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# Experimental and numerical investigation of core cooling of Li-ion cells using heat pipes

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ABSTRACT

While Li-ion cells offer excellent energy conversion and storage capabilities for multiple applications, including electric vehicles, heat removal from a Li-ion cell remains a serious technological challenge that directly limits performance, and poses serious safety concerns. Due to poor thermal conductivity of Li-ion cells, traditional cooling methods like air cooling on the cell surface do not effectively access and cool the core. This may lead to overheating of the cell core. This paper investigates the cooling of Li-ion cells using an annular channel through the axis of the cell. Air flow through this channel and heat pipe insertion are both shown to result in effective cooling. A temperature reduction of 18–20 °C in the cell core is observed in heat pipe experiments, depending on heat pipe size, for 1.62 W heat dissipation. Similar effect is observed when a thin metal rod is used instead of a heat pipe. Experimental measurements are close to finite-element simulation results. Experiments demonstrate that a heat pipe successfully prevents overheating in case of sudden increase in heat generation due to malfunction such as cell shorting. This paper illustrates fundamental thermal-electrochemical trade-offs, and facilitates the development of novel and effective cooling techniques for Li-ion cells.



## 1. Introduction

Lithium-ion cells offer excellent energy conversion and storage for a variety of applications, including consumer electronics, electric vehicles and military electronics [1,2]. Despite the excellent electrochemical characteristics of Li-ion cells compared to alternate energy storage and conversion technologies [3,4], the application of Li-ion cells has been severely limited by concerns over overheating during operation [5–8]. A significant amount of heat is generated, particularly at high discharge rates [9], and the poor thermal conductivity of Li-ion cells [10] results in large temperature rise within the cell [11,12]. Besides reduced performance and reliability at high temperatures, this also presents a serious safety concern [5,9]. Once the cell temperature exceeds a certain threshold, a series of exothermic processes occur within a Li-ion cell [13,14]. This thermal runaway situation eventually results in catastrophic failure and fire that may have led to several well-publicized recent incidents [6]. Several other undesirable effects, including capacity fade [15,16], power fade [5] and self-discharge [17] are also known at high temperature. Due to the importance of thermal management in a Li-ion cell, a variety of approaches for cell cooling have been investigated. The use of a heat pipe with a metal fin has been found to be effective for heat dissipation [18]. Analysis of convective cooling with air or liquid flow over the cell has been presented [19]. Phase change cooling has been shown to provide better heat dissipation than air cooling in certain conditions [20]. The role of phase change cooling on prevention of thermal runaway has been investigated [21]. The use of heat pipes distributed between cells has been shown to limit temperature rise [22].

The operation of a Li-ion cell depends on a complicated, multiscale coupling between several physical processes including charge/ion transport, electrochemistry, heat transfer, etc. [23–25]. Heat generation in a Li-ion cell is an undesirable side effect of the primary electrochemical energy conversion and storage function of the cell. Heat generation occurs due to a variety of mechanisms, including Ohmic losses, exothermic heats of reaction, etc. Theoretical analysis of these processes [26,27], as well as measurement of heat generation rates, have been presented in the past. This includes measurements at very high rates of discharge, using calorimetry [28] and measurement of heat stored and lost [9]. Due to the tight winding of the electrode-separator roll in a Li-ion cell, it is reasonable to assume that heat generation within a Li-ion cell is

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spatially uniform, except possibly for greater heat generation at the tabs due to Ohmic losses. However, due to the relative proximity of the outer parts of a cell to a heat transfer path offered by air cooling or cold plate cooling, the outer parts of a cell cool down much more effectively than the core of the cell. Such approaches do not sufficiently address heat removal from the core of the cell, which remains thermally difficult to access.

Fundamentally, heat removal from a Li-ion cell is a two-step process – heat generated inside the cell is first conducted to the outside surface of the cell, followed by heat removal from the surface [11]. The second step of this process occurs typically through convection with a coolant, such as air, or conduction through the surrounding material of the battery pack. It has been shown that thermal conduction within the Li-ion cell is usually the slower, and hence rate-determining step [11]. This emanates from the poor thermal conductivity of the Li-ion cell, particularly in the direction normal to the electrodes [29]. This makes it particularly difficult to remove heat generated in the core of the cell, resulting in a hot core and a large temperature gradient within the cell. Measurements have shown as much as 24 °C temperature gradient between the core and outer surface of a 26650 cell at 10C discharge rate [9]. In addition, this results in a large temperature gradient within the cell based on both estimates [30] and actual measurements [31], which is undesirable for performance and reliability.

