

Thermal Management of Lithium-ion Battery Packs

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Introduction

Temperature affects batteries in five major ways:

- operation of electrochemical system;
- efficiency and charge acceptance;
- power and energy efficiency;
- safety and reliability; and,
- life and life-cycle costs.

Li-ion batteries are extremely sensitive to low and high temperatures.

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').



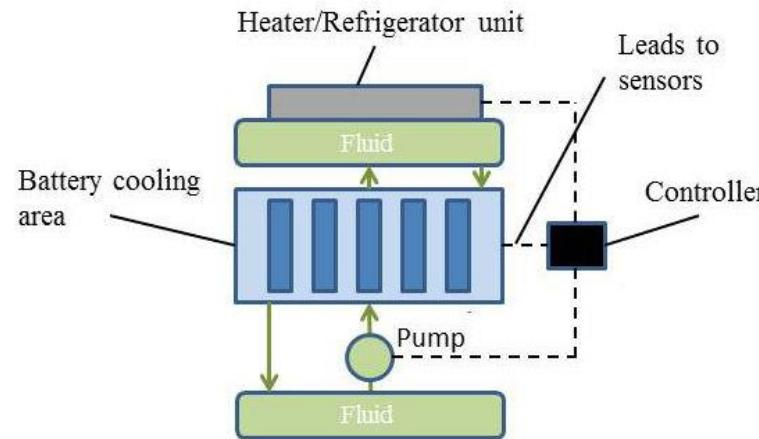
Cooling/Heating Methods

- 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.
- 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.
- Indirect liquid cooling of battery packs (both passive and active) can prove an efficient method for dissipation or addition of heat.
- 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 20°C to 30°C, although ambient temperatures can vary from -50°C to 50°C.



Thermal Management System

- When designing battery pack should be compact, lightweight, have low cost manufacture and maintenance, and, have easy access for maintenance.
- The management system should 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.



- **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.**

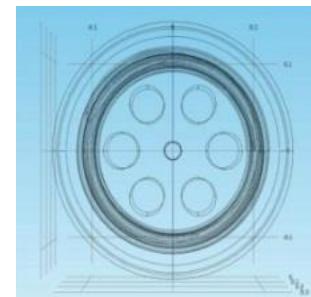


Use of COMSOL Multiphysics - 1

A model of six cells placed in an aluminium block was built as shown:-



Front



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.



Use of COMSOL Multiphysics - 2

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,

$$\nabla \cdot \mathbf{u} = 0$$
$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} - \nabla \cdot [\nu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] = -\frac{1}{\rho} \nabla p$$

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

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

Solid Domain

The equation governing pure conductive heat transfer was,

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

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



Boundary Conditions and Settings

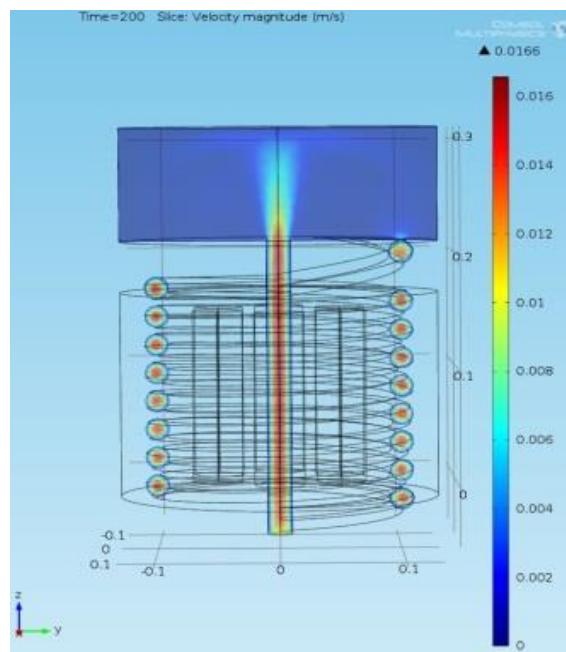
Settings:	
Outer dimensions of battery pack	height = 360 mm, radius = 130 mm
Cell dimensions	height = 150 mm radius = 20 mm
Number of cells	6
Cooling pipe radius (r_{inner})	10 mm
Coolant	H ₂ O
Mesh cell setting	fine meshing
Boundary conditions:	
Outer wall	cooling: 293.15 K, heating: Neumann
Coolant/solid interface	conjugate heat transfer
Conditioner/coolant	$T = f(T_f)$
Cooling pipe inlet	$u_{in} = 0.01 \text{ m/s}$, $T_{in} = 293.15 \text{ K}$
Cooling pipe outlet	$P_{out} = 101,325 \text{ Pa}$
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 of time-dependent studies for 1D cells.
- It has been found that, for example, a Li-ion battery having LiMn₂O₄ as the cathode can reach slightly more than 313.15 K when cycled at ambient temperature with currents greater than 2C, while battery having LiFePO₄ as the cathode can reach temperatures higher than 349.15 K.



