an even temperature, perhaps with small variations, is maintained between the cells and within the pack. However when designing such a system, regard must also be paid to the fact that the battery pack should be compact, lightweight, have low cost manufacture and maintenance, and, have easy access for maintenance. The management system should also have low parasitic power, allow the pack to operate under a wide range of climatic conditions and provide ventilation if the battery generates potentially hazardous gases. The thermal management control strategy is enacted using an electronic control unit. A general schematic of the proposed thermal management system is given on Figure 1. The method employed is fundamentally to surround the cells with a conducting material, that is, a form of heat sink, and remove or add heat using fluid.

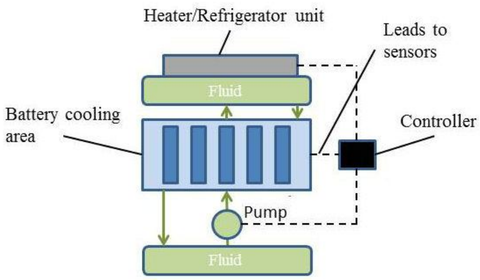
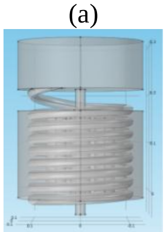


Figure 1. Schematic of thermal management system.

3. Use of COMSOL Multiphysics

The design of the battery cooling area was analyzed using COMSOL Multiphysics. A model of six cells placed in an aluminium block was built as shown on Figure 2.

(a)



(b)

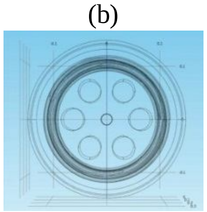


Figure 2. Battery cooling area, (a) Front, (b) Plan.

The model solves in 3D, with fluid pumped through a central vertical tube and returned through a helix tube just within the aluminium block for efficient heat transfer and protection against damage. The fluid is conditioned using a heater/refrigerator unit placed on the top surface of the plenum chamber.

2.1 Fluid Domain

The fluid flow was considered as laminar, incompressible and with no body forces so the following equations were used for continuity and momentum transport equations,

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} - \nabla \cdot [\nu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] = -\frac{1}{\rho} \nabla p \tag{2}$$

where, ν is the kinematic viscosity, ρ is the density, $\mathbf{u}$ is the velocity field and p is the pressure.

The heat equation used, written in terms of absolute temperature T, and ignoring viscous heating and pressure work was,

$$C_p \frac{\partial T}{\partial t} + C_p \mathbf{u} \cdot \nabla T = \nabla \cdot \left(\frac{k}{\rho} \nabla T\right) \tag{3}$$

where, C_p is the specific heat capacity, and k is the thermal conductivity.

2.2 Solid Domain

When the velocity is set to zero in Equation (3), the equation governing pure conductive heat transfer is obtained, i.e.,

$$C_p \frac{\partial T}{\partial t} = \nabla \cdot \left(\frac{k}{\rho} \nabla T\right) \tag{4}$$

Conjugate heat transfer was used between the solid domain and fluid domain.

2.3 Boundary Conditions and Settings

The cooling fluid is modelled using the material properties of water. The fluid properties were calculated using the inlet temperature. A summary of the settings and boundary conditions is set out in Table 1.

Table 1: Boundary conditions and settings

Settings:	
Battery pack outside dimensions	height = 360 mm, radius = 130 mm
Cell dimensions	height = 150 mm radius = 20 mm
Number of cells	6
Cooling pipe radius (r_{inner})	10 mm
Coolant	H_2O
Mesh cell setting	fine meshing
Boundary conditions:	
Outer wall	cooling: 293.15 K, heating: Neumann
Coolant/solid interface	conjugate heat transfer
Conditioner/coolant	$T = f(T_f)$
Cooling pipe inlet	u_{in} = 0.01 m/s, T_{in} = 293.15 K
Cooling pipe outlet	P_{out} = 101,325 Pa
Cell initial temperatures	cooling: 313.15 K 349.15 K heating: 253.15 K

The model is solved sequentially in two studies, one study for each physics interface. The fluid flow is solved for first, followed by the quasi-stationary temperature of the battery pack, at the desired time in the load cycle.

