Novel PCM Thermal Management Makes Li-ion Batteries a Viable Option for High Power and High Temperature Applications

Peter Tamburrino and Alan ElShafei
MicroSun Technologies, LLC
Lisle IL 60616

Riza Kizilel, Abdul Lateef, Mohammed M. Farid, and Said Al-Hallaj*
Center for Electrochemical Science and Engineering
Department of Chemical and Environmental Engineering
Illinois Institute of Technology
Chicago, IL 60616

ABSTRACT

Thermal Management of Li-ion batteries plays a significant role in large power applications by addressing the thermal safety in addition to improving the performance and extending the cycle life. The electrochemical performance of the Li-ion battery chemistry, charge acceptance, power and energy capability, cycle life and cost are very much affected by the operating temperature. One of the side effects of exposure to high temperature is accelerated capacity-fade as well as safety risks. Therefore, maintaining an optimized and continuously regulated temperature necessitates an efficient thermal management system in Li-ion battery pack applications.

Researchers at the Illinois Institute of Technology (IIT), Chicago, IL, have proposed and demonstrated successfully a passive thermal management system using phase change material (PCM) for Li-ion batteries for electric car and scooter applications. All Cell Technologies, LLC, an IIT spin off startup company, has licensed the PCM technology (US Patent No. 6,468,689) to MicroSun Technologies, LLC to develop high power Li-ion battery packs for a variety of portable and military applications. In this work, our team has developed a strategy for portable high power applications with a controlled thermal environment and has demonstrated successfully a passive thermal management system using PCM for Li-ion batteries to be used for extreme conditions, such as ambient temperature of 45 °C and discharge rate of 2.08 C-rate.

*Corresponding author: alhallaj@iit.edu, Tel: 312-567-5118

INTRODUCTION

Lithium ion cells have shown great promise for fulfilling high specific power and energy requirements in portable and transportation applications[1-4]. However, the electrochemical performances of Li-ion batteries are highly dependent on the operating temperature[5]. Today, many of the high power applications, which use Li-ion batteries as an energy source, suffer from the high temperature environment and/or the complexity of the cooling process[6].

Temperature of the Li-ion battery has to be regulated within the optimum window, failing of which can adversely affect the electrochemical performance of Li-ion cell charge acceptance, power and energy capability, reliability, cycle life, safety and cost[7-9].The operation of most lithium-ion cell is limited to a temperature of 20°C to 55°C, in which heat generation due to internal resistance and polarization is easily controllable by working with the voltage window and range of charge/discharge rates recommended by the manufacturers. Abuse conditions, such as an operation at high temperatures, steeply accelerate the accumulation of thermal energy in Li-ion cells.

The use of active air and liquid cooling adds considerable complexity and limits the full use of the battery's capacity[10]. However, thermal management using phase change material (PCM) eliminates to the need for the additional cooling systems and improves the power use. Battery packs can be maintained at an optimum temperature with proper thermal management, which can be optimized by integrating PCM in the battery[11]. PCM is capable of removing large quantities of heat due to its high latent heat of fusion. In principle, during discharge of the battery, the heat generated could be absorbed by the PCM integrated in between the cells in the battery module. It acts as a heat sink absorbing the heat generated by the battery. When the temperature of the module exceeds the melting point of the PCM, it starts to melt and the high latent heat of the PCM will prevent the battery temperature from rising sharply. This method of thermal management will eliminate the need for any kind of manifold, fans, or pumps, which are usually necessary in existing conventional thermal management systems. The rate of heat removal is improved by impregnating the PCM in a graphite matrix which leads to higher thermal conductivity.

MicroSun Technologies LLC and the Illinois Institute of Technology (IIT) have established a strategy for developing portable high power applications with a controlled thermal environment. This technology aims at minimizing the thermal problems associated with current rechargeable lithium battery technology. As of now, MicroSun has sampled, tested, and produced batteries that have been in the high 20s to low 30s voltage range with battery pack capacity in excess of 8.0 Ahr. The controlled thermal environment with PCM allowed lithium ion battery packs to be a viable alternative where it was not previously due to safety concerns. Utilizing the PCM technology allows the battery pack to operate safely under different ambient temperatures; from room temperature to 45 C and at different discharge rates, and to optimize the performance and the cycle life of the battery pack.

EXPERIMENTAL WORK

a) Preparation of Battery Packs

Graphite matrix filled with commercial PCM was prepared in 13.7cm x 5cm x 6.5 cm dimension. The matrix was drilled with holes of 18.2 mm diameter to place fourteen commercial Type 18650 Li-ion cells with 2.4 Ahr capacities. The module was integrated with safety circuits to regulate cells voltage and prevent over-charge, which can cause undesirable effects on the battery operation. All of the strings in the module were connected in 7Sx2P configuration (7 cells in series and 2 strings in parallel) with a safety circuit that was rated at required current and potential. The specifications of the pack are summarized in Table 1 and PCM/Graphite matrix is summarized in Table 2[12].

b) Testing

The 7Sx2P battery packs with and without PCM were assembled and tested at room temperature and 45°C at Microsun Technologies, LLC. Two thermocouples (K-type) were placed inside the pack; one at the center and the other one at the corner, to measure the temperature response at the two extreme locations in the pack. The battery pack was charged first in Galvanostatic mode at 0.7 C-rate with a voltage cut-off limit of

29.4 V and then in a Potentiostatic mode until the current drops to 100 mA. An hour resting period was then followed by 2.08C discharge rate until the voltage drops to 21.0 V after which a 2-hour discharge-resting period completed one full cycle. The experimental setup is shown in Figure 2.

Same battery packs were tested at 4.8 A 8.0 A, and 10 A discharge currents to study the effect of various discharge rates on the battery safety and performance.

