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Heat dissipation design for lithium-ion batteries

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Abstract

A two-dimensional, transient heat-transfer model for different methods of heat dissipation is used to simulate the temperature distribution in lithium-ion batteries. The experimental and simulation results show that cooling by natural convection is not an effective means for removing heat from the battery system. It is found that forced convection cooling can mitigate temperature rise in the battery. Nevertheless, a non-uniform distribution of temperature on the surface of the battery is inevitable and this makes thermal management difficult.

As a better means of suppressing increases in temperature, a heat pipe has been used to effect heat dissipation. The connection between the heat pipe and the battery wall pays an important role in heat dissipation. Inserting the heat pipe in to an aluminum fin appears to be suitable for reducing the rise in temperature and maintaining a uniform temperature distribution on the surface of the battery. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Lithium-ion batteries; Heat dissipation; Heat pipe; Thermal behavior

1. Introduction

Lithium-ion batteries have received considerable attention for use in portable electronics and electric vehicles due to their relatively high specific energy and good cycle-life. In order to afford the required power, a large-scale battery of cells connected either in series or in parallel is required. In this case, the safety issue arising from temperature rise in the battery must be taken into account. There is a strong interdependence between temperature variation within the battery and electrochemical performance. In general, a rise in temperature during the course of charging and discharging battery is detrimental to battery performance in that it may accelerate degradation of the electrolyte, electrodes and separator. Consequently, temperature distribution and heat dissipation are important factors in the development of thermal management strategies for lithium-ion batteries. Although there have been several studies of the thermal behavior of lead-acid [1–3], lithium-ion [4,5] and lithium-polymer batteries [6–9], heat dissipation designs are seldom mentioned.

Chen and Evans [8] investigated heat-transfer phenomena in lithium-polymer batteries for electric vehicles and found that air cooling was insufficient for heat dissipation from large-scale batteries due to the lower thermal conductivity of polymer as well as the larger relaxation time for heat conduction. Choi and Yao [2] pointed out that the temperature rise in lead-acid batteries cannot be lowered sufficiently by means of either natural or forced convection. Most of the aforementioned studies showed that the rise in the temperature of a battery could not be significantly alleviated by means of natural or forced air convection, particularly in large-scale batteries. To date, only a few researchers have used extended surfaces to increase heat dissipation from batteries. In our previous study [10], cold plates with extended surfaces were used to enhance sufficiently heat dissipation from nickel–metal-hydride batteries.

In this paper, the thermal behavior of a large-scale lithium battery is investigated. A metallic aluminum fin and heat pipe are employed to mitigate the temperature rise during discharging of the battery. A heat pipe is a self-contained heat pump that has the capability of transporting heat at a high rate over substantial distances without external pumping power [11]. Although its use for cooling electronic applications has met with some success [11], it has seldom been employed in heat dissipation designs for batteries. Thus, the use of a heat pipe in lithium-ion batteries to improve heat dissipation represents an innovation. A two-dimensional transient thermal model has also been developed to predict

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the heat dissipation behavior of lithium-ion batteries. Finally, theoretical predictions obtained from this model are compared with experimental values.

2. Experimental

A 12 A h, cylindrical, lithium-ion battery (40 mm in diameter, 110 mm in length) was used as a test sample to investigate the temperature distribution during discharging. The electrodes were encased in a container made of stainless steel. The charging and discharging were controlled by a charge–discharge unit (Maccor Instrument 4000). The discharging voltage was cut off at 2.8 V. Next, the variation in surface temperature at different locations during the charging and the discharging processes was measured by three thermocouples (k-type) attached to the battery wall. The voltage and temperature data were then recorded by a personal computer.

