ISSN 1975-8359(Print) / ISSN 2287-4364(Online)
The Transactions of the Korean Institute of Electrical Engineers Vol. 66, No. 12, pp. 1889~1894, 2017
http://doi.org/10.5370/KIEE.2017.66.12.1889

# 전기자동차 배터리팩 열관리시스템에서 상변화물질 적용에 관한 고찰

# A Study on the Application of Phase Change Material for Electric Vehicle Battery Thermal Management System using Dymola

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**Abstract** - Global automobile manufacturers are developing electric vehicles (EVs) to eliminate the pollutant emissions from internal combustion vehicles and to minimize fossil fuel consumptions for the future generations. However, EVs have a disadvantage of shorter traveling distance than that of conventional vehicles. To answer this shortfall, more batteries are installed in the EV to satisfy the consumer expectation for the driving range. However, as the energy capacity of the battery mounted in the EV increases, the amount of heat generated by each cell also increases. Naturally, a better battery thermal management system (BTMS) is required to control the temperature of the cells efficiently because the appropriate thermal environment of the cells greatly affects the power output from the battery pack. Typically, the BTMS is divided into an active and a passive system depending on the energy usage of the thermal management system. Heat exchange materials usually include gas and liquid, semiconductor devices and phase change material (PCM). In this study, an application of PCM for a BTMS was investigated to maintain an optimal battery operating temperature range by utilizing characteristics of a PCM, which can accumulate large amounts of latent heat. The system was modeled using Dymola from Dassault Systems, a multi-physics simulation tool. In order to compare the relative performance, the BTMS with the PCM and without the PCM were modeled and the same battery charge/discharge scenarios were simulated. Number of analysis were conducted to compare the battery cooling performance between the model with the aluminum case and PCM and the model with the aluminum case only.

**Key Words** : Electric vehicle, Battery pack, Battery thermal management system, Phase change material, Dymola

## 1. Introduction

Due to environmental pollution and depletion of fossil fuels, the use of internal combustion engines is being minimized more and more and the spread of electric vehicles is getting stronger and stronger mainly through initial government subsidy policies for environmentally friendly vehicles in many countries. However, because of the short driving range of typical electric vehicles, it is mainly limited to the urban driving. On top of that, its use is still suffering from the limited number of charging infrastructures and the long charging times. Accordingly, in order to overcome these shortcomings of the electric vehicle and meet the needs of consumers, electric vehicles equipped with a large-capacity battery pack comes out on the market more and more despite of high battery cost. According to the battery studies, the optimum operating temperature of lithium ion battery is around 35~40°C. However, as the battery pack of large capacity increases cell density, it generates heat above proper temperature range depending on charging/discharging situations. When the temperature of the battery is higher than the proper operating range, the reaction rate of the cathode material and the anode material increases, and the life of the battery may decreases. As a result, thermal runaway could be caused in some cases and potentially fire or explosion may occur. Therefore, a carefully designed battery thermal management system (BTMS) is certainly required.

In this paper, we simulated a battery thermal management system using natural convection, forced air cooling, and water cooling method along with the heat storage characteristics of PCM using Dymola. The feasibility of the battery thermal management system with the PCM was studied through the performance comparison of the various configurations.

PCM is a material that can absorb, store and release heat

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Received : October 22, 2017; Accepted : November 17, 2017

through phase change at a specific temperature [1]. It can maintain the temperature of the battery pack at a constant temperature due to the heat storage effect from phase change, and can utilize the energy more efficiently by reusing the wasted heat appropriately.

## 2. Simulation Model

Model creation and simulation were performed using Dymola from Dassault Systems, which has the advantage of modeling and simulating the dynamic behavior of a multi-physics system and the system interaction [2]. As shown in Fig. 1, the BTMS model consists of the module case model, the cooling model, and the battery model, which is the heat management subject. Each model is connected to a heat port.