RESULTS AND DISCUSSIONS

Figure 2 depicts the temperature profile of the battery packs without PCM at different discharge rates. At high discharge rates, high power battery packs were unable to complete discharge. When the discharge rate was 1C, the battery packs ran 56 min and utilized about 93% of its nominal capacity. On the other hand, at high discharge rates, such as 8A and 10A, the packs were able to run for only 20 and 12.7 min, respectively, and the experiments had to be stopped manually to protect the pack. These durations were less than the complete discharge periods.

It is clear that the heat generated at 1C during discharge not high enough to cause safety concerns at this condition and the temperature of the pack remained within the safety limit, which is below thermal runaway temperature, i.e. ~90 °C. This result was confirmed earlier using computer modeling and simulation work conducted by researchers at IIT[6, 11, 12]. Electrochemical reaction rates are enhanced and internal resistances are increased at high temperature. As a result rapid increase in temperature was observed during discharge due to the exothermic reactions in the cell. Thus, one of the main problems associated with these packs is that, at high discharge C-rates, they were unable to utilize high percentage of their nominal capacity due to safety risks. For example, at discharge rate of 10A, the utilized capacity of the pack without PCM was only 2.08 Ah which was less than 50% of the battery nominal capacity. The tests, which were run at 8A and 10A of discharge rates, were ended immediately when the temperature at the center of the pack reached 86 °C (see Figure 2). However, in many cases it is necessary to run the system at high discharge rates during the whole discharge period. Therefore, optimum operating temperature of the batteries is an important aspect of any thermal management system in order to utilize the full capacity of the battery packs.

The temperature profiles of the battery packs with PCM at different discharge rates are shown in Figure 3. The packs were tested at an ambient temperature of 30°C. As the discharge rate increases from 1C to 2.08C, the heat generated by the battery pack increased significantly causing cell temperature to increase fast. As shown in Figure 3, the PCM was capable of removing heat due to its high latent heat of fusion, while the high thermal conductivity of the graphite used to contain the PCM, insured high rate of the removal of heat and minimized the temperature distribution in the battery pack. PCM starts to melt when the temperature of the module exceeds the melting point of the PCM, and regulates the temperature around the melting point of the PCM, which is around 55 °C. This behavior can be seen clearly in Figure 4 as the change of slopes of the temperature-time curve happens during melting of the PCM. The utilized capacities at 4.8 A and 10 A discharge were 4.48 Ah and 4.28 Ah, respectively. These results clearly demonstrate that with PCM, it is possible to utilize the full capacity of the battery at high discharge rates even at elevated temperatures. At the end of the test, the packs were not affected by the heat and no disintegration was observed. Afterwards, the packs were cycled several times at normal operating conditions during which full capacity utilization was observed.

The difference in temperature profile between packs with and without PCM during 10 A discharge current is shown in Figure 4. The test without PCM could not be completed due to safety concerns. Therefore careful attention should be given to battery packs when attempting to use natural convection air cooling, as less than 50% of the nominal capacity can be achieved, especially if the pack is used at elevated ambient temperatures. On the other hand, packs with PCM utilized safely most of its stored capacity regardless of the discharge rate up to 10 A discharge current.

Figure 5 shows typical discharge voltage profiles at 1C and 2.08 C discharge rates for the 7Sx2P battery pack. There was a small difference in the utilized capacity at 1C or 2.08 C discharge-rates (i.e. 4.48 Ahr at 1C vs. 4.28 Ahr Ahr at 2.08 C). In other words, the percentage utilization of nominal capacity at 1 C and 2.08 C discharge rates were about 93% and 89%, respectively.

The 7Sx2P pack was also tested at elevated temperature, i.e. T=45°C. Figure 6 shows the temperature profile for the pack at 45 °C during 10 A current discharge with PCM compared with to the test at 30 °C at the same 10 A discharge current. The pack without PCM was not safe to operate after less than 13 minutes while the one with PCM was completely discharged safely even at and elevated temperature of 45 °C.

Figure 7 shows the temperature profile of a pack with two charge-discharge cycles at 45°C. The maximum temperature reached at the end of the discharge was 88 °C at the center of the pack. The small temperature difference (2-3 °C) between the center and the corner confirms the uniform distribution of PCM in the matrix and that the heat is conducted efficiently throughout the graphite matrix. The PCM integrated in the matrix removed the heat generated by the pack and kept the temperature within safety limits. The amount of PCM and its melting temperature had a significant effect on keeping the temperature of the battery pack within safety limits. The results also showed that with PCM thermal management about 90% of the nominal capacity was utilized even at extreme conditions with high discharge rate and high ambient temperature.

Finally, the operating voltage and current as a function of time for two cycles are shown in Figure 8 for extreme conditions, i.e. at 45°C and 2.08C discharge rate. No significant difference between the performances of the cell during the two cycles can be observed. Long term testing of battery cycling at these conditions is undergoing and will be the subject of future publications.

CONCLUSIONS

Test results conducted in this work clearly demonstrated the advantage of using the novel PCM thermal management systems over conventional active cooling systems. The compactness of the packs not only decreases the volume occupied by the packs and its associated complex cooling system, but also decreases the total weight for large power application.

From these results, it was demonstrated that the thermal stability of the pack requires controlled thermal management during fast discharge and high temperature applications (i.e. 10 A discharge and 45^{o}C temperature). To our best knowledge, this is the first time that such accomplishment was achieved using a passive thermal management system under such extreme conditions.

ACKNOWLEDGEMENT

Technical assistant by Rami Sabbah, Hisham Teymour, Panos Perzes, and the workshop staff at the Department of Chemical and Environmental Engineering at IIT is highly appreciated.

REFERENCES

1) Broussely M. and Archdale G., *Journal of Power Sources*, 136, 2004 386–394.

