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PERFORMANCE MODELING OF A NOVEL “SMART” MAGNETIC PARTICLE-EMBEDDED PCM LAYER FOR THERMAL MANAGEMENT SYSTEMS

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ABSTRACT

Developing stable and environmentally friendly phase change materials (PCM) has been an active area of research due to many applications, such as industrial energy storage system, cooling/heating applications in buildings, and thermal management for electronics equipment as well as for batteries and photovoltaic modules. However, previous studies confirmed that most PCMs suffer a serious disadvantage of low thermal conductivity. A novel design of PCM layer is investigated here for thermal management application. The novel PCM layer is comprised of a PCM and magnetic particles coated on the shell. When a magnetic field is applied in the thermal management system, due to the magnetic of the particles, PCM layer are attached to the heat source to absorb heat, which significantly improves the heat transfer between PCM and the heat source. The melting temperature of the PCM and Curie temperature of the magnetic particles are carefully selected to optimize the performance and to ensure materials compatibility. A numerical study is conducted to reveal the heat transfer and performance improvement of the PCM layer.

1. INTRODUCTION

Thermal management systems have been widely applied in electronic components, batteries, and photovoltaic modules to enhance the performances or to avoid the failure of devices. Traditional thermal management technologies, e.g. active liquid cooling and air cooling, have the drawbacks such as low heat transfer rate, high initial and maintenance cost and the complexity of equipment, which constrain the implement of thermal management systems in such fields. To overcome the disadvantages of traditional thermal management technologies, it is desired to develop a novel thermal management system with rapid heat dissipation, compact size and light weight.

Lots of investigations were dedicated to implementing PCM on thermal management systems, since PCMs absorb/release a large quantity of latent heat when they change the phase (Tyagi et al. 2012; Karaman et al. 2011; Alkan et al. 2011; Zalba et al. 2003) . It showed that PCM based thermal management system is much lighter, compacter and higher efficiency comparing to the tradition systems (Mahmoud et al. 2013; Hallaj & Selman 2000; Ramandi et al. 2011), which has attracted an increasing interest in studying PCM based systems. Difference PCMs have been tested for different temperature applications, e.g. Paraffin (Cheng et al. 2010), Hexadecane (Darkwa & Zhou 2010), N-octadecane (Li et al. 2010), N-docosane (Sarı & Karaipekli 2007), Eicosane (Siahpush et al. 2008), and so on. However, most of PCM based thermal management systems suffer a serious disadvantage of low thermal conductivity, resulting in a low heat transfer rate. different designs of the PCM based thermal management systems are reported to enhance the heat transfer. Mahmoud et al., (Mahmoud et al. 2013) conducted a study to compare six types of heat sink designs. They discovered that heat transfer to PCM can be enhanced by increasing the number of fins, while the effect of heat sink design on heat dissipation rate is more significant at higher power levels. However, with a fixed volume, increasing the number of fins did not always lead to the thermal performance improvement.

Baby et al. (Baby & Balaji 2013; Baby & Balaji 2012) found that when the volume fraction of fins is 9%, the enhancement obtained from fins reaches the highest level. Further increase of the number of fins will degrade the performance of the thermal management due to the lack of PCM to utilize. Shaikh and Lafdi (Shaikh & Lafdi 2009) demonstrated heat sinks using 3-layer PCMs, which have different melting temperature. 3-layer PCMs design could provide greater energy storage and heat dissipation capacity than the single-layer design. Ramandi et al. (Ramandi et al. 2011) also reported the same advantage from their 2-layer PCMs design.

The PCM based passive thermal management systems are only suitable for the equipment working periodically, e.g. cell phone. Otherwise, the temperature keeps rising when the latent heat of PCMs is run out and heat is generated continuously. To apply PCM based thermal management systems to the continually working equipment, an extra heat dissipation technique must be combined into the thermal management systems. Alawadhi (Alawadhi 2009) designed a thermal management system by combining PCM with the forced air cooling. From his design, it was found that the PCM was effective in reducing the peak temperature by 13.7–26.8%, and successfully delaying the time to reach the peak temperature. Wang and Baldea (Wang & Baldea 2013) combined PCMs with active cooling as a hybrid cooling system for mobile devices. The results showed that the usage of PCMs could save the energy consumption of the active cooling.