3. Results and discussion

A two-dimensional, transient heat-transfer model was used to simulate the temperature distribution in the lithium-ion battery under different conditions of heat dissipation. The battery comprised a metal case, electrode plates, electrolyte, and separators. The heat-transfer equation of the battery with precise thermal physical properties corresponding to different regions is difficult to calculate. Most studies [2,8,12] have shown that the treatment of a composite electrode as a quasi-homogeneous medium is sufficiently accurate to predict the thermal behavior of the battery. Therefore, the density, thermal conductivity and heat capacity of the cell components are assumed to be uniform throughout the battery, and to remain constant within a certain range of temperature. The motion of the electrolyte due to the change in porosity of the electrode during the charging and the discharging processes is neglected. Based on these assumptions, the two-dimensional, transient heat-transfer model can be written as follows:

$$\rho C_p \frac{\partial T}{\partial t} = k_r \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + k_z \frac{\partial^2 T}{\partial z^2} + q \quad (1)$$

where ρ denotes the average density, C_p the average heat capacity, k_r and k_z the average thermal conductivities in the r direction and z direction, respectively. The major thermophysical properties were obtained from literature [4,13,14]. The rate of heat generation per unit volume is denoted by $\dot{q}$. Assuming the heat generation is distributed uniformly throughout the battery, the rate of heat generation is given by [15]:

$$\dot{q} = \frac{I}{V_b}\left[(E_o - E) + T\frac{dE_o}{dT}\right] \quad (2)$$

where V_b is the volume of battery, I the current ($I < 0$ for charging and $I > 0$ for discharging), E the cell potential, E_o the open-circuit potential.

It is further assumed that only cooling by convection is significant at the boundary, and that radiation effects can be neglected. Assuming a constant heat-transfer coefficient over the external surface of the battery, the boundary conditions can be written as follows:

$$\frac{\partial T}{\partial r} = 0, \quad r = 0,\ 0 < z < Z \quad (3)$$

$$-k_r \frac{\partial T}{\partial r} = h_r(T - T_\infty), \quad r = R,\ 0 < z < Z \quad (4)$$

$$k_z \frac{\partial T}{\partial z} = h_z(T - T_\infty), \quad z = 0, 0 < r < R \quad (5)$$

$$-k_z \frac{\partial T}{\partial z} = h_z(T - T_\infty), \quad z = Z,\ 0 < r < R \quad (6)$$

where h denotes the convection heat-transfer coefficient at the outer surface of the case, T_∞ the ambient temperature, R and Z the radius and height of the battery, respectively.

Generally, the transient heat-transfer problem can be treated as a series of quasi-steady states. As the metallic fins are attached to both sides along the r direction, the following boundary conditions are obtained:

$$\int\int q\,dA = h_0\eta_0 A_t[\bar{T}_s - \bar{T}_f], \quad r = R \quad (7)$$

where the term on the left side is the total heat fluxes at the surface of $r = R$, and that on the right side is the total heat transferred by the metallic fin. The average convection heat-transfer coefficient is denoted by h_0, whereas η_0 represents the overall efficiency of the metallic fin and A_t is the total heat-transfer area. $\bar{T}_s$ and $\bar{T}_f$ denote the average surface temperature and film temperature, respectively.

In this study, the battery is kept at ambient temperature prior to charging and discharging. Therefore, the initial condition can be written as:

$$T = T_\infty, \quad t = 0,\ 0 < r < R,\ 0 < z < Z \quad (8)$$

Herein, a finite difference method using the alternating direction implicit (ADI) method [16] is employed to derive the mathematical model.

In our studies (simulation and experimental results), the increases in temperature of lithium-ion batteries were not conspicuous in the course of charging. Therefore, we focused primarily on the thermal behavior of lithium-ion batteries during discharge history. The calculated center temperature behavior of a lithium-ion battery at different stages of discharge with different discharge currents is shown in Fig. 1. Obviously, the temperatures are increased stepwise by increasing the state-of-discharge. It is worth nothing that the temperatures increased rapidly at the end of discharge. This can be attributed to a large polarization at the end of discharge. In addition, as expected, temperatures