2) Colin A. V., Solid *State Ionics,* 134, 159-167, 2000.

3) Tarascon J.-M. and Armand M., *Nature*, 414, 359-367, 2001.

4) Brodd R. J., Bullock K. R., Leising R. A., Middaugh R. L., Miller J. R., Takeuchi E., *Journal of The Electrochemical Society*, 15, 3, K1-K11, 2004.

5) Fan J., *Journal of Power Sources,* 117, 170–178, 2003.

6) Khateeb S. A., Farid M. M., Selman J. R., Al-Hallaj S., *Journal of Power Sources*, 128, 292-307, 2004.

7) Venugopal R., “Characterization of thermal cut-off mechanism in prismatic lithium-ion batteries”, *Journal of Power Sources*, 101, 2, 231-237, 2003.

8) Ning G., Haran B., Popov B.N., “Capacity fade study of li-ion batteries cycled at high discharge rates”, *Journal of Power Sources*, 117, 1-2, 160-169, 2003.

9) Peseran A., “Battery Thermal models for hybrid vehicle simulations”, *Journal of Power Sources*, 110, 2, 377-382, 2002.

10) Peseran A., "Battery Thermal management in EV's and HEV's: Issues and Solutions", Presented at First annual Advanced Automobile Battery Conference, 2001, *http://www.ctts.nrel.gov/BTM/fctsht.html#2001*, Date accessed-February, 2005.

11) Al-Hallaj S., Selman J.R., "A novel thermal management system for electric vehicle batteries using phase-change material", *Journal of Electrochemical Society*, 147, 9, 3231-3236, 2000.

12) Mills A., Farid M.M., Al-Hallaj S. "Thermal conductivity enhancement of phase change materials using graphite matrix", *First Australasian Workshop on Phase Change Materials for Thermal Storage in Buildings and Other Applications.* Auckland, New Zealand, 12 December 2003.

Table 1. Specification of Battery Packs

Cell Type…………………………..	Type 18650
Cell Capacity………………………	2.4 amp-hour
Pack Operating Voltage …………	21.0 – 29.4 V
Max. Discharge…………………...	2.08 C-rate (10 A)
Max. Charge………………………	0.7 C-rate (3.36 A)
Ambient Temperature…………… (Under *up to 2.08 C discharge and suitable for dessert conditions*)	25 - 45 °C
Total weight of pack (lb)…………	~ 2.1 lbs

Table 2. Thermo-physical properties of PCM/Graphite composite [12]

Property	**Units**
Thermal Conductivity……………….	16.6 W/m.K
Latent Heat…………………………..	185 kJ/kg
Specific Heat ………………………...	1.98 kJ/kg.K
Bulk Density of composites.…….......	789 kg/m^3
Bulk Density of Graphite.……...........	210 kg/m^3