In present work, a novel PCM, the “smart” magnetic particle-embedded PCM, is introduced, which is fabricated by PCM base with magnetic metal particles. The new PCM has the following advantages: 1) the magnetic metal particles could improve the apparent thermal conductivity of the PCM, which also has been reported by (Park et al. 2014); 2) the applied force (e.g. magnetic force) could significantly enhance the heat transfer between the surface and PCM; 3) a compact automatic control system is easily to realize using novel PCM. An active thermal management system is designed for electronic components, batteries, and photovoltaic modules, which could reach a much higher efficiency than the conventional PCM based thermal management system. Implementing the “smart” characteristic of the novel PCM, an automatic control of active system could be realized, which leads to a thermal management system with much compacter size and lighter weight. Then a numerical model is developed to simulate a battery pack with the active thermal management system based on the novel PCM. The modeling results show a great thermal management capacity of the new system.

2. MAGNETIC PARTICLE-EMBEDDED PCM

The temperature, at which the PCM goes phase change is called melting temperature (or freezing temperature). When a PCM reaches its melting temperature, it absorbs/releases a large quantity of latent heat when it undergoes phase change from solid state to liquid state or vice versa. During the process, the PCM temperature will be fixed to melting temperature. As the most important property of PCM, different PCMs have different melting temperatures, which are widely distributed along the working temperature of electronics equipment and batteries. Therefore, it is easy to find a suitable PCM for an implement of electronics equipment or batteries with a specific temperature.

On the other hand, the magnetic particle is made of magnetocaloric material (MCM), whose magnetic property depends on its Curies temperature. When the MCM temperature is lower than its Curies temperature, the MCM is a magnet. If a magnetic field is applied, it exists a magnetic force at the MCM. If the MCM temperature is higher than its Curies temperature, the MCM no longer has magnetic property. As a result, the magnetic force will disappear even if the MCM is put inside of a magnetic field. The Curies temperature of most pure metals are very high, e.g. 1043 K for iron and 1400 K for cobalt. However, with the development of marital science, alloys with low Curies temperatures have been successfully synthesized. The Curie temperature can be tuned by carefully adjusting the material composition of magnetic alloys. Presently such material in the range of −30 to 150°C is available on the market.

The novel “smart” magnetic particle-embedded PCM is comprised of a PCM base, and magnetic particles. Figure 1 is an example of a magnetic embedded PCM layer. It shows that a matrix of magnetic particles is immersed and fixed in the PCM layer. In the novel “smart” magnetic particle-embedded PCM, the melting temperature of the PCM and Curie temperature of the MCM are carefully selected to optimize the performance and to ensure compatibility. When the PCM is in solid phase and temperature is relatively low, the PCM layer sticks on the hot surface to absorb heat. After heat absorption, the PCM liquefies and the PCM layer is released from the hot surface automatically due to demagnetization. Another low temperature PCM layer will continue to stick on the hot surface to have a continuous heat removal processes.

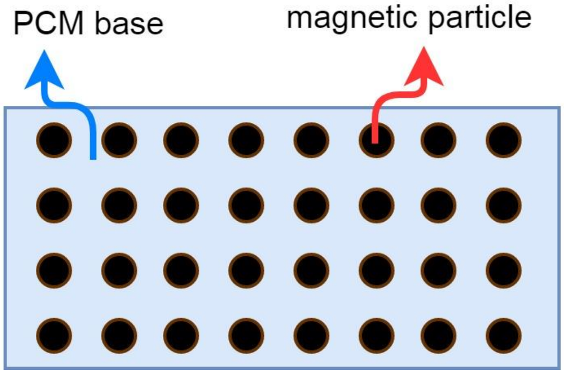

Figure 1 A schematic view of a layer of magnetic embedded PCM

3. WORKING PRINCIPLE OF A THERMAL MANAGEMENT SYSTEM BASED ON MAGNETIC PARTICLE-EMBEDDED PCM

Based on magnetic particle-embedded PCM, a thermal management system was designed for electric vehicles (EV) battery pack. As shown in Figure 2, the thermal management system is comprised of two layers of magnetic particle-embedded PCM locating at the two sides of the EV battery pack, in which the melting temperature of the PCM is matching the Curies temperature of the MCM particles. A magnetic field is applied to the system from permanent magnets, whose direction is normal to the EV battery pack side toward inside, so when the temperature of MCM in the PCM layers is lower than its Curies temperature, the magnetic force always plays the role to attract the PCM layers towards the battery pack. Each PCM layer connects to the EV battery pack using a spring system, in which the mechanic force from the springs is carefully calculated to fit the magnetic force. When the PCM temperature is lower than MCM Curie temperature and the PCM layer attaches the battery pack, the spring force is less than the magnetic force. When the PCM temperature is higher than MCM Curie temperature, the magnetic force disappears, so only spring force works, to push the PCM layer away from the battery surface.