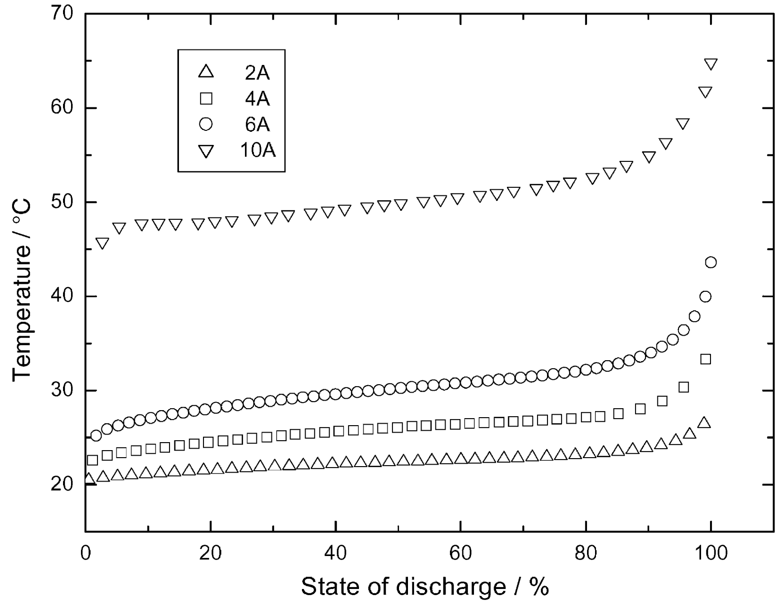

Fig. 1. Calculated temperature histories at center of lithium-ion battery at different stages of discharge with different discharge currents.

are higher for a larger discharge current. All temperature profiles are found to be lower than 40 °C except for discharge at 10 A. This means that at lower discharge currents, the heat generated during discharging can be dissipated effectively even under natural convection conditions. When the discharge current exceeds 10 A, however, the temperature increases and can reach 65 °C at the end of discharge. Evidently, it is more difficult to remove the heat generated from the battery to the surroundings at high-rate discharge currents under natural convection cooling. Consequentially, a more effective design of heat dissipation is necessary.

The temperature distribution in the r and z directions at the end of discharge under nature convection conditions is presented in Fig. 2. It is obvious that less uniform distribution of temperature is found in the r direction than in the z direction. The battery temperature remains high and unchanged in the center of the battery. This means that the heat generated in this region cannot be easily dissipated by convection cooling. The difference between the maximum and minimum temperatures at the end of discharge is around 20 °C. Song and Evans [17] attributed this difference in temperature distribution to the higher rates of heat generation at the end of the cell stack due to the fact that the

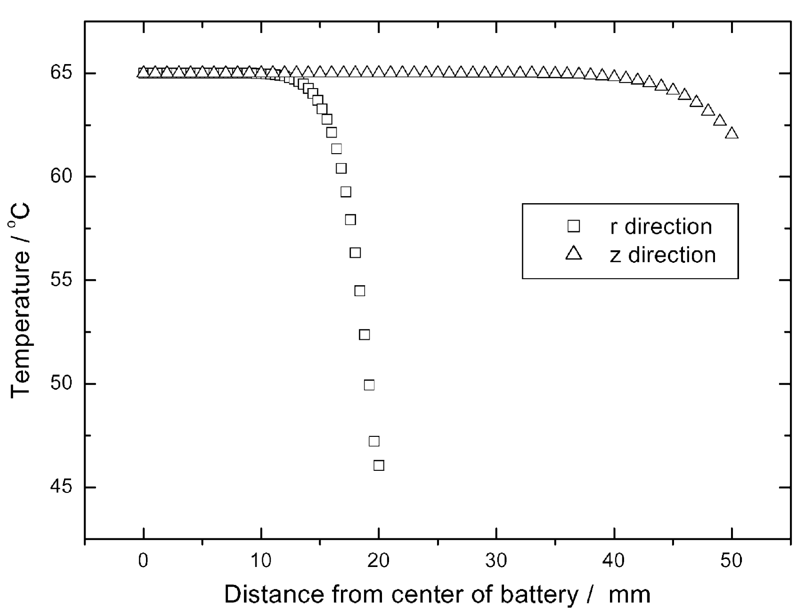

Fig. 2. Temperature distribution in r and z directions at end of discharge under natural convection conditions.