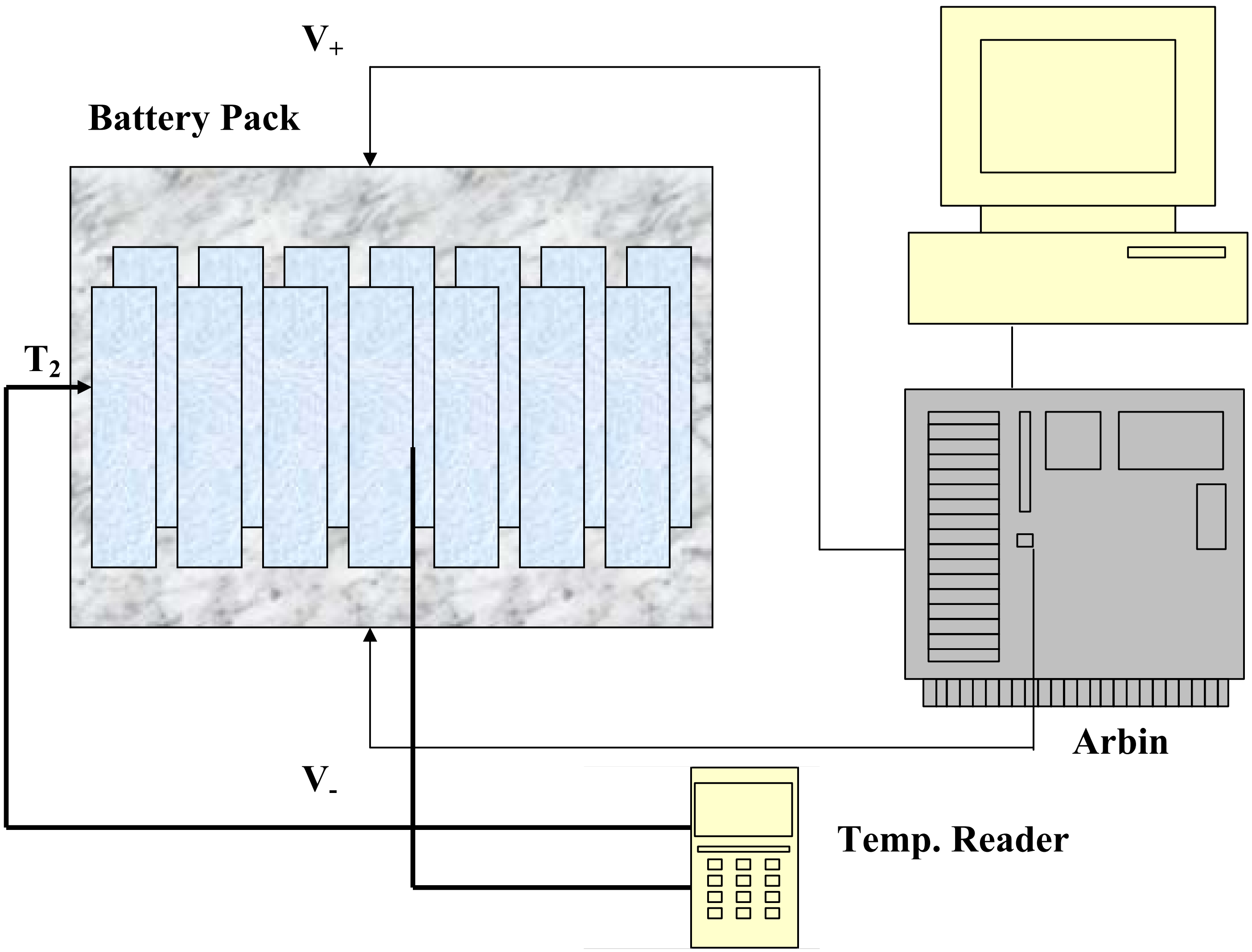

Figure 1. Schematic of experimental setup

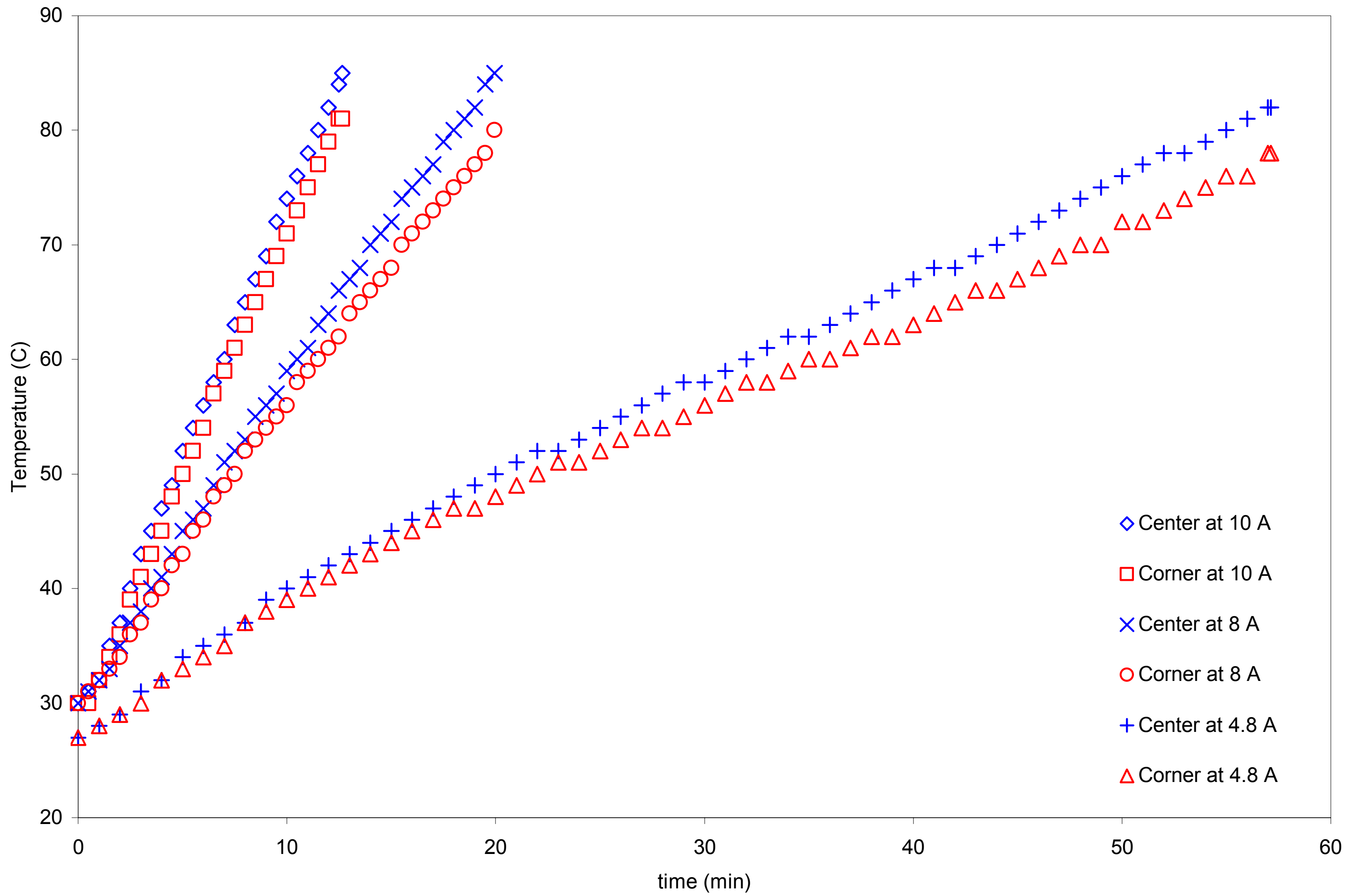

Figure 2. Temperature profile of packs without PCM at different discharge rates (T_{amb}=27-30 °C)