Figure 2 indicates the working principle of the thermal management system. Initially, when both two PCM layers are in the low temperature, the temperatures of PCM and MCM are lower than the melting temperature and Curies temperature, respectively, in both PCM layers. PCM in the both layers are in solid state, while the magnetic force for both PCM layers direct to the battery pack. A switcher is used to block one of the PCM layer (PCM layer 2) and only allows PCM layer 1 to attach hot surface. After the PCM layer 1 absorbs enough heat, PCM phase has turned to liquid and MCM has been above its Curies temperature. As a result, magnetic force disappears, and the spring force will push the PCM layer releasing from the hot surface and attaching a heat exchanger surface, which will cool the PCM and MCM temperature to be lower than melting temperature and Curie temperature, respectively. Simultaneously, the switcher releases the PCM layer 2 and locks the PCM layer 1. PCM layer 2 will attach the hot surface as well to absorb the heat. After the PCM layer 2 absorbs enough heat, the spring force will push it to the heat exchanger since the PCM has melt and MCM has been above the Curie temperature. PCM layer 1 will be released from the heat exchanger and attach the hot surface to absorb heat again. The switchers of the PCM layer at the heat transfer side trigger by the attaching and releasing of the other PCM layer at the hot surface. The process will be repeated to realize an active and long term thermal management system for EV battery pack without any other controlling module.