To ascertain possible "worst case" temperature cooling from each of the cells, separate studies have already been carried out [12-13] of time-dependent studies for 1D cells. It has been found that, for example, a Li-ion battery having $LiMn_2O_4$ as the cathode can reach slightly more than 40°C when cycled at ambient temperature with currents greater than 2C while battery having LiFePO4 as the cathode can reach temperatures higher than 75ºC.

3. Results

3.1 Cooling the battery pack

In this part of the study, the temperature history of the battery pack was modelled with ambient conditions (T_0) set at 293.15 K, and each of the cells set first at T_{init} = 313.15 K and then T_{init} = 349.15 K. This study is important because, in addition to testing if the chosen geometry parameters are suitable, it also gives an indication concerning the selection of a suitable pump and heater/refrigeration unit. Typical velocity contours for the battery pack are shown on Figure 2. The important aspect here is that heat could be added/removed to the water in the plenum chamber efficiently. It can be seen that there was slow moving water adjacent to the heating/refrigerator unit hence giving enough time for absorption/dissipation of heat.

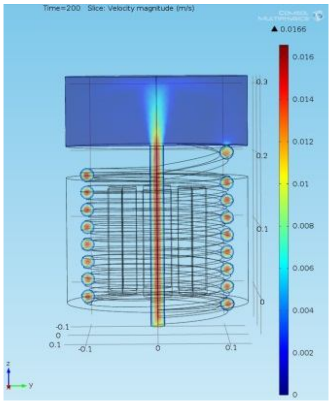


Figure 3. Velocity contours u_{in} = 0.01 m/s, T_{in} = 20°C, r_{inner} = 10 mm, and T_0 = 20°C.

Several tests were initially conducted, where the battery pack was cooled to find appropriate values for the parameters, u_{in}, T_{in}, r_{inner} and helix turn number per length with the cells' temperature initially set at 313.15 K and then 349.15 K. Temperature profiles at different times for each starting temperature were determined as in the example shown on Figure 4. Importantly here was that temperature uniformity within each cell was achieved as well as from cell to cell to ensure maximum cycle life (i.e., minimum long-term degradation) of cell and pack. It can be seen from Figure 4 that after about 10 s the temperature across the cells had acceptable uniformity.

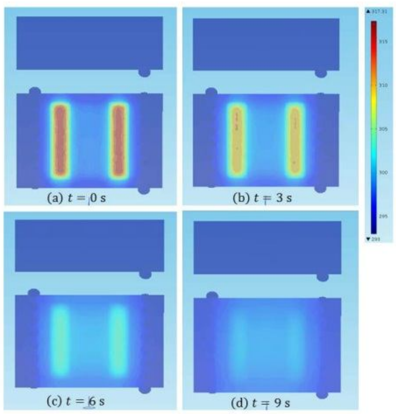


Figure 4. Front views of temperature profiles in two adjacent cells for T_{init} =313.15 K, u_{in} = 0.01 m/s r_{inner} = 10 mm, T_0 = 293.15 K and T_{in} = 293.15 K.

This uniformity is also confirmed by looking at the temperature profiles in the radial direction through the centre of the battery pack and a cell plotted against time. Gradually the profiles move from an initial profile distorted by the hot cell to a very acceptable final uniform profile in the reasonably short time of 15 seconds.

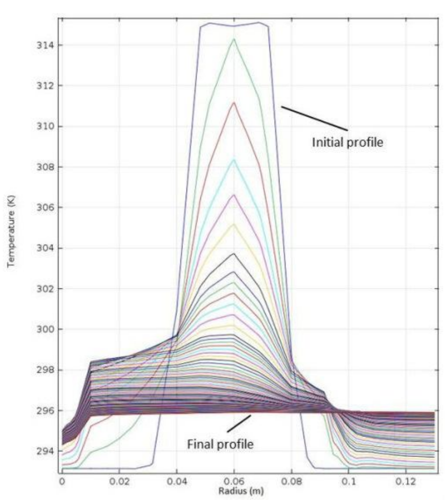


Figure 5. Temperature profiles in the radial direction for T_{init} =313.15 K, u_{in} = 0.01 m/s, r_{inner} = 10 mm, T_0 = 293.15 K and T_{in} = 293.15 K.

Similar tests were conducted for initial cell temperatures of 349.15 K, with acceptable uniformity across cells reached after 15 s.

Figure 6 shows the temperature profiles versus times for the centre of cells for the two initial temperatures of 313.15 K and 349.15 K. It was found that the cells had reached acceptable temperatures after 80 s and 20 s respectively.