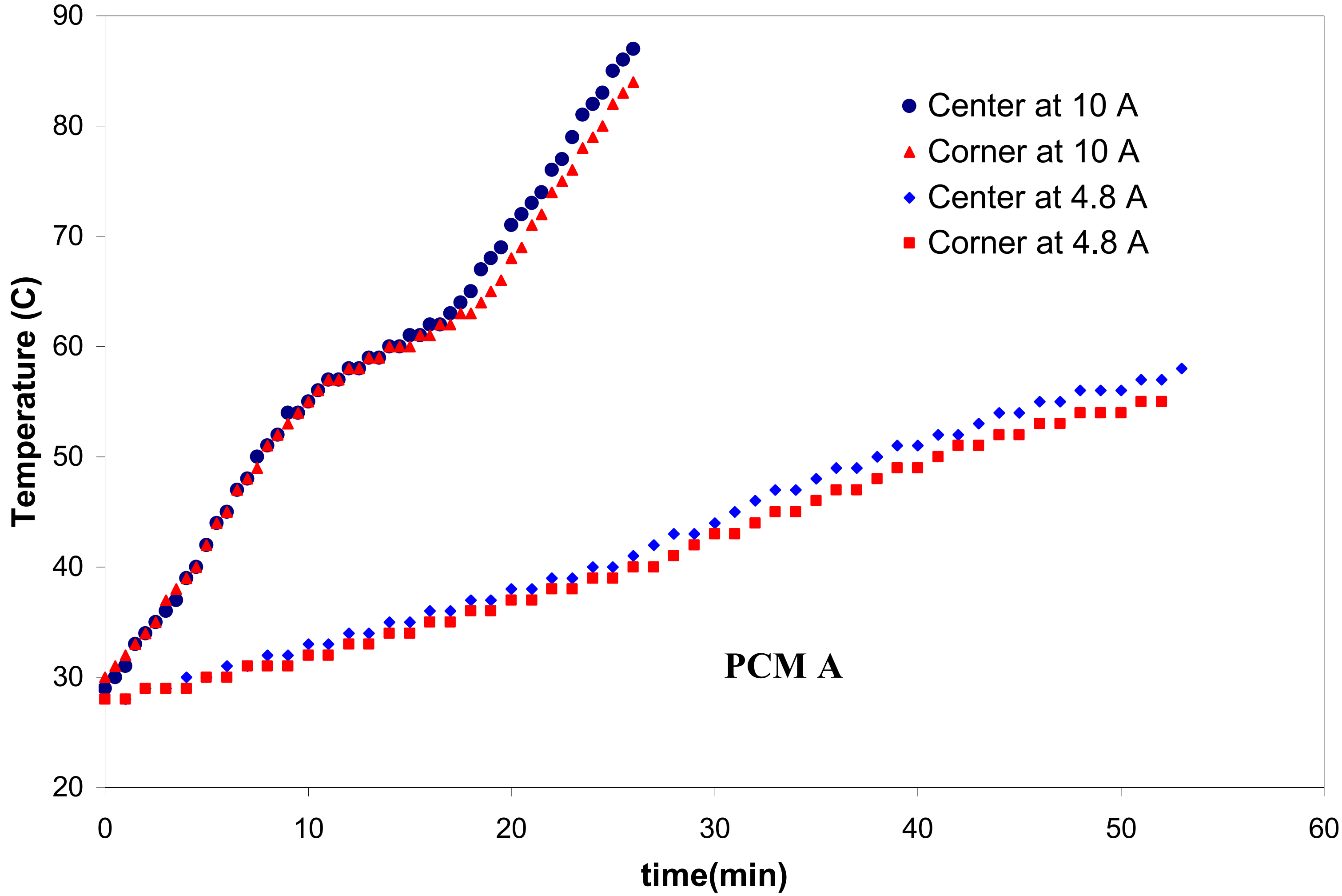

Figure 3. Temperature profile of packs with PCM at 4.8 and 10 A discharge currents