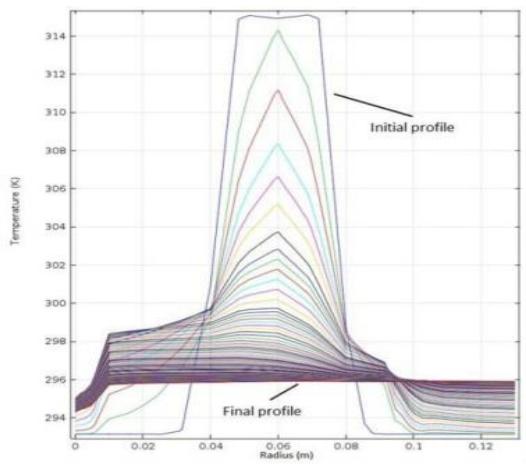
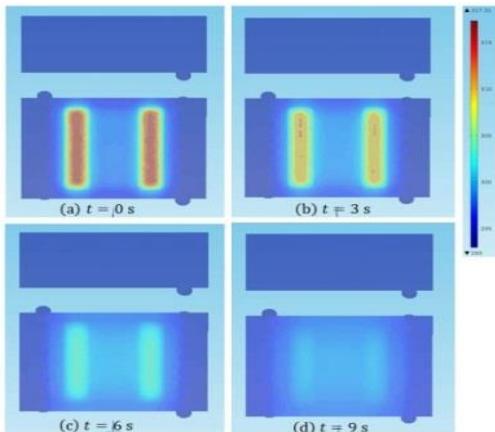
Results - Cooling the battery pack

- The temperature history of the battery pack was modelled with ambient conditions (T_0) 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 the chosen geometry parameters, it also gives indication for selection of pump and heater/refrigeration unit.
- Typical velocity contours for the battery pack are shown below:-



Results - Cooling the battery pack

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.

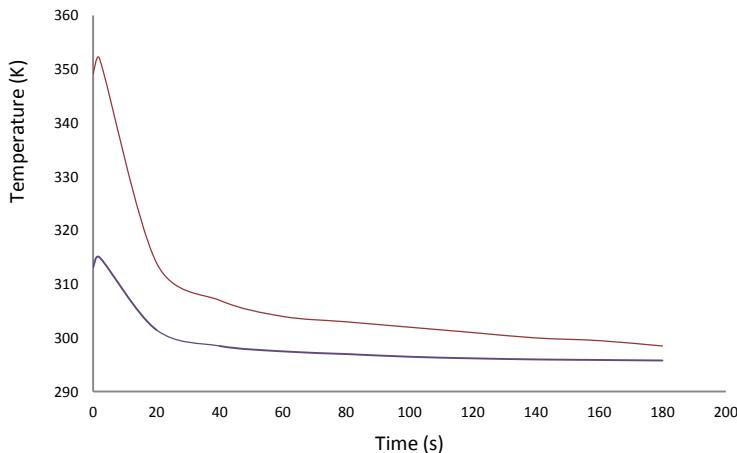


- Temperature profiles at different times for each starting temperature were determined.
- It can be seen from Figure that after about 10 s the temperature across the cells had acceptable uniformity
- This uniformity is confirmed by looking at the temperature profiles in the radial direction plotted against time.
- Gradually the profiles move from an initial profile distorted by the hot cell to an acceptable final uniform profile in 15 seconds.



