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Khan, Mohammad Rezwan; Kær, Søren Knudsen

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Investigation of Battery Heat Generation and Key Performance Indicator Efficiency using Isothermal Calorimeter

Mohammad Rezwan Khan[1], Søren Knudsen Kær[1]
[1]Department of Energy Technology, Pontoppidanstræde 101, Aalborg University, DK-9220 Aalborg, Denmark.
e-mail: rezwankhn@gmail.com;mrk@et.aau.dk

***Abstract*— In this experiment-based research, the performance and behaviour of a pouch type Li-ion battery cell are reported. The commercial test cell has a Lithium Titanate Oxide (LTO) based anode with 13Ah capacity. It is accomplished by measuring the evolution of surface temperature distribution, and the heat flux of the battery cell at the same time. Temperatures on the surface of the cell are measured using contact thermocouples, whereas, the heat flux is measured simultaneously by the isothermal calorimeter. This heat flux measurement is used for determining the heat generation inside the cell. Consequently, using the heat generation result the important performance constituent of the battery cell efficiency is calculated. Those are accomplished at different temperature levels (-5°C, 10°C, 25°C and 40°C) of continuous charge and discharge constant current rate (1C,2C,4C,8C,10C (maximum)). There is a significant change in heat generation in both charge and discharge events on different temperature and C-rate. The heat flux change level is non-linear. This nonlinear heat flux is responsible for the nonlinear change of efficiency in different C-rate in a particular temperature. The presented experimental technique is a very precise determination to profile the battery cell. The result of the research can be incorporated in constructing a precise datasheet for a battery cell which can assist the researchers, engineers, and different stakeholders to enhance different aspects of battery research.**

Keywords*— *Surface temperature; spatial distribution; Isothermal Calorimeter; Lithium Titanate Oxide (LTO), Battery thermal management, battery efficiency, heat Generation, key performance indicator (KPI), battery behaviour.

I. Introduction

Different operating conditions may impose non-uniformity of temperature over the surface of a battery. Temperature excursions and non-uniformity of the temperature are observed when a battery is exposed to high power charge and discharge [1]. Obviously, it is a consequence of heat generation inside the battery cell. The battery is an electrochemical device. It signifies different electrochemical states during corresponding operating condition. The thermodynamics of lithium-ion cells are complicated by the presence of liquid electrolyte mixtures as well as single-phase and multiphase solids. Those phenomena represent complex ecosystems that stay inside a battery cell. Heat generation is a consequence from mixing and phase change, as well as the main electrochemical reactions [2]. The phenomenon is observable in a wide variety of application from stationary storage to electro-mobility application [3, 4]. Different operating conditions (e.g., unbalanced state of charge (SoC) [5, 6], different ageing conditions [7, 8], flow rates [9, 10], etc.) may affect battery cells' performance. Those are the very important influential parameters to cause the thermal gradients. Additionally, heat generation and the maximal increase of temperature inside the cell has a correlation [11, 12]. Reliable prediction of temperature profiles of individual cells, and of a battery system as a whole requires first of all accurate level measurement of the total heat generation rate. Inevitably identifying and understanding those behaviours (heat generation) and related performance indicator (efficiency) are very important to ensure the appropriate operation of the battery. Thus, measurements of temperature rise and the heat dissipation or absorption of battery cells are essential. Those are accomplished using available state of the art sensors for measuring the required characteristics. After that knowledge of the individual cell can give a good indication of the behaviour inside a pack [13]. Likewise, by assuring these, the optimal operation of the battery cell is possible to achieve [14].

The non-uniform heating behaviour and thermal gradients are observed because the battery cell is made up of non-homogeneous materials. Depending on different operating condition, the battery cell shows a different heating response [15]. A practical implication of the problem is that a limited number of temperature measuring sensors can be utilized due to cost and other practical constraints for instance that the surface area of the battery is inaccessible. It is evident that understanding the temperature evolution and finding key performance indicator i.e. efficiency of the battery is very important.It assists in choosing the battery cell for a specific application. Both of them can provide very valuable information. Furthermore, the results can be used to build a thermal model. Moreover, the research can assist in the design of different cooling options. Additionally, it can lead to choosing the optimal battery cell for desired application.