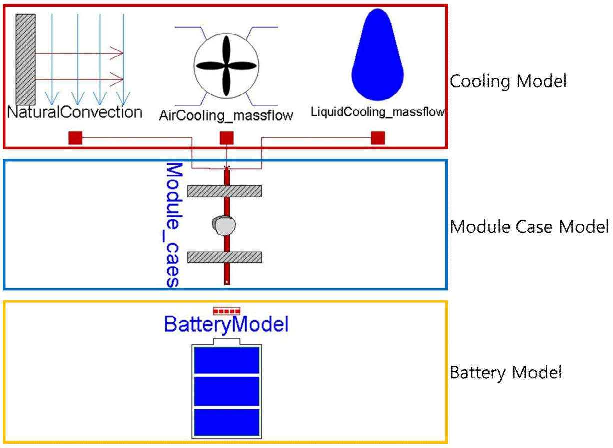


Fig. 1 Battery thermal management system model

### 2.1 Battery Model

We used a typical 3.7V, 2.1Ah cylindrical 18650 cell model [3]. OCV, SOC, SOH, internal resistance and heating characteristics are imported from the data file table in Dymola.

In the battery module [4], 24 cells are arranged side by side in the x and y directions to constitute a module of 6 in series and 4 in parallel, total voltage 22.2V, capacity 8.4Ah. Fig. 2 (a) shows the schematic of a battery model, a current cycle and a thermal port. Fig. 2 (b) depicts the size of the three-dimensional model. The electrical connections are arranged in series in the x-direction and are arranged in parallel at both ends of the direction. Fig. 2 (c) indicates the arrangement and electrical connection of the battery cells.

Thermal connection is radially symmetric and the inter-cell temperature transfer occurs. The module has a housing wall thickness with a specific material applied and inner-walls between the cells and they both affects the heat transfer.

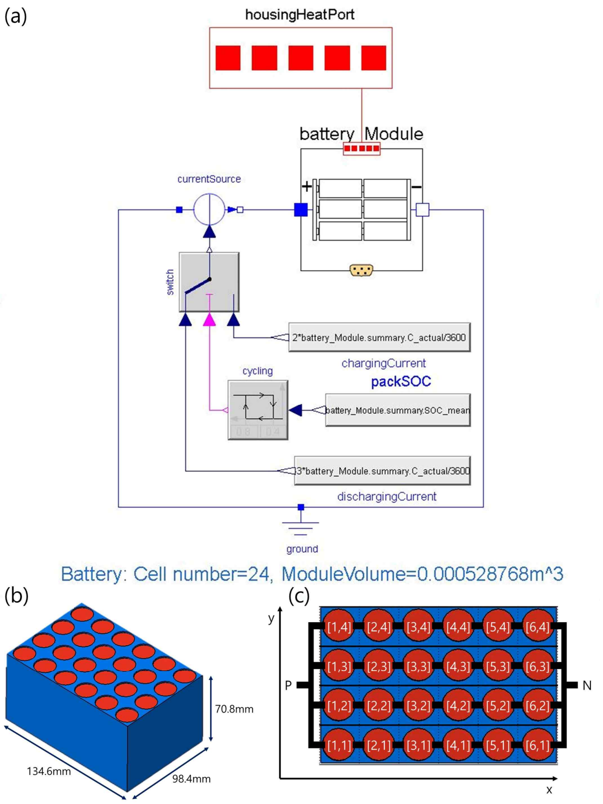


Fig. 2 (a) Battery model (b) Schematic Presentation of 6S4P Battery Module (c) Battery Cell Array

### 2.2 Module Case Models (Aluminum, PCM)

For the current study, two different battery modules were developed. First one is made with aluminum case only and the second one is made with aluminum and PCM. The material is a thermally conductive uniform material for the calculation of transient or steady state heat transfer. Numerical approximation of heat conduction is modeled as a transient state with no phase change, a transient state with phase change, and a steady state heat transfer [5].