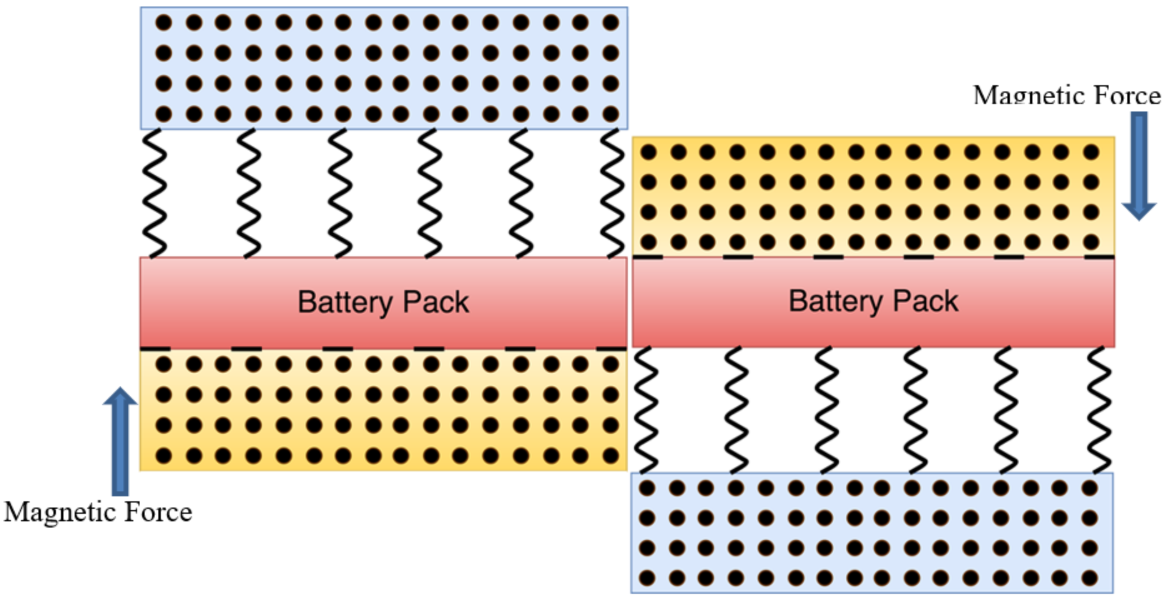

Figure 2 Working principle of the thermal management system

4. PRELIMINARY MODELING OF THE THERMAL MANAGEMENT SYSTEM BASED ON MAGNETIC PARTICLE-EMBEDDED PCM

To validate the effect of the thermal management system based on magnetic particle-embedded PCM, a preliminary model has been developed to reveal the performance of the concept design. This preliminary model only focuses on the validation the concept design, so the volume and thermal conductivity enhancement of magnetic particle are ignored in present model. The schematic view of the model is shown in Figure 3. A battery pack with size 0.44 m by 0.186 m is sandwiched by two layers of PCM with thickness of 2 mm, which are made of paraffin. The properties of the battery pack and paraffin are shown in table 2. The heat generation rate of the battery pack is assumed as 2000 W/m3 in present model. The governing equations include energy equation for heat transfer with both the sensible enthalpy and the latent heat, momentum equations for fluid flow driven by melting and solidification process, which can be found in the ANSYS FLUENT 12.0 User's Guide.

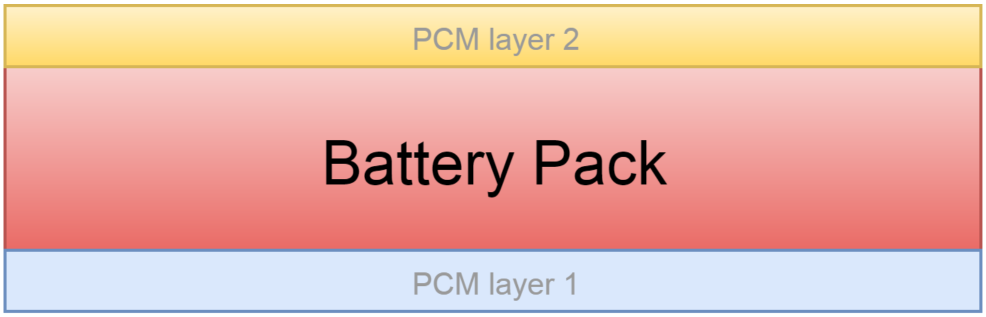

Figure 3 The schematic view of the simulation domain

The numerical result indicates that the in the 7 hours, it exists a dynamic balance from PCM melting time and battery pack temperature, which leads to a mechanism of self-adjustment of the thermal management system to control the battery pack temperature. As a result, the temperature of the battery pack does not exceed 305.5 K, which

is only 5 degrees above the initial temperature. It indicates that the PCM layers based thermal management system could provide a continue thermal management to the battery pack.

The initial temperature of all three regions is 300.5 K. To mimic the alternate charging/discharging process of both the slices of PCM, the boundary conditions changes alternately. When the PCM layer 1 is charging, the boundary between PCM layer 1 and battery pack is set to coupled, indicating that continue heat flux through the boundary. On the other hand, the boundary between PCM layer 2 and battery pack is set to be heat insolated. In addition, the temperature of PCM layer 2 is set back to its initial temperature 300.5 K by assuming fully discharging accomplished. Vice versa when the PCM layer 2 is charging. The charging/discharging process will be switched when charging PCM layer is fully charged (the PCM is fully liquefied). The commercial code, ANSYS/FLUENT was employed to conduct the simulations. The mesh is fine enough to guarantee the mesh independent of the simulation.