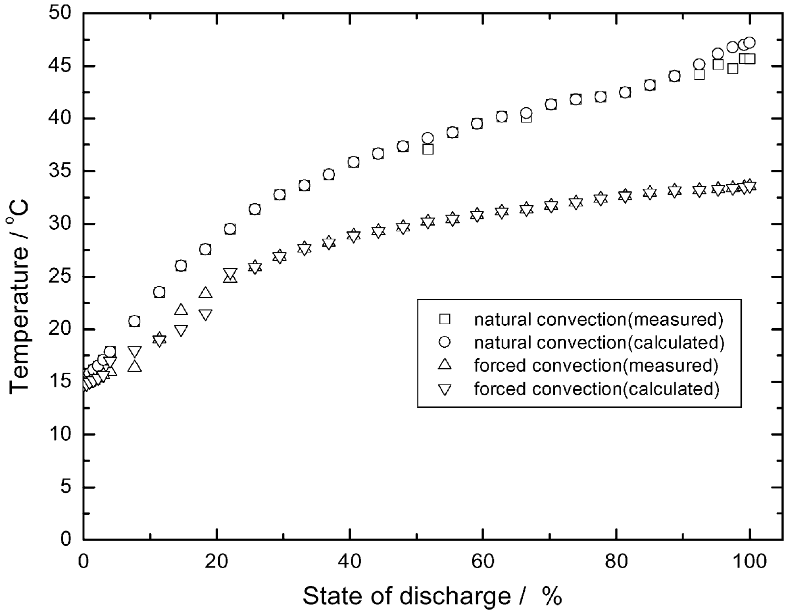

Fig. 3. Measured and calculated surface temperatures under natural and forced convection.

temperature there is lower. On the other hand, there is only a small temperature gradient in the z direction due to the higher thermal conductivity in that direction. Similar results were founded in the studies of Song and Evans [17].

The measured and calculated surface temperatures under natural and forced convection are shown in Fig. 3. There is a good agreement between the measured and calculated results. The temperature rise can be suppressed under forced convection conditions. The temperature reaches 47 °C under natural convection, but only 33 °C under forced convection conditions. These findings suggest that forced convection cooling is capable of dissipating heat, and is the reason why such cooling is preferred in many heat dissipation designs.

The surface temperatures at different positions were measured by means of three k-type thermocouples. These results are illustrated in Fig. 4. With natural convection cooling, the temperature profiles are similar in different positions. This finding agrees with our assumption that the temperature distribution is independent of θ directions. On the other hand, as mentioned, the temperature distribution in the z direction is uniform due to the large thermal conductivity in this direction. So the main temperature variation within the battery occurs only in the r direction,

