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Battery thermal management system for electric vehicle using heat pipes

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ABSTRACT

Thermal management of battery systems in electric vehicles is critical for maintaining energy storage capacity, driving range, cell longevity and system safety. In this paper, heat pipe based thermal management system for high power battery, with eight prismatic cells, has been proposed, designed and tested for heat load up to 400 W. The heat pipe system consists of two parts: heat pipe cooling plates to extract heat from the individual prismatic cells of the battery module, and remote heat transfer heat pipes to transport heat from the module to liquid cooled cold plates located 300 mm away. As compared to a conventional liquid cooled system, two-phase heat pipe based thermal control will provide better cell/module temperature uniformity, less complicated design and a safer system (no leakage issues in high voltage areas). Modeling of the complete system was done based on two-phase analysis for the heat pipe portion, and single phase analysis for the cold plate portion. The system manufacturing and evaluation method has been covered in detail. Based on controlled experimentation using a dummy battery module, it was estimated that the proposed system is able to successfully dissipate 50 W heat load from each cell while keeping their temperature below the given 55 °C limit using water coolant with a 25 °C inlet temperature and 1 lit/min flow rate.

1. Introduction

Lithium-Ion cells represent the state of the art in energy storage for electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). The current high costs and limited energy density require that existing cells are used to the fullest potential [1]. By maximizing battery lifetime and facilitating the ideal operating conditions, electric vehicle range and lifetime can be maximized. Lithium-Ion cells are inherently subject to aging not only over time, but also due to operating conditions influences including their state of charge (SOC), current, and extreme temperatures [2]. These factors have varied effects on the multitude of cell chemistries in use today, but temperature has a universal influence on the performance degradation of nearly all Lithium-Ion chemistries [3]. The high cell currents mandated by consumer requirements such as rapid charging during performance driving result in high heat losses in the cells [1]. Heat is produced in a battery cell due to three fundamental reasons: activation interfacial kinetics, concentration species transport, and ohmic Joule heating from the movement of charged particles, which becomes very significant for larger cell sizes such as those discussed in this paper. Not only the average or maximum temperature in a cell influences aging, but also the temperature gradient across a cell or module [4]. Premature aging of a single cell can degrade the performance of a module noticeably.

The goal of a battery thermal management system (BTMS) is to increase the lifetime of Lithium-Ion cells and thus the battery system by regulating the temperature level and distribution. A BTMS is especially necessary when the cells are susceptible to high rates of charging (e.g. rapid charging or regenerative breaking) and discharging (e.g. high performance vehicles, plug-in hybrids), and when the vehicle is operated in very high or low ambient temperatures. For prismatic cells, like those considered in this work, a cooling plate integrated in a coolant or refrigerant circuit is implemented in most currently available PHEVsvehicles and mentioned in numerous patents from major vehicle and cooling system manufacturers [5ndash;9-9]. The heat transfer possible through such BTMS appears adequate, yet the safety of the system can become critical, for example in the event of a leakage or accident, the coolant or refrigerant can leak onto the battery cells, potentially causing a short circuit. Additionally, the coolant channels require a minimum hydraulic diameter to resist clogging and maintain an acceptable pressure drop. In experiments performed within the scope of this research, channels with a hydraulic diameter much below 1 mm did not perform robustly. As the thickness of a cooling plate reduces, the spectrum of materials and production techniques available is limited, making the manufacturing process more complex and costly.

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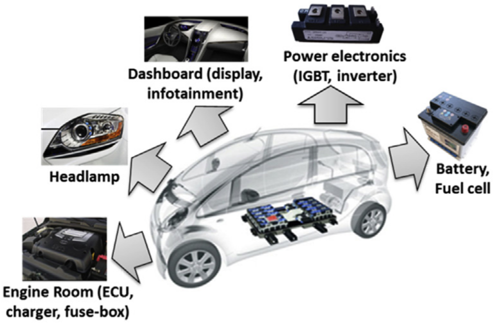

Fig. 1. Potential areas in automotive for heat pipe thermal control [27].

The ideal BTMS should be able to operate safely and robustly within the restricted space available in a modern vehicle, provide the necessary heat transfer, and be possible to economically manufactured. Under these boundary conditions, heat pipes provide an interesting solution due to their small size, passive operation, long lifetime, superior thermal performance, and history in the consumer electronics [10]. The application of heat pipes specifically for battery thermal management has been explored experimentally on various cell types, most of these researches has, however, focused on individual heat pipe performance, instead of the effect of such a system on a module of actual battery cells [11–19]. Patents in the field are also becoming more prevalent [20,21].