The research is a continuation of the established experimental methodology. The detailed experimental setup, as well as corresponding materials and equipment, can be found in [16]. In the paper, Section II presents the methodology. The experimental procedures with necessary apparatuses i.e. thermocouples, calorimeter, and temperature controller are described in Section III. It also associates the data acquisition platform, calibration of the corresponding instrument and the final setup of the experiment. The analysis of the data and the relevant discussions are detailed in Section IV. The evaluation of the cell thermal behaviour and the experimental at different operating conditions are described and discussed in Section IV. At last, the conclusions of this work are provided in Section V.

II. Methodology

The profiling of the battery corresponds to the recording and plotting of the heat generation and efficiency values at different operating condition (dissimilar current rate and diverse temperature). It is accomplished through full charge and discharge cycle in respective operating condition. The principle is to measure them simultaneously in a calorimeter chamber in an inert atmosphere so that external and ambience based influencing factors are avoided. These make the achieved results comparable.

The primary thermal attributes of the battery cell are measured. The isothermal calorimeter is employed to measure the raw heat flux from the battery cell. Besides, the surface temperature is measured alongside using contact thermocouples. Those are placed at different spots over the surface of the battery. Those temperatures are measured to track and trace the thermal gradients on the surface of the battery. It should be noted that isothermal calorimetric measurement represents the global heat generation flux inside the cell for the specific current profile and temperature.

Using the raw heat flux measurement as measured by isothermal calorimeter the heat generation inside the cell is determined. The electrical input is determined by the area of the electrical power input. The area enclosed by calorimetric heat flux area correspond the loss incurred due to the heat generation inside the battery cell. Using the input electric power and heat generation inside the battery that corresponds loss, efficiency is determined.

III. Experimental Setup

Using the experimental framework, the performance indicator efficiency and heat generation of a cell is measured. The battery cell temperature measurement is made up of five type K thermocouples.

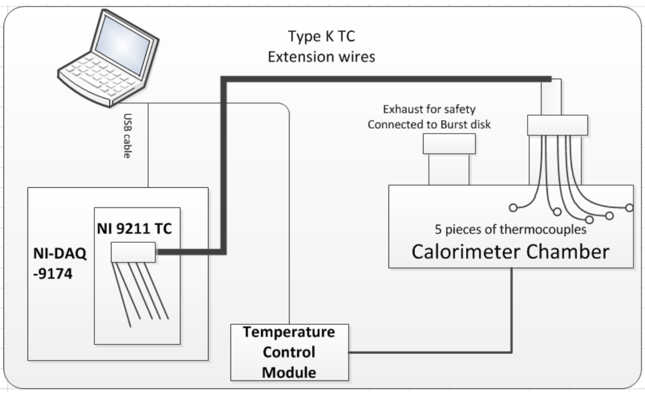

Fig. 1. Schematics of thermal experiment setup.

Those contact thermocouples are mounted inside the battery cell in the calorimeter chamber with temperature control. The experimental setup is controlled by graphical user interface (GUI) of LabVIEW front panel interface. The used isothermal battery calorimeter Netzsch® IBC 284 is a robust instrument designed for the accurate measurement of heat flux generated by batteries while being charged or discharged under isothermal conditions. The PTC10 Programmable Temperature Controller manufactured by the Stanford Research System™ is employed. It is a modular system that is used for temperature control of the calorimetric experiment. The schematics of the experimental setup is shown in Fig.1.

IV. Results

The variation of heat generation, total energy loss, efficiency between at different charging and discharging (Cycling) at a different temperature is found experimentally i.e. from 100% SoC to 0% SoC and tabulated in TABLE I. Detailed calibration and experimental procedures are described in [16].