It is clearly important to remove heat directly from the core of the cell. Merely enhancing heat transfer on the outside surface, for example by increasing the coolant flowrate or improving cold plate design does not sufficiently enhance the cooling of the core of the cell, and may actually worsen the temperature gradient. In order to effectively cool the core of the cell, it is critical to thermally access the cell core and remove heat directly from the source of heat generation. A hollow metal tube that may be inserted along the axis of the cell during the electrode roll winding and assembly process may offer a mechanism for this purpose, for example, through the insertion of a heat pipe in the annular region. Heat pipes are passive devices that facilitate directional heat transport through evaporation and condensation of an enclosed working fluid in a spatial loop. Heat pipes have been widely used in several other applications, including electronic devices such as RF power device [32], microprocessors [33]. insulated-gate bipolar transistors (IGBTs) [34], data centers [35], photovoltaic cells for energy conversion [36] and district heating applications [37], high power LEDs [38], thermal energy storage [39], etc. but not so much for Li-ion cells. Some work has been recently reported on inserting heat pipes between cells in a pack without [22] and with heat spreaders [40]. There may be several technical challenges in the use of heat pipes, such as integration with present manufacturing processes, interference with electrical conductors and heat removal from the condenser end of the heat pipe. Further, the previously adopted approach of embedding a heat pipe between Li-ion cells has limited benefit as it does not access the core source of heat generation within the cell. It would be a lot more effective if the heat pipe can be inserted into the cell, since this would give a direct heat transfer pathway for the heat generated inside the cell to be dissipated. Due to the poor thermal conductivity, and hence large thermal resistance of materials inside a Li-ion cell, such a direct approach is expected to be a lot more effective than what has been investigated so far.

This paper investigates the thermal management of a Li-ion cell utilizing cooling through a hollow tube passing through the cell. The effectiveness of cooling a thermal test cell through internal air flow, as well as heat pipe and metal rod insertion is experimentally investigated. A thermal test cell of the same dimensions as a 26650 Li-ion cell, and similar thermal properties is fabricated. Heat generation in the test cell through Joule heating is used to mimic electrochemical heating in a Li-ion cell. Experimental data are shown to be in good agreement with finite-element simulation results. This approach is shown to result in effective cooling of the Li-ion cell due to the direct access provided to the core of the cell. Despite the several manufacturing challenges and thermal-electrochemical trade-offs that an embedded heat pipe may present, the dramatic improvement in thermal management may make this an attractive approach for thermal management of Li-ion cells.

The next section discusses fabrication of the thermal test cell, experimental setup and thermal measurements. Finite-element simulations are described next, followed by a discussion of key results and conclusions.

## 2. Experimental approach

### 2.1. Fabrication of annular thermal test cell

Electrochemical heat generation rate in a Li-ion cell varies as a function of the depth of discharge [31], and is difficult to measure directly [9]. Moreover, it is also not straightforward to measure temperature inside a Li-ion cell because a Li-ion cell is a hermetically sealed system, and drilling a hole to insert a thermocouple will disrupt the electrochemical function of the cell. As an alternative, a thermal test cell capable of precise, well-controlled heat generation through Joule heating and internal temperature measurement through embedded thermocouples is fabricated. This allows precise thermal measurements at well-controlled and measurable heat generation rates corresponding to discharge at various C-rates without the added uncertainty due to the electrochemistry of an actual Li-ion cell. The thermal test cell is designed and fabricated to be the same dimensions as a 26650 cell, and the constituent materials are chosen in order to closely match the thermal transport properties of an actual Li-ion cell [10,41].

Two thermal test cells with inner diameter of 2 mm and 6 mm are fabricated. A steel tube is first cut to approximately 110 mm in length. The outer surface of the tube is insulated with Kapton tape to prevent short circuiting. Next, a 25 μm thick stainless steel foil is cut 1000 mm long and approximately 62.5 mm wide. One side of this foil is insulated with Kapton tape to prevent the foil from short circuiting itself. Two 16 gauge wires are soldered to opposite ends of the foil for connecting to a power source. Seven T-type thermocouples are then placed at increasing distances from one another along the foil (Fig. 1a). The foil is then wrapped around the steel tube as tightly as possible in order to increase total heater length and hence electrical resistance. Once tightly wound, the roll is secured with tape (Fig. 1b). The tube and metal sheet roll are then placed inside the casing of a 26650 cell, and a thermocouple is also attached to the inside of the cell casing (Fig. 1c). The cell is filled with poly-dimethylsiloxane (PDMS), which is a thermally-curable polymer that fills up air voids within the test cell. Also, an additional ninth thermocouple is placed within the small layer of PDMS in between the foil and casing. All wires are threaded through a cap that is then inserted at the open end of the cell. PDMS inside the cell is cured at room temperature over a 24 h period. Since uncured PDMS is very viscous, in order to fully remove air bubbles, PDMS is topped off and self-cured once more.

Fig. 1d shows a top view image of the thermal test cell before sealing the top cap, showing the tightly wound metal heater coil and wires leading to the embedded thermocouples. The room temperature resistance of the heater coil is found to be 0.23 Ohms and 0.27 Ohms respectively for the heaters for the 6 mm and 2 mm hole diameter test cells, which was measured in a four-wire configuration due to the small value of the resistance. Resistance