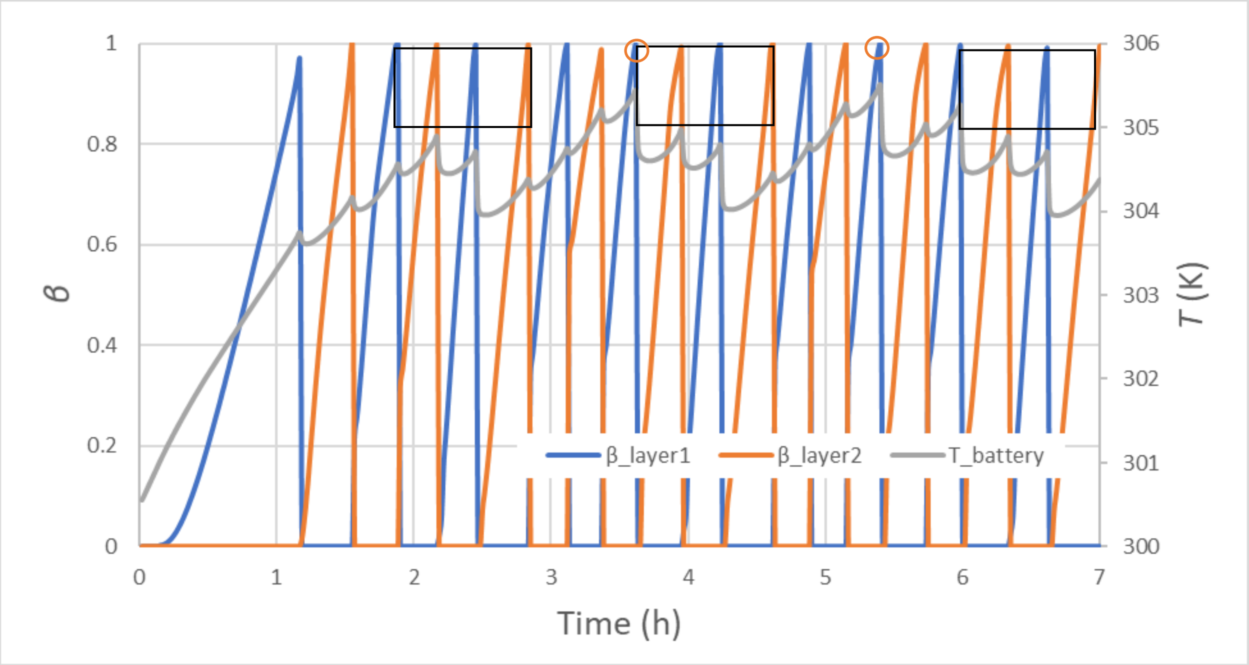

Figure 4 Temperature in battery pack and liquid fractions in two PCM layers VS time.

The simulation duration is 7 hours, which contains totally 10 cycles. Note that initially, PCM layer 1 is charged. Figure 4 depicts the average temperature of battery pack (green curve), and average liquid fractions for PCM layer 1 (blue curve) and 2 (red curve), respectively. During the 7 hours, initially, the battery pack temperature is low, leading to a slow melting speed of the PCM layers (about 20 minutes). As a result, the battery pack temperature keeps increasing to reach a peak temperature (about 305.5 K). The first peak happens in the 5th cycle (in red circle). To overcome the peak, the PCM layers melt every quickly (within 15 minutes), so after the peaks, the battery pack temperature drops dramatically. Then the battery pack temperature reaches a very low level, which delays the PCM melting speed again. When the PCM layers melt too slowly, the battery pack temperature recovers to the secondary peak at the 8th cycle (in red circle). Then due to the same mechanism, the battery pack temperature decreases again at the end of the 7 hours. From Figure 4, one also can discover a repeated shape (black rectangles) in the battery pack temperature curve. This “M” shape process of temperature change lasts two cycles, it records the PCM effects on the battery pack temperature from a high value to a low value and then back to high temperature. Corresponding the repeated battery pack temperature change, PCM melting speed also changes through the path “quick -> slow -> quick” simultaneously. Figure 5 shows the temperature distribution after 1, 3 and 7 hours in the battery pack. It indicates that temperature distributes pretty much evenly in the battery pack.

The numerical result indicates that the in the 7 hours, it exists a dynamic balance from PCM melting time and battery pack temperature, which leads to a mechanism of self-adjustment of the thermal management system to control the battery pack temperature. As a result, the temperature of the battery pack does not exceed 305.5 K, which is only 5 degrees above the initial temperature. It indicates that the PCM layers based thermal management system could provide a continue thermal management to the battery pack.