A. Heat Generation inside the cell

Since during full charge and discharge corresponds to different peaks, for the given current rate, a separate heat calculation is pursued, so the peaks (refer to Fig. 2) depict heat during battery charging and discharging respectively. Heat flux area represents the integration of the measured raw heat sensor data collected by a calorimeter. To directly calculate heat flux from the raw heat flux measurement, it is needed to set up the left limit of the area, the instance just before the required experiment (for example discharge at 4C-rate) starts. The heat is generated and released from the cell during both charge and discharge. If the heat generated in the cell is not removed, so it is stored. This will raise the temperature of the cell.

The amount of heat generation is determined by the enclosed area by heat flux divided by the of total experiment time (the difference between End time, $t_f$and Start time, t_s). Within this procedure, average heat generation over the event (charge or discharge) is accomplished. The value is used to find the total heat loss by the battery cell on the defined operation.

The heat generation can be found by Eqn (1):

$$\text{Heat generation} = \frac{\text{Heat Flux-Area}}{t_f - t_s} \tag{1}$$

B. Determination of battery efficiency

The next step is to measure battery efficiency. It is achieved by determining the absolute power area i.e. input absorbed power during discharge or extracted output power while in charge operation. Heat flux area is subtracted from the absolute electrical power area and normalised by the absolute power area to find the battery efficiency. It should be noted that efficiency is given by the difference between electrical input and the loss incurred inside the battery normalised by the electrical input. More specifically, Eqn. (2) is used for determining the efficiency:

$$\eta = \frac{\text{Absolute Power Area} - \text{Heat Flux Area}}{\text{Absolute Power Area}} \tag{2}$$

The post-processing analysis of the data is accomplished using the Netzsch® Proteus software as shown in Fig. 2.

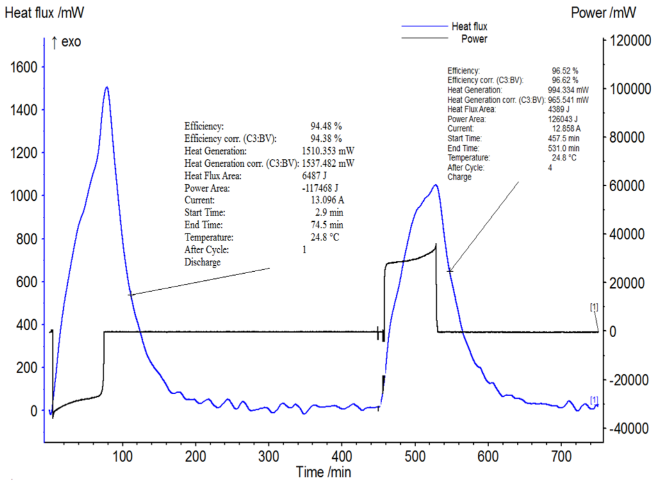

Fig. 2. Analysis of the heat flux to find the heat efficiency and heat generation

C. Variation Heat Generation in different temperature

The evolution of heat flux at -5°C, 10°C, 25°C and 40°C temperature levels are shown in Fig. 3, Fig. 4, Fig. 5 and Fig. 6 respectively. The result of the analysis is tabulated in TABLE I.

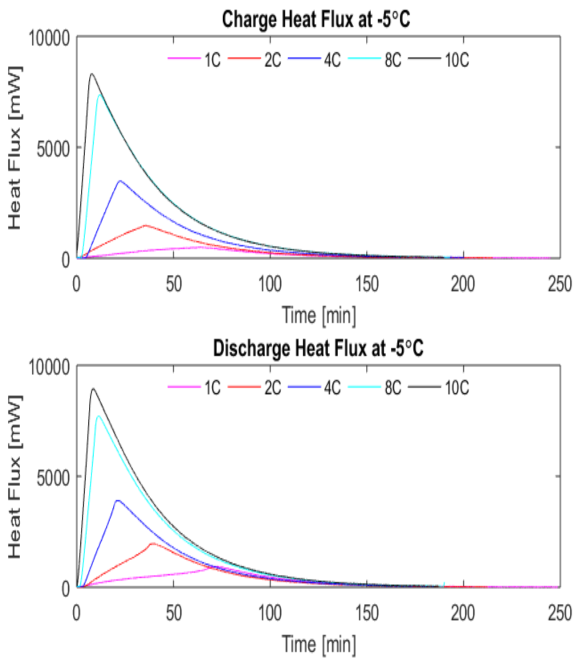

Fig. 3. The evolution of the heat flux -5°C in different current rate.