Capillary driven heat pipes have been investigated for range of thermal control applications in the automotive sector [22,23]. A heat pipe can transfer heat at orders of magnitude higher than a similar size of solid metal rod, without the use of moving parts [24–26]. For electronic devices such as LED headlamps and LCD displays, heat pipes can be invariably used to transfer, spread and dissipate heat by fully passive means. Heat pipes have a high potential for various applications within an automobile, as identified in Fig. 1 [27]. In a properly designed heat pipe system, thermal functionality can be guaranteed regardless of orientation [28,29]. Additionally, heat pipes can be produced in various shapes and sizes (Fig. 2), allowing them to be tailored to each application.

The typical automotive environment is harsh and constantly changing with driving and weather conditions. Dynamic mechanical forces and vibrations, a wide spectrum of climatic operating conditions, and exposure to corrosive substances are just some of the operational requirements facing a BTMS. Most of the structural and operational requirements for a heat pipe BTMS could be addressed by optimizing wick flow properties (pore size, permeability, porosity), working fluid (type, charging ratio) and the assembly process (coating process, joining/fastening technology, integration principle).

Copper-water is the most efficient material-fluid combination for heat pipes due to the high thermal conductivity of copper (~400 W/mK) and high figure of merit for water. The two primary challenges for copper-water heat pipe are the structural strength of the copper container and the freezing of water. The strength of the copper container can be enhanced by using different copper alloys, increasing wall thickness and reducing pipe diameter, however, the effect on mass must be considered. The bi-directional functionality of heat pipes allow for a BTMS to facilitate both cooling and heating.

Fig. 2. Flattened copper-water heat pipes (left) and a heat pipe cross section showing wick structure along the inner periphery (right).

The assembly method of the heat pipes within the BTMS is critical for guaranteeing a long product lifetime. The most reliable method to join heat pipes with other components is soldering; however, mechanical fixing is also possible assuming the degree of freedom of the parts is well constrained by enclosure walls and other mechanical barriers. To protect against corrosion, a nickel coating can be applied. This work covers the design, theoretical layout, production, and experimental validation of a multi-component heat pipe thermal management system for module of prismatic Lithium-ion battery cells.

2. Existing battery system

A sample prismatic battery-cell module from the BMBF research project eProduction is used. It contains eight PHEV-2 format prismatic cells that are joined at the terminals and constrained by mechanical bracing. The baseline case utilizes a liquid cold plate attached at the foot of the cells for thermal dissipation. Having the reference system shown in Fig. 3 (a & b) allows various BTMS to be compared directly. In Fig. 3c, overall cooling system with 8 cold plates connected in series, mechanical pump to circulate liquid through the cooling loop and remotely located radiator to remove heat from the coolant, is presented.

In this conventional layout, the cell casings must be electrically insulated from one another to prevent a short circuit. The cells are electrically connected at their terminals via so-called bus bars. The interface at the foot of the cell must also ensure electrical insulation as well, which in the case of typical aluminum cold plates requires thermal interface film, pad or gap-filler. Due to the manufacturing tolerances in the cell and the cooling plate, as well as the requirement of electrical insulation, this interface becomes complex to manufacture and inefficient thermally, however, this is the primary heat transfer path for battery thermal management. Additional heat transfer between the cells occurs via the bus bars, as these are connected to the cell terminals which inturn are connected directly to the aluminum and copper-intensive "jelly-roll" (where the cell's active chemistry is located).

The battery stack comprises of 8 Li-ion prismatic cells with individual cell dimensions of 148 (L) x 91 (W) x 26.5 (T), making up total stack length of 279 mm. Each cell has max 4.2 V with 25 Ah capacity. The cells were held together in stack using arrangement of end plates with four threaded rods that provided high compressive force of 11 kN to contain thermal expansion of cells during operation, and to provide proper thermal contact for the flow of heat from cell interiors to side/bottom via metal spacer plates.

This work investigates the use of heat-pipe spacers between the cells (i.e. in place of the "spreader plate/spacer" in Fig. 3) and to transport heat from battery module to remotely located heat sink, in order to address the aforementioned challenges in the heat transfer between cells and BTMS.

3. Proposed heat pipe system

The proposed battery thermal management system, as shown in Fig. 4, has three modules:

i. Heat extraction module (for cell level thermal control): consists of heat pipe cooling plates (HPCP) to maintain uniform battery cell temperature and transfer heat from between the cells to an external spreader plate.
ii. Heat transfer module (for transferring the heat away from the battery module): consists of remote heat transfer heat pipes (RHE-HP) to transfer heat from the spreader plate connected to the HPCPs to a remotely located liquid cooling system
iii. Heat dissipation module (for system level thermal control): consists of liquid cooled cold plate(s) to transfer the heat from the battery module and associated electronics to coolant which would in turn