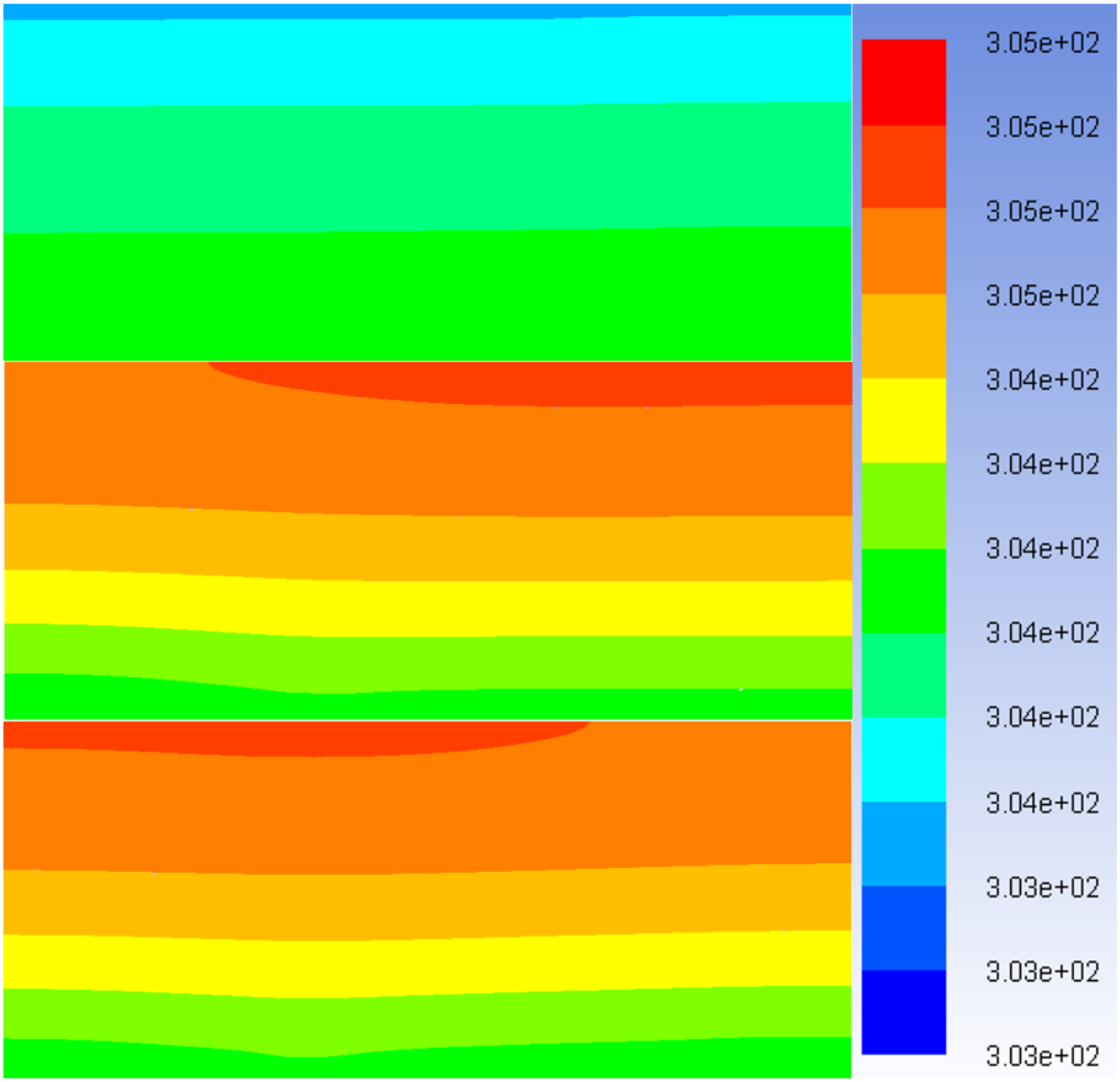

Figure 5 Temperature distribution in the battery pack after 1, 3 and 7 hours.

4. CONCLUSIONS

A novel "Smart" Magnetic Particle-embedded PCM Layer was introduced in present work, which is comprised of a PCM base, and magnetic particles. Some benefits could be obtained from this new material, including improvement of thermal conductivity due to the metal particles, enhancement of heat transfer rate to the contacting heat transfer and compactness of the control system due to the "smart" characteristic.

A thermal management system was designed based on magnetic particle-embedded PCM layer, in which a spring system was employed to balance the magnetic force to realize the automatic control.

To exam the effect of the designed thermal management system, a preliminary numerical model was developed. A dynamic balance from PCM melting time and battery pack temperature was observed from the modeling. The temperature of the battery pack does not exceed 305.5 K, which is only 5 degrees above the initial temperature. Consequently, the magnetic particle-embedded PCM layer based thermal management system could provide a continue thermal management to the battery pack.

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