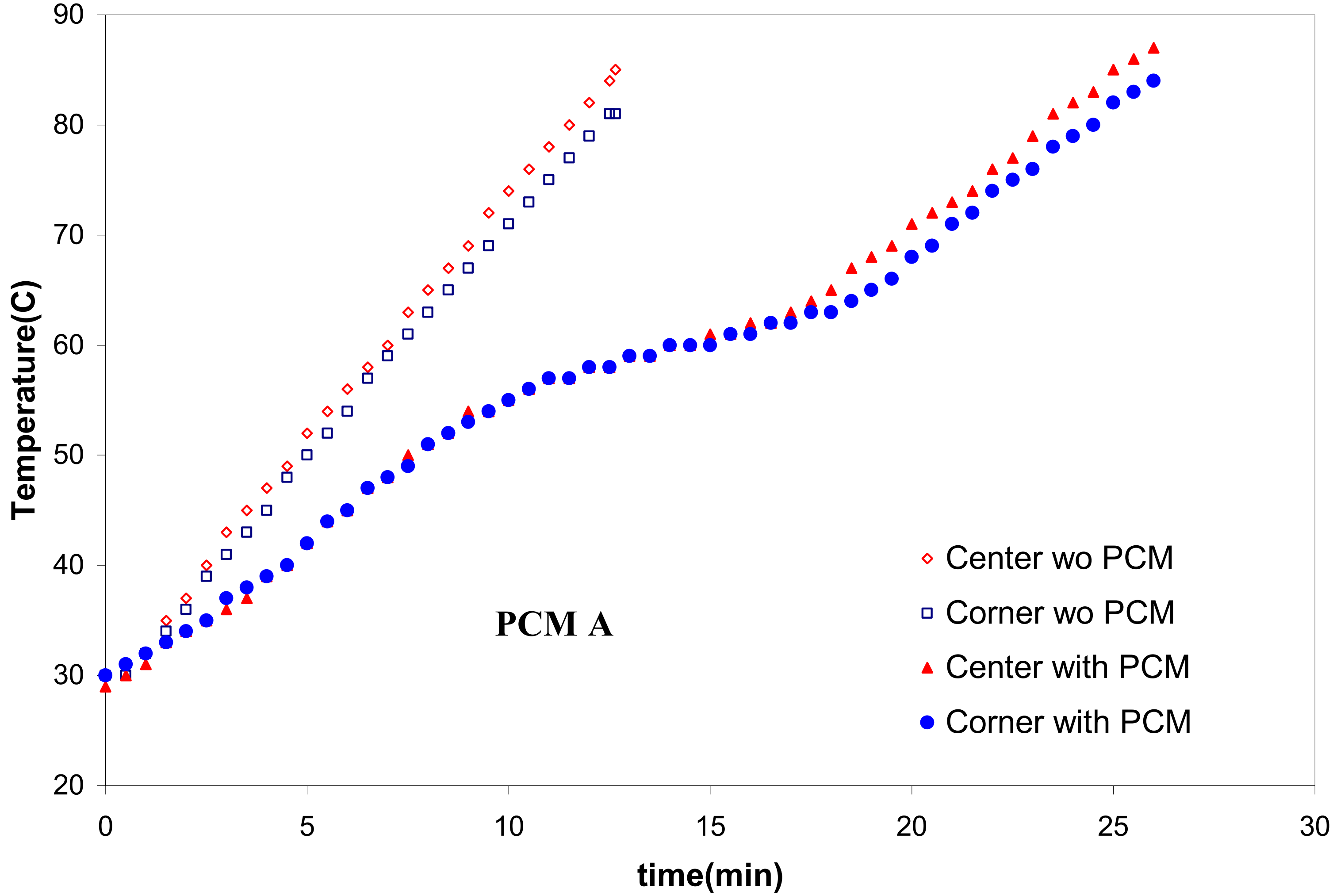

Figure 4. Temperature profile of packs with and w/o PCM during discharge at 10A

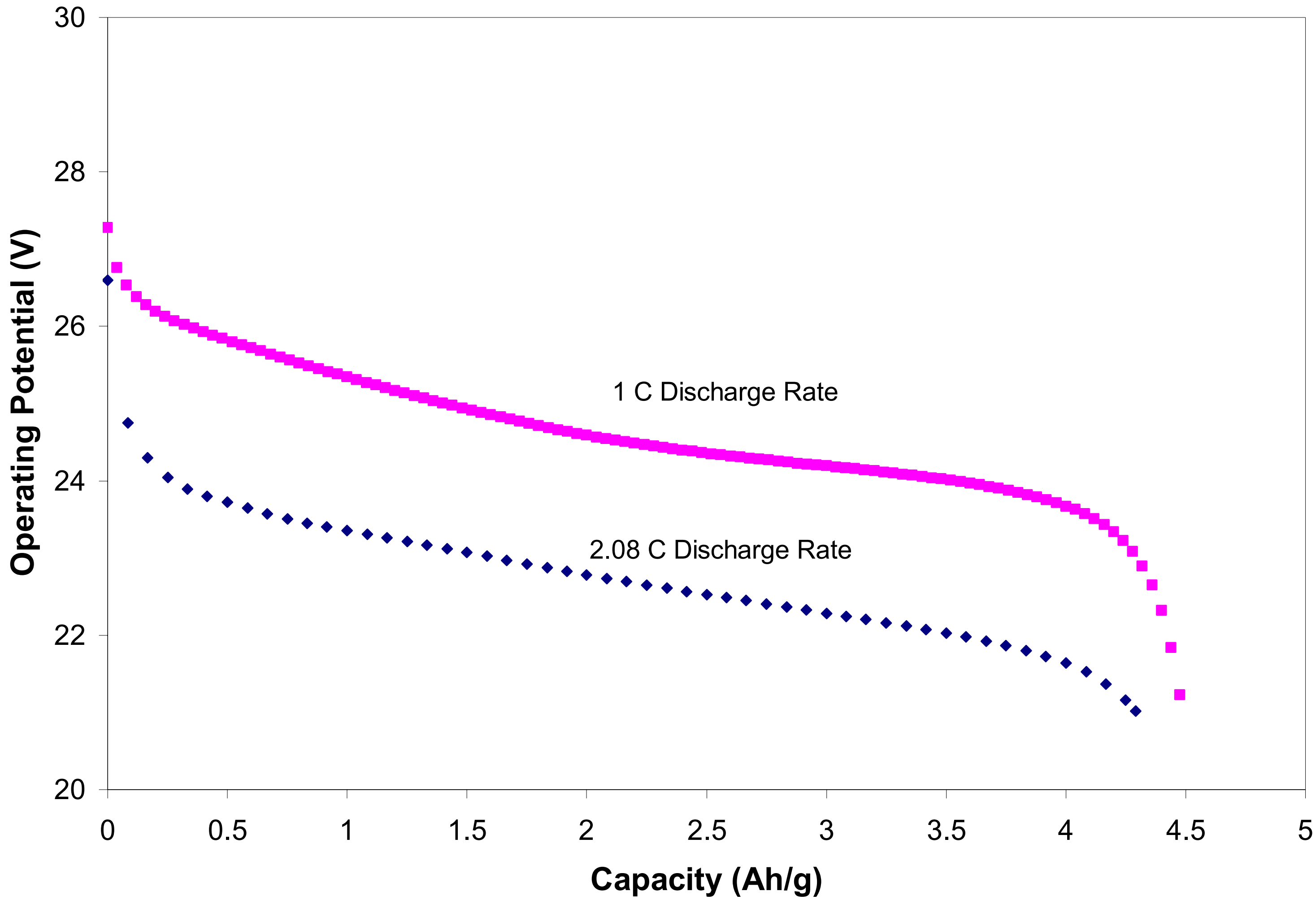