In the absence of phase change, the transient heat flow rate is represented in Eq. (1) and for the case of phase change, the transient heat flow rate is represented in Eq. (2).

$$Q_T = \rho * c * (dT(s,t)/dt) \tag{1}$$

$$Q_{T.PCM} = \rho * (du(s,t)/dt) \tag{2}$$

The internal energy is expressed by Eq. (3) for three different states depending on the solid, phase change, and liquid temperature [6].

$$u = \begin{cases} c_{p_s} * T & , T \leq T_{Sol} \\ c_{p_s} * T * L_{heat} * \dfrac{2*(T - T_{Sol})}{T - T_{Sol}} & , T_{Sol} < T < T_{Liq} \\ c_{p_l} * T & , T \geq T_{Liq} \end{cases} \tag{3}$$

In Eq. (3), $T \leq T_{Sol}$ is the solid state temperature before the phase change, $T_{Sol} < T < T_{Liq}$ is the temperature of the phase change process, and $T \geq T_{Liq}$ is the liquid temperature after the phase change.

Finally, the steady state heat flow rate is represented by Eq. (4).

$$Q = A * k/x (T_a - T_b) \tag{4}$$

The detailed models of aluminum cooling only and the aluminum and PCM cooling is illustrated in Fig. 3. For the case of aluminum only, Eq.(1) and Eq.(4) are applied and for the case of aluminum with PCM, Eq.(1), Eq. (2), Eq. (3) and Eq.(4) are applied accordingly. Since the PCM has a low thermal conductivity, the certain amount of the aluminum material for the case is added to improve the cooling performance and this case is modeled in this study. The material property of PCM is selected based on the Li-ion battery performance at its best between the temperature of 35~40°C. In other words, it is favorable to have a PCM that has a melting point within the operating temperature range and has a small volume change during the phase change. An organic PCM material A36 from a company P that has no degradation and reversible coagulation/melting property, was selected for the current simulation study.

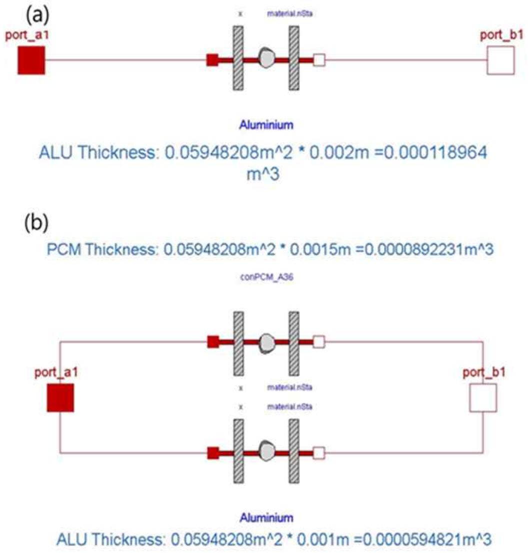


**Fig. 3** Module Case Models as Thermal Conductor: (a) Aluminum only and (b) Aluminum + PCM

Table 1 Material Properties of PCM and Aluminum

| Property | PCM_A36 | Aluminum |
|---|---|---|
| Density ($kg/m^3$) | 790 | 2700 |
| Specific heat capacity ($kJ/kg \cdot K$) | 2.37 | 0.8969 |
| Thermal conductivity ($W/m \cdot K$) | 0.18 | 237 |
| Latent heat ($kJ/kg$) | 217 | 396.9 |
| Phase change temp (°C) | 36 | 660.32 |

### 2.3 Cooling Models

A natural convective cooling, a forced air cooling and a liquid cooling method are modeled with appropriate boundary conditions, respectively. The exit temperature and the emitted heat are represented as follows by applying the energy conservation law [7].

$$T_{c.out} = T_b + (T_{c.in} - T_b) \times \exp\left(-h \times \frac{A}{\sum(\dot{m} \times C_{p.c})}\right) \tag{5}$$

$$Q_c = m \times C_{p.c} \times \dot{(}T_b - T_{c.out}) \tag{6}$$

As shown in Fig. 4(a), the air cooling model consists of an air inlet, a heat exchange volume, an air outlet and a convection model.