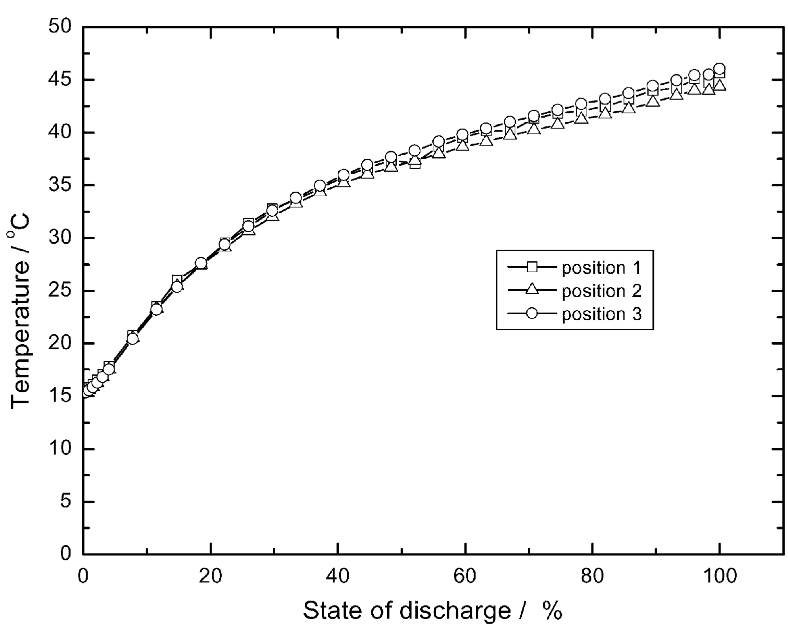

Fig. 4. Measured surface temperature at different positions under natural convection cooling.

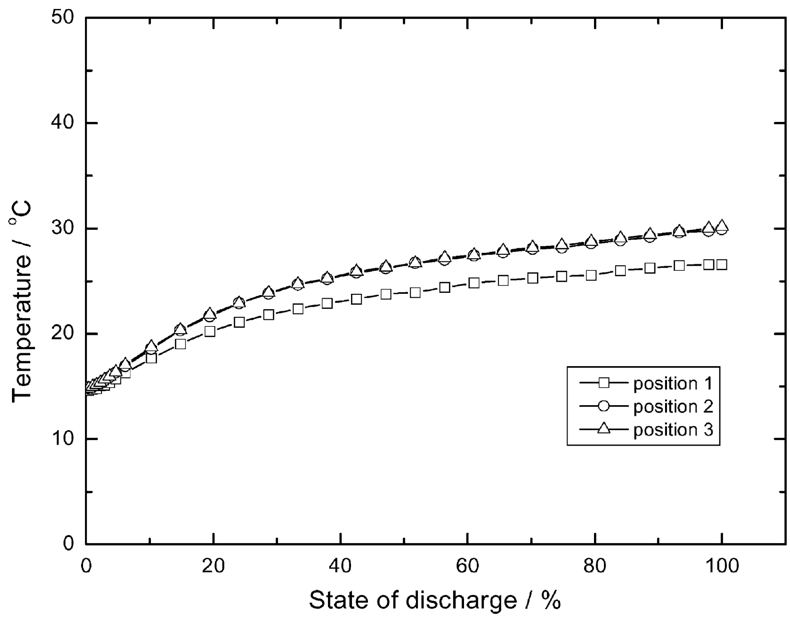

Fig. 5. Measured surface temperature at different positions with forced convection cooling.

irrespective of both z and θ directions. By contrast, the temperature profile measure at various positions shows different results, as can seen in Fig. 5. This is responsible for the difference in the local heat-transfer coefficient (h) as air flows past the surface of a cylindrical battery. Thus, the heat dissipated with the help of airflow may cause a non-uniform temperature distribution on the surface of battery. The temperature at position 1 has a much lower value due to the fact that it has a larger heat-transfer coefficient in that position. The temperatures at positions 2 and 3 are higher than that at position 1 resulting from the smaller heat-transfer coefficient. The major problem has been how to maintain a uniform flow of air past the battery surface so as to ameliorate the rate of dissipation.

Metallic fins have been found to be effective in improving heat dissipation from different types of battery. For example Cho and Halpert [18] studied the heat dissipation from high-rate Li–$SOCl_2$ primary cells and found that metallic fins can effectively enhance the transfer of heat. Kim et al. [19] obtained similar results with a nickel–hydrogen battery. Therefore, in this work, the effect of aluminum fins for lithium-ion batteries has been investigated. In this case, two annulus aluminum fins of 5 mm in thickness and 80 mm in diameter were attached to the battery wall. The calculated