Figure 5. Voltage profile during discharge at 1C and 2.08C rates

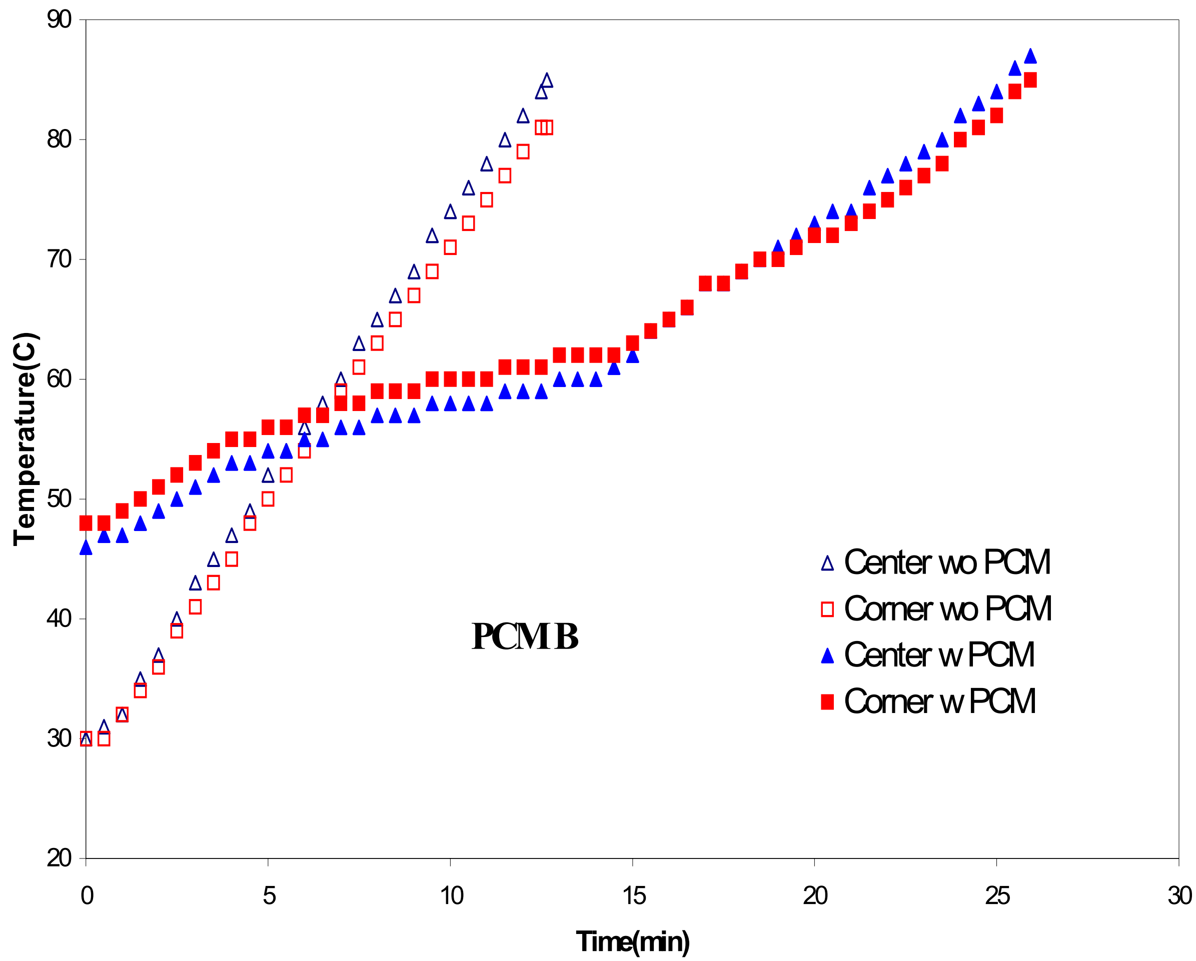

Figure 6. Temperature profile for the pack at 10 A discharge current, at 45 °C with PCM compared to 30 °C w/o PCM