Heat exchange mainly depends on the volume flow rate. Forced convection is assumed for the forced air cooling model applying the relationship between the cooling area (one surface out of six surfaces) of the battery module and the air velocity.

$$Q_{flow} = A \times 7.8 \times \nu^{0.78} \tag{7}$$

The liquid cooling model consists of an air inlet, an air outlet, a radiator inlet, a radiator outlet, a heat exchanger volume, and a pump as depicted in Fig. 4(b) [8]. A radiator that exchanges heat between the air and the liquid uses a heat transfer effectiveness table that is mapped directly from the mass flow rate of both flow channels. Air and ethylene glycol 50% are used as heat exchange medium respectively for the cooling methods. The mass flow rates are assumed to be constant during the simulation accordingly for each method. The physical properties are shown in Table 2.

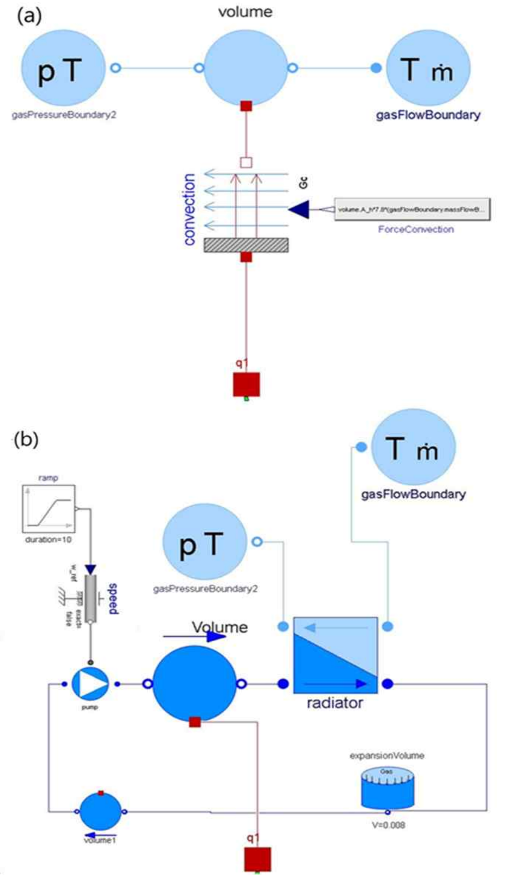


Fig. 4 (a) Air Cooling Model (b) Liquid Cooling Model

Table 2 Property of cooling medium

| Property | Air (30°C) | Ethylene Glycol 50% |
|---|---|---|
| Density ($kg/m^3$) | 1.149 | 1.146 |
| Specific heat capacity ($kJ/kg \cdot K$) | 1.005 | 1.005 |
| Thermal conductivity ($W/m \cdot K$) | 0.0264 | 0.2675 |

## 3. Simulation

### 3.1 Simulation condition

The initial condition of the battery module was assumed to be in thermal equilibrium with the external temperature (30°C) under the conditions of simulation [9]. To mimic the battery overload condition, 2 C-rate charging / discharging current was set and the initial SOC of 0.6 was selected. Charging started at SOC of 0.4 and discharging started at SOC of 0.8, and the simulation was performed for 3600 seconds. In Fig. 5, a graph of input current and output voltage is illustrated.