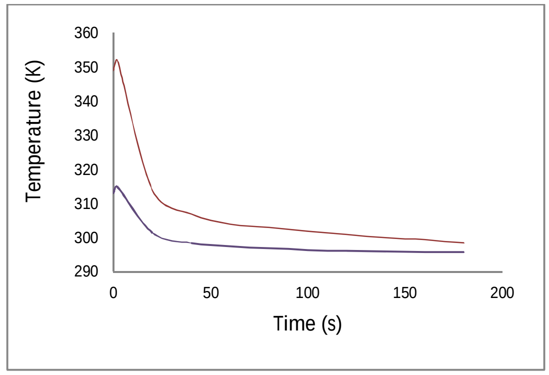


Figure 6. Temperature profiles versus time at the centre of cells for T_{init} = 349.15 K (red) and 313.15 K (purple), u_{in} = 0.01 m/s, r_{inner} = 10 mm, T_0 = 293.15 K and T_{in} = 293.15 K.

The next series of tests were conducted on the battery pack which had, in addition to initial temperatures of 313.15 K and 349.15 K, an internal heat source for each cell of either 0.25, 0.5 or 1 W. Results for the pack with cells each having an internal heat sources of 1 W are shown on Figures 7 and 8. As with the previous tests, what was important was the control of temperature between acceptable limits, and a good uniformity of temperature across each cell.

It can be seen from Figures 7 and 8, that in the early stages of cooling, non-uniformity was found, but after say 1 minute, there was acceptable uniformity throughout each cell, and certainly after 2 minutes each cell was within desired operating temperatures. At times greater than 2 minutes the heat loss to the atmosphere was slightly more than heat production within the cells, even at 1W so reducing the need for further cooling. In the proposed prototype the temperature would be monitored using a thermostat and further cooling would ensue intermittently as necessary.

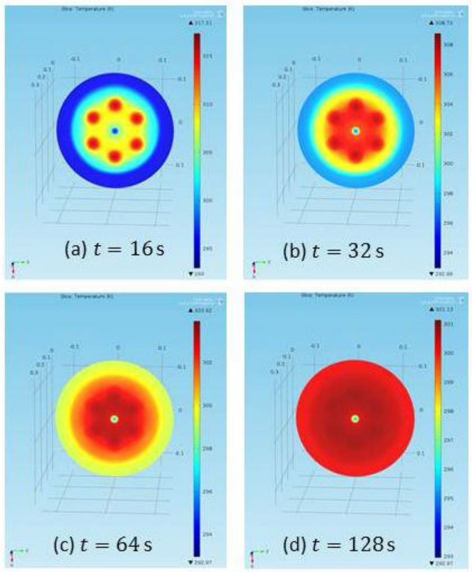


Figure 7. Plan view of temperature profiles for T_{init} =313.15 K, u_{in} = 0.01 m/s, r_{inner} = 10 mm, T_{in} = 293.15 K, and heat source within each cell of 1 W.

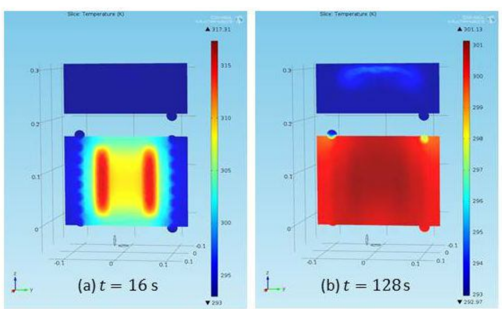


Figure 8. Front view of temperature profiles for T_{init} =313.15 K, u_{in} = 0.01 m/s, r_{inner} = 10 mm, T_{in} = 293.15 K, and heat source within each cell of 1 W

3.2 Heating the battery pack

Simulations were carried out to document temperature rises within the battery pack for different T_{in}, u_{in} and r_{inner} values. Examples of temperature rises for a location at the centre of a cell and 80 mm from the bottom are shown on Figure 9. It can be observed that the water within the centre pipe and helix has to be heated quite significantly (in this example to 60°C) to raise the cell to an acceptable temperature and within a reasonable time scale.