The analysis shows (as shown in TABLE I. , Fig. 3, Fig. 4, Fig. 5, Fig. 6 and Fig. 8), there is a significant rise in heat generation in both charge and discharge events on diverse temperature and C-rate. Heat flux levels at -5°C and 40°C shows same heating rate behaviour (Refer to Fig. 8). Besides, Refer to Fig. 4 and Fig. 8, 10°C shows a higher heat flux. However, refer to Fig. 5 and Fig. 8, 25°C provides the lowest amount of heat generation. To observe the effect of the current rate on heat flux measurement, the heat flux magnitude is compared, and it is found that the magnitude of the heat flux 8-10 times higher from 1C charge-discharge rate to 8C charge-discharge rate. However, C-rate and temperature dependency shows different behaviour. In discharge event, there is a dramatic increase in heat generation and corresponding heat loss for -5°C, 10°C and 40°C.

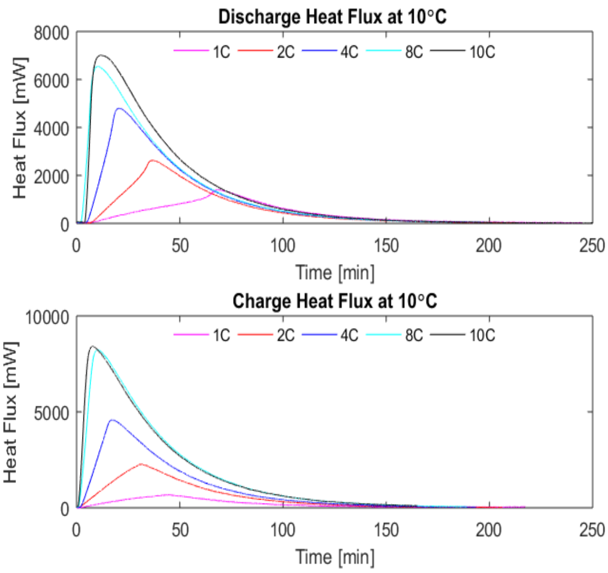

Fig. 4. The evolution of the heat flux 10°C in different current rate.

However, in 25°C discharge event, there is a lower increase in heat generation and corresponding heat loss (refer to Fig. 5).

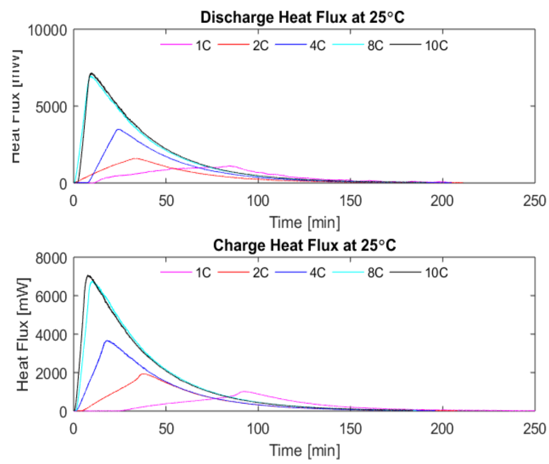

Fig. 5. The evolution of the heat flux 25°C in different current rate.

A common observation is that for LTO battery cell charging produces different heat flux than that produced by discharging. Besides at higher current rate, there is a non-linear increase in heat flux.