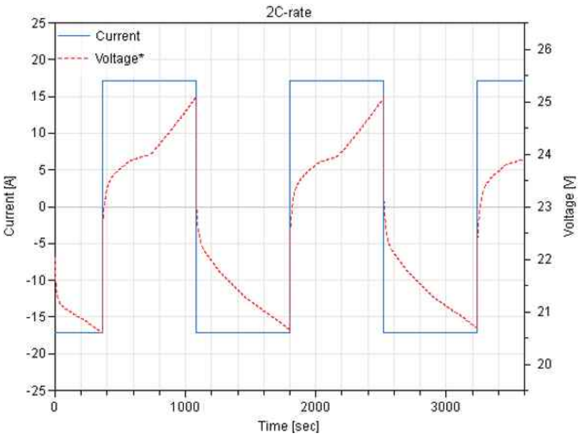


Fig. 5 2C charge/discharge current and output voltage

Three different cooling methods, namely a natural convection, a forced air cooling and a liquid cooling method, were applied for the two different module cases. Total of six cases were simulated to understand the heat problem under the 2-C charge / discharge condition. The air flow rate was set at 2 kg/s for both the forced air cooling and the liquid cooling and the liquid flow rate was set at 10 kg/s for the liquid cooling model. For all cases, the heat exchange area between the air and the one surface of the battery module where the natural/forced convection occurs is set at 0.01 $m^2$. The natural convection occurs on the other five surfaces of the battery module for all cases. The representative temperature of the battery was measured for each model. For 3 cases of PCM+aluminum module case, temperatures of PCM and aluminum were measured and graphed in the following figures. Table 3 shows the thickness, area and mass of PCM and Aluminum.

Table 3 Geometric Configuration of PCM+Aluminum Module Case and Aluminum Only Case

| Configuration | PCM + Aluminum | | Aluminum |
|---|---|---|---|
| | PCM | Aluminum | |
| Area ($m^2$) | 0.0594 | 0.0597 | 0.0597 |
| Thickness ($m$) | 0.0015 | 0.001 | 0.002 |
| Mass ($kg$) | 0.07 | 0.16 | 0.32 |
| Total mass ($kg$) | 0.23 | | 0.32 |

### 3.2 Simulation results and discussion

As shown in Fig. 6, the average temperature of the battery increased as the charge/discharge cycle repeat. It is clear that the PCM + aluminum case and the aluminum only case performed the appropriate thermal management to keep the battery temperature under and around 40˚C. In terms of the cooling performance in relative manner, the results showed that a PCM + aluminum with liquid cooling > PCM + aluminum with a forced air cooling > aluminum only with a liquid cooling > aluminum only with a forced air cooling > PCM + aluminum with a natural convection > aluminum only with a natural convection, as expected from the first. In terms of cooling medium, it is clear that the liquid cooling, which can transfer more heat due to the higher thermal conductivity, has better performance than air cooling and it successfully kept the battery temperature at 36.5˚C from 1000 seconds to 2600 seconds, approximately. Natural convection is slow in heat exchange with slow air motion and it was not adequate for the thermal management method. In terms of PCM module cases, the latent heat of the phase change process of PCM satisfactorily maintained the battery temperature at 35~40˚C, which is the optimum operating temperature of the lithium ion battery, from 800 seconds to 3600 seconds.

In summary, the aluminum only module case showed the consistent increase of the battery temperature while the PCM + aluminum module case displayed the certain period of time where the battery temperature was at fixed level. For the cases between the forced air cooling and the liquid cooling showed minimal difference during the phase change period of PCM and this clearly demonstrated the great possibility of successful BTMS implementation with the forced air cooling which is a lot less expensive compare to the liquid cooling method. Even with the natural convection case, the PCM + aluminum module case showed the glimpse of possibility of satisfactory BTMS implementation.

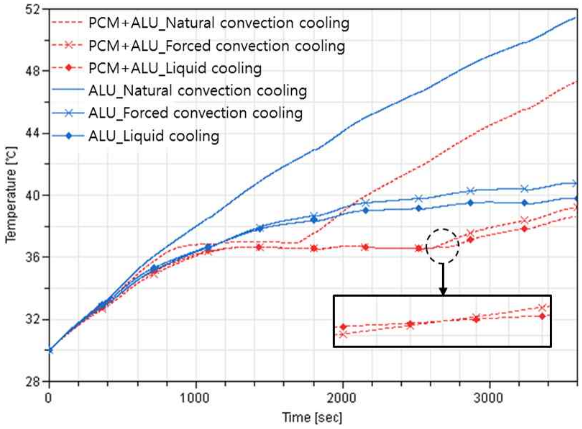


**Fig. 6.** Battery Module Temperature for All Six Cases

In Fig. 7, temperatures for all cases are displayed. The heat from the battery caused the aluminum temperature to rise instantaneously while the PCM temperature increased to the phase change temperature and then stayed constant due to the heat absorption with the phase change. This means that the length of the section storing the latent heat is determined by the amount of the PCM. This can be a good BTMS design point for the use of PCM since the typical driving distance per ride can be estimated or averaged from the consumer survey. With this in mind, the amount of PCM can be determined to produce the lowest cost BTMS system to cover most of the driving situations.