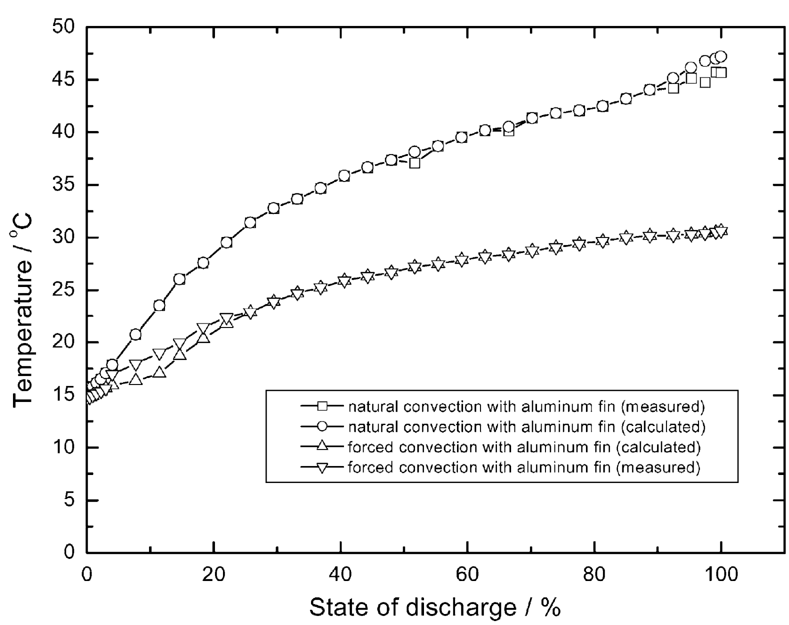

Fig. 6. Calculated and measured surface temperature profiles of battery fitted with an aluminum fin and under different cooling conditions.

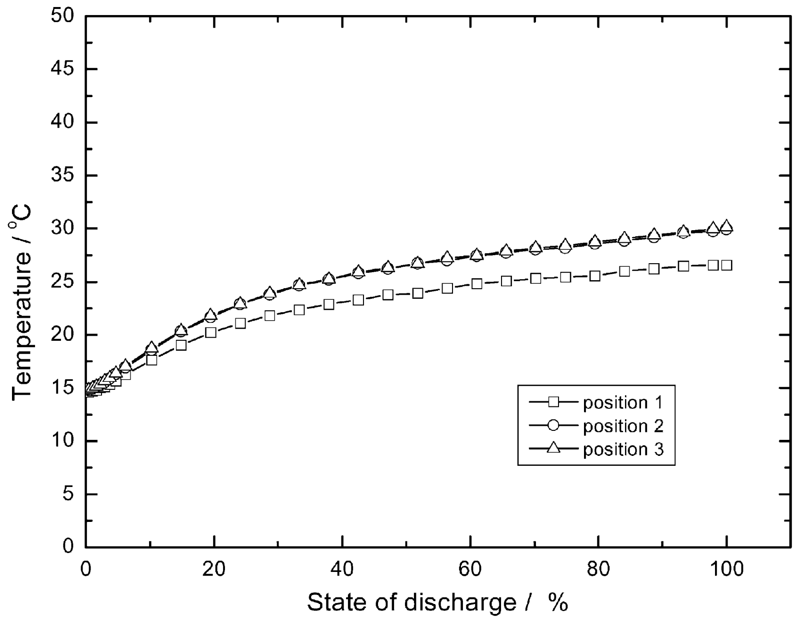

Fig. 7. Measured surface temperature profiles at different positions on battery fitted with an aluminum fin and under forced convection cooling.

and measured surface temperature profiles for a battery fitted with aluminum fins and operated under different cooling conditions are shown in Fig. 6. Under natural and forced convection, the temperature can reach about 46 and 32 °C, respectively. The lower temperature profile under forced convection (compare Fig. 3) is due to the fact that aluminum fins provide a greater area for heat transfer which assists the removal of generated heat. Nevertheless, a non-uniform temperature profile is again present under forced convection conditions as shown in Fig. 7.