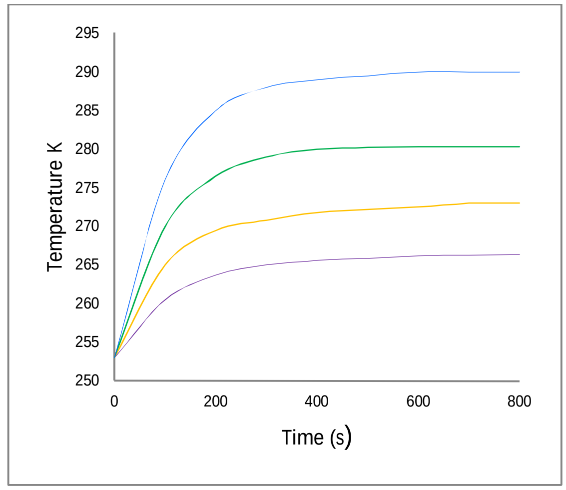


Figure 9. Temperature profiles at the centre of a cell when heating at various T_{in}, and u_{in} values, with r_{inner} = 10 mm, and T_0 = 253.15 K.
(purple:- U_{in} = 0.1 m/s, T_{in}= 303.15 K
orange:- U_{in} = 0.1 m/s, T_{in}= 313.15 K
green:- U_{in} = 0.2 m/s, T_{in}= 313.15 K
blue:- U_{in} = 0.2 m/s, T_{in}= 333.15 K)

As usual the uniformity of temperature within the cells was of concern. Figure 10 shows temperature profiles at various times along a cell vertical centre-line from the 0 s to 600 s

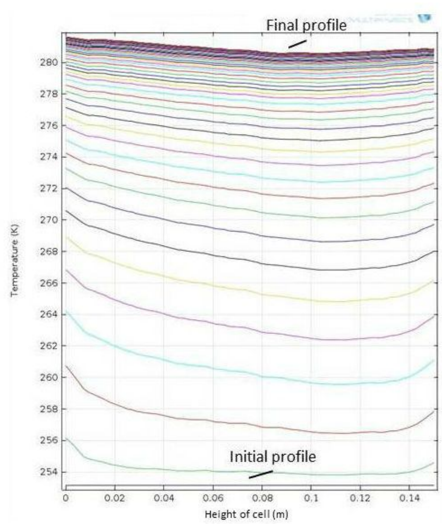


Figure 10. Temperature profiles in the vertical direction for T_{init} = 253.15 K, T_0 = 253.15 K, u_{in} = 0.2 m/s, and T_{in} = 333.15 K during the heating process.

It will be noted that the vertical profiles remain reasonable constant throughout the heating process for the values given on Figure 10. At higher T_{in} values and with T_0 at 253.15 K or less a distortion in the vertical temperature profiles was noted after thermal equilibrium was reached. An example is shown on Figure 11, where the ambient temperature (T_0) is set at 233.15 K.

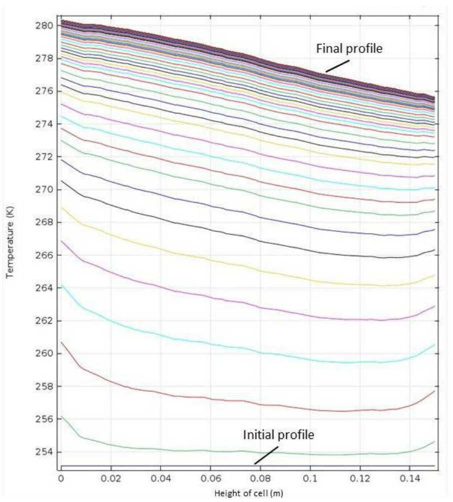


Figure 11. Temperature profiles in the vertical direction for T_{init} = 233.15 K, T_0 = 233.15 K, u_{in} = 0.2 m/s, and T_{in} = 313.15 K during the heating process.

It can be seen that the design of the battery pack for these extreme cold conditions may require the inclusion of an insulation layer around the body of the pack.

4. Conclusions

Preliminary results useful to the final design of a prototype battery pack have been produced. The values found for the important parameters help in confirming the chosen geometry, and, give indications of necessary pump and heating/refrigeration specifications need when assembling the prototype. A point of concern was noted in that for very low ambient temperature a non-uniform temperature profile was not found across the battery pack, and more importantly across the cells. This will be investigated further probably by using a thin insulating layer around the battery pack.

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