Results - *Cooling the battery pack*

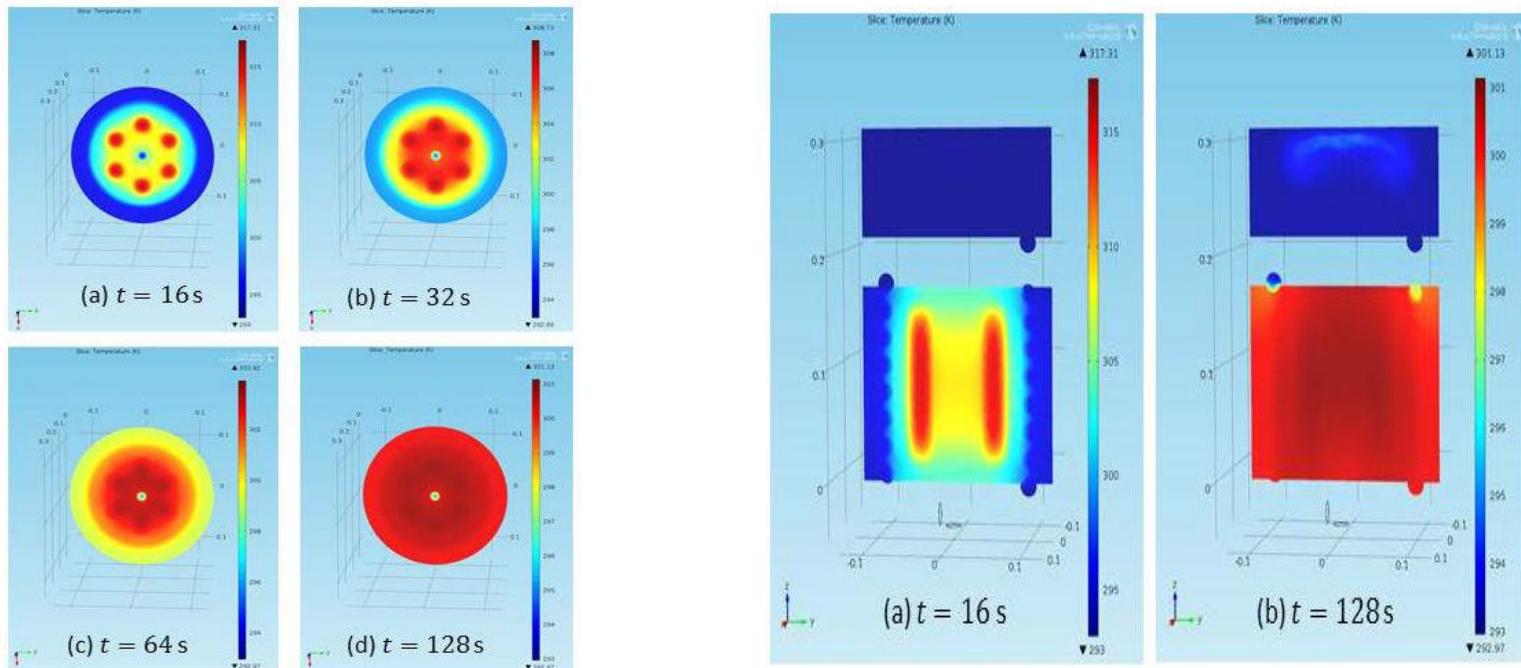
The temperature profiles versus time for the centre of cells are shown below for the two initial temperatures of 313.15 K and 349.15 K.



- 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 the next slide.



Results - Cooling the battery pack

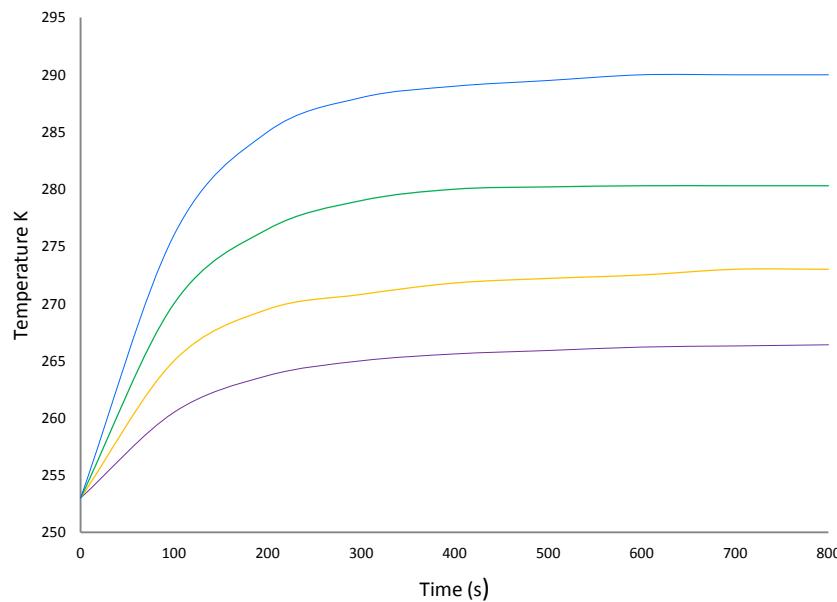


- In the early stages of cooling, temperature non-uniformity was found across the cells.
- After approximately 1 minute, there was acceptable uniformity throughout each cell.
- After 2 minutes each cell was within desired operating temperatures.
- At times > 2 minutes heat loss to the atmosphere was slightly more than heat production within the cells, even at 1W so reducing the need for further cooling.