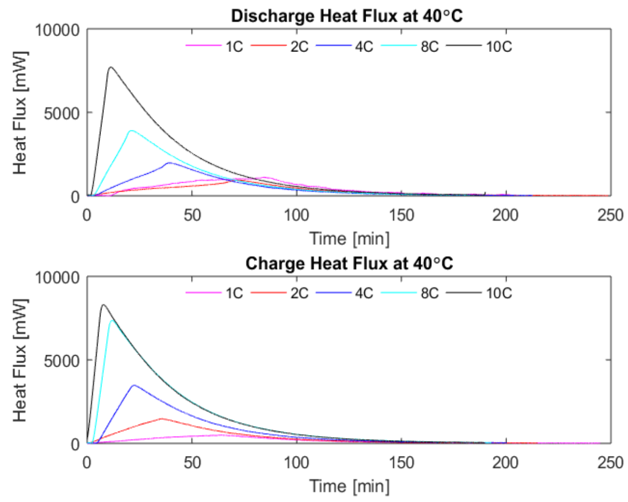

Fig. 6. The evolution of the heat flux 40°C in different current rate.

D. Variation of efficiency in different temperature

The phenomenon of increasing heat loss amount is responsible for the steep decrease in efficiency especially in a discharge case. However, in charge case, there is only a moderate decrease in the efficiency. The effect of charge-discharge events in different temperature at the different current rate is illustrated in Fig. 7 and tabulated in TABLE I.

The heat flux change level is non-linear. This nonlinear heat flux is responsible for the nonlinear change of efficiency in different C-rate in a particular temperature (Refer to Fig. 7). In 10°C discharge case efficiency of low C-rate is higher than that of high C-rate. In numeric percentage, it changes from 92.91% (at low C-rate) to 65.87% (at high C-rate). While in the corresponding 10°C charge case, efficiency at low C-rate drops below than that of high C-rate i.e. from 96.92% to 80.76%. But 25°C shows a little bit different behavior.

In 25°C discharge case efficiency of low C-rate is higher than that of high C-rate. In numeric percentage, it changes from 96.45% (at low C-rate) to 78.62% (at high C-rate). While the corresponding 10°C charge case, efficiency at low C-rate drops below than that of high C-rate i.e. from 96.52% to 85.13%. So the change of the efficiency is non-uniform in different temperature and different C-rate. However, it should be noted that the efficiency performance levels may be of the same order of magnitude of the variation shown by the both -5°C and 40°C levels. The efficiency change levels are non-linear in both different C-rate and temperature levels.

Battery cell efficiency is a key performance indicator. It can assist to choose the best design parameter efficiency among different battery cell options. So it helps to attain the optimal design of a specific application. This is particularly critical for designing a pack that is made up of the same type of battery cells since a battery user (for instance EV manufacturers) has to buy a bulk amount of batteries for the specific application. Choosing the appropriate battery cell with a right efficiency can aid to avoid different uncertainties for instance: application failure and non-efficient sub-standard performance. It positions as a very promising parameter because it is crucial to choose with an appropriate efficiency so that an optimal battery cell inside an application can be chosen from different candidate options. Evaluating thermal management of batteries in the light of the developed measurement framework will lead to the verifiable and decisive conclusion that the key performance indicator efficiency is one of the choice parameters to select from different options. The actual choice depends on different stakeholders represents the best or optimal performance.

The results of the experimental framework propose and delivers an important parameter to be included in the datasheet of a battery cell that contains the key performance indicators information. The inclusion of these values inside a datasheet will enhance the current datasheet's acceptability. Manufacturers and stake holders can reap the benefit of the inclusion of these key performance values. Awareness of the key performance indicators helps the stakeholders to choose the optimum battery cell that is very significant for designing an appropriate design of an application.

V. CONCLUSIONS AND FUTURE WORK

The calorimetric experiments are used to determine efficiency and heat generation for the LTO battery cell. Both of them are critical performance indicators for the battery operation. Evidently, the magnitude of heat generation is associated with the corresponding current rate. Particularly this fact assists on the thermal modelling. For this purpose, the corresponding heat generation in function of battery current rate can be used as input as the heat source of a model. This can be conveniently accomplished by a lookup table of heat rate versus applied current profile. Furthermore, the surface temperatures that are measured in this research work can be used for the validation of the thermal model of the battery. Additionally, large cells can be tested safely and efficiently with the electro-thermal testing platform as established in the paper. The experimental platform has