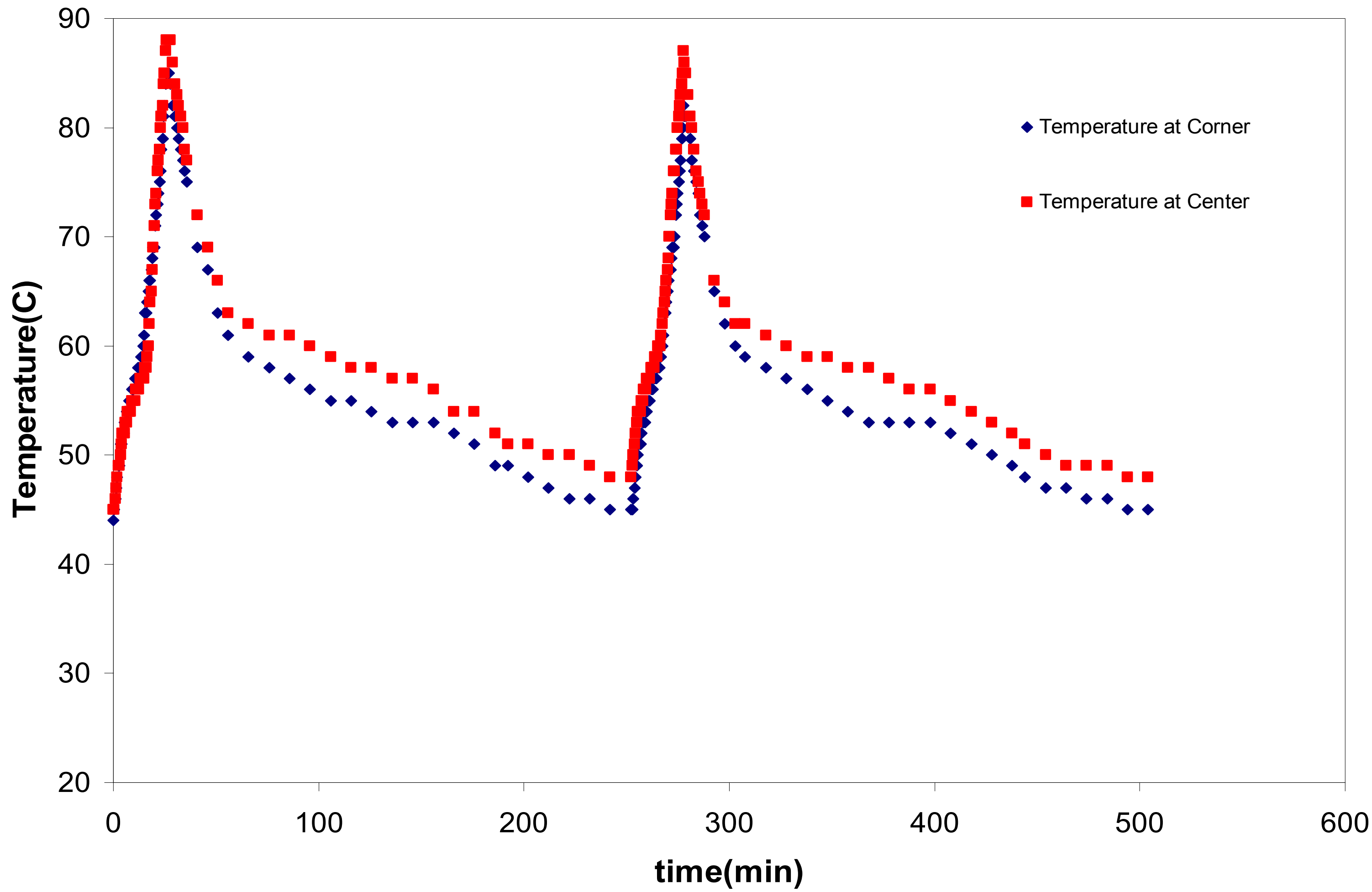

Figure 7. Temperature profile of the pack with PCM during cycling with 10A discharge and 45 °C ambient temperature

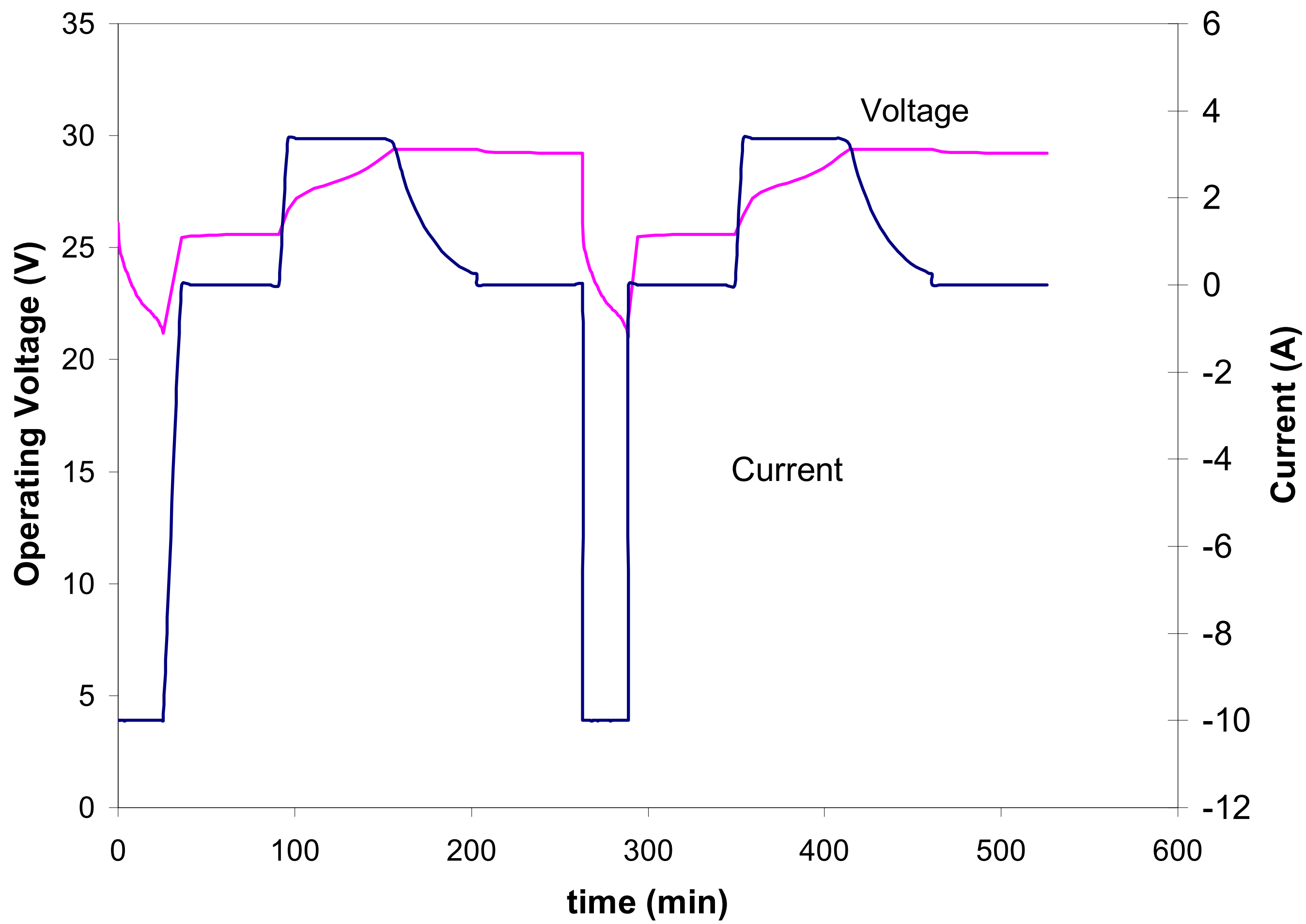

Figure 8. Voltage-Current profile for the battery pack during two cycles with PCM at 45°C ambient temperature