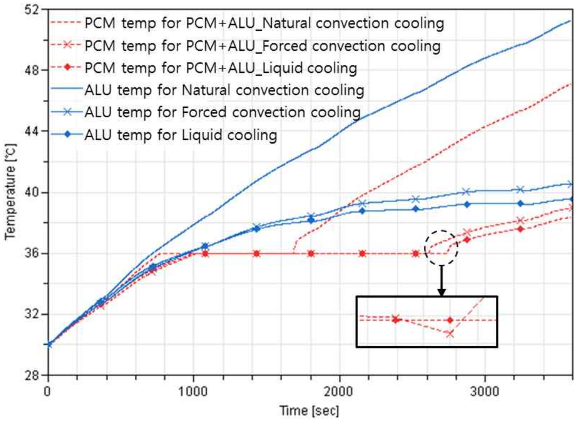


**Fig. 7** Module Case Temperature for All Six Cases

## 4. Conclusion

This study was conducted to apply the characteristics of PCM to the battery thermal management system. PCM and aluminum module case were used to simulate the characteristics and the following conclusions were drawn.

(1) It can delay the maximum temperature of battery due to the heat absorption by the PCM and it is expected that it will be able to maintain the optimum temperature of the battery if properly designed for the certain driving situation.

(2) With the PCM properly designed, the battery temperature may become constant at the optimal temperature for the battery operation and then the life cycle of the battery can be expected to last longer.

(3) We will build a control strategy of the BTMS through various driving cycles and build a model that can predict the amount of PCM to be used in the BTMS. Also, by conducting experiments, we will secure the reliability of the model based on actual battery charge/ discharge data.

## References

[1] Kim, M. J., Oh, M. H., and Yoon, Y. S., "Development of Automotive Battery Thermal Management Technology using PCM," Korea Automotive Technology Institute, 2015.

[2] Shin, J. H., Jeong, D. W., Yi, J. H. and Heo, S. J., "Modeling of Electric Vehicle Platform using Dymola," The Korean Society of Automotive Engineers, pp. 1747-1752, 2013.

[3] Battery Library by Dassault Systemes

[4] Kizilel, R., Sabbah, R., Selman, J. R., Al-Hallaj, S., "An Alternative Cooling System to Enhance the Safety of Li-ion Battery Packs," *Journal of Power Sources*, vol. 194, pp. 1105 – 1112, 2009.

[5] Teasung SNE Technical Support Team of FEA division, Heat Transfer Analysis: ANSYS ED CD. Teasung SNE, pp. 329-339, 2009.

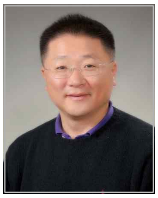
[6] Lee, D. G., Park, S. C., Jung, "D. Y., and Kang, C. D., "A Study on the Characteristic of Heat Transfer of PCM (Phase Change Material) at the Simultaneous Charging and Discharging Condition," Korean Journal of Air-Conditioning and Refrigeration Engineering, Vol. 28, No. 8, pp. 305-310, 2016.

[7] Han, J. Y., Kim, S. S., and Yu, S. S., "Lithium-ion Battery Thermal Management Two-Dimension Modeling for Hybrid Vehicles Thermal Management," The Korean Society of Automotive Engineers, pp. 2338-2343, 2012.

[8] Liquid Cooling Library, http://www.modelon.com

[9] Choi, J. W., Cho, G. Y., Park, J. H., Lim, J. H., Jeong, H. C., and Cha, S. W., "Effects of Battery Thermal Management System in EV Based on Simulation," The Korean Society of Automotive Engineers, pp. 2617-2621, 2011.

## 저 자 소 개



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