In order to improve the uniformity of the temperature distribution of the surface of the battery under air convection cooling, two heat pipes were attached to the battery wall. The result indicated that there was no appreciable change in the rise in temperature, the value can reach around 45 °C. This was attributed to a bad connection between the heat pipe and the battery wall. On inserting the heat pipe into aluminum fins, however, the temperature decreases to 38 °C at the end of discharge, as illustrated in Fig. 8. This decrease results from a good connection between the aluminum wall and heat pipe. Consequentially, the heat generated within battery can transfer easily through the heat pipe. In general, a heat pipe is comprised of three sections: an evaporator, an adiabatic section, and a condenser section. The condenser

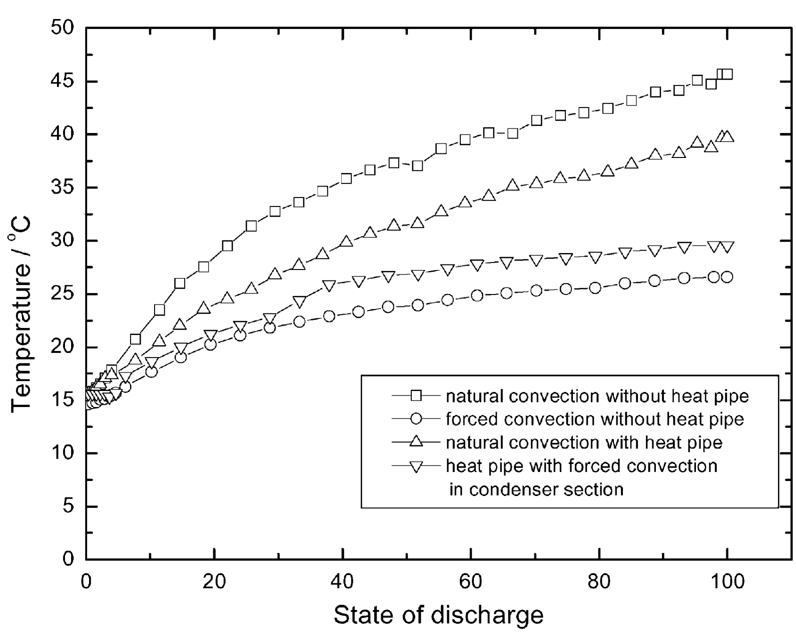

Fig. 8. Temperature profiles for battery with/without a heat pipe under natural/forced convection.

section of the heat pipe may play an important role in improving the rate of heat transfer. At the condenser end, heat is removed by condensation and is ultimately dissipated through an external heat sink such as a finned array. A cooling fan has been used as a heat dissipation tool in many applications. Therefore, an attempt was made to enhance the rate of heat dissipation in the condenser section of the heat pipe by the use of a finned array and a cooling fan. The result (lowest curve, Fig. 8) shows that attaching metallic fins to the condenser section of the heat pipe and adding a cooling fan can reduce the surface temperature of the battery to around 32 °C. In this case, the measured temperatures are very close to each other at different positions. Thus, such a heat pipe can be used to conduct heat effectively out of the battery instead of an airflow, and a uniform temperature distribution can be obtained.

4. Conclusions

Based on the results obtained from model prediction and experimental measurement, we can conclude the following for lithium-ion batteries.

(i) During discharging, the battery temperature increases stepwise with increasing state-of-discharge and is higher for a larger discharge currents. When the discharge current exceeds 10 A, the temperature increases rapidly and can reach 65 °C at the end of discharge.

(ii) It is not easy to dissipate heat generated in the center of the battery. The difference between the maximum and minimum temperatures at the end of discharge is around 20 °C. There are differences in the surface temperature profiles measured at various positions on the battery.

(iii) For the sake of safety, efficient heat dissipation is essential for large-scale lithium batteries. In this study, the use of a heat pipe is proposed to reduce increases in temperature. A heat pipe in direct contact with the battery provides no appreciable improvement in heat removal. When the heat pipe is inserted into an aluminum fin, however, the rise in temperature is significantly reduced, especially with the help of a cooling fan in the condenser section of the heat pipe. In the latter case, the temperature difference on the battery surface disappears.

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