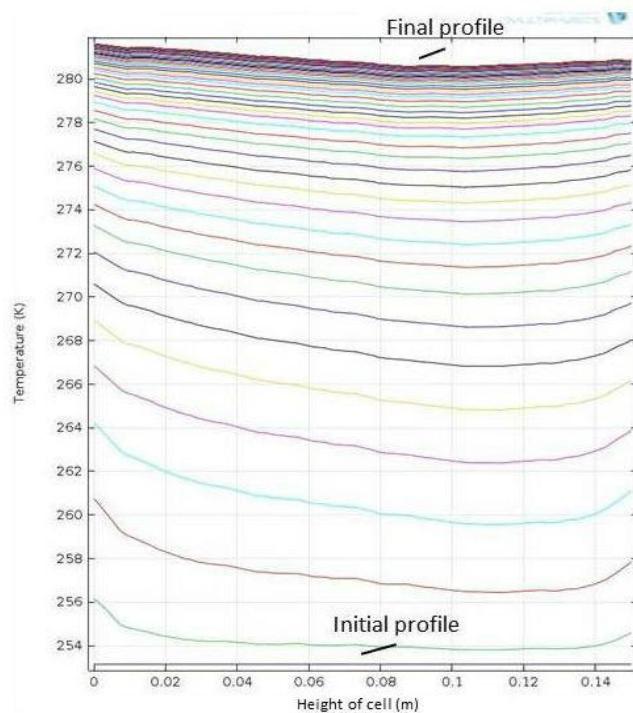
Results - Heating the battery pack

- 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:



Results - Heating the battery pack

- Due to its importance for battery operation the uniformity of temperature within the cells was again investigated.
- Figure below shows temperature profiles at various times along a cell vertical centre-line from 0 s to 600 s.

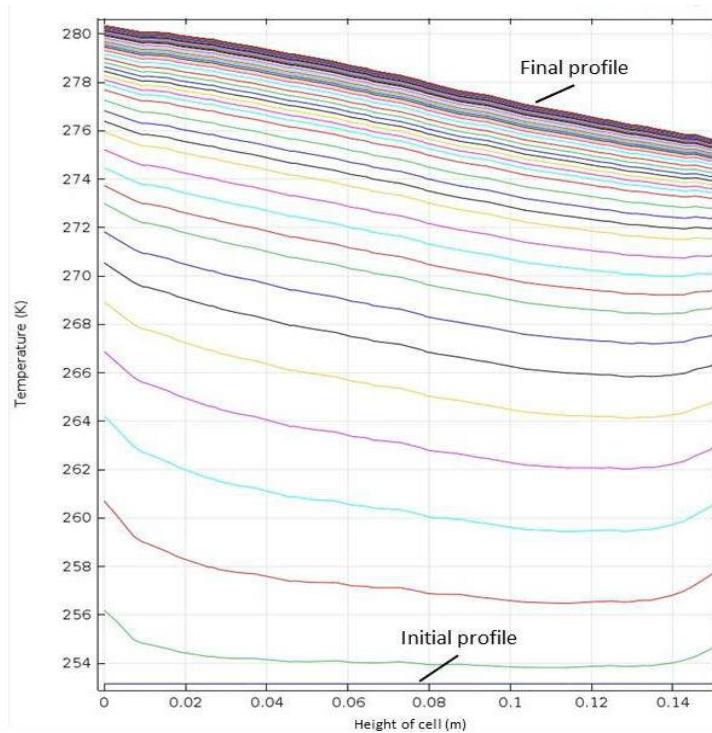


Temperature profiles in the vertical direction for $T_{init} = 253.15 \text{ K}$, $T_0 = 253.15 \text{ K}$, $u_{in} = 0.2 \text{ m/s}$, and $T_{in} = 333.15 \text{ K}$ during the heating process.

- It should be noted that the vertical profiles remain reasonable constant throughout the heating process.

Results - Heating the battery pack

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 below, where the ambient temperature (T_0) is set at 233.15 K.



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 pack body. This work is will be considered as part of future studies

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 needed when assembling the prototype.
- A point of concern was noted in that for very low ambient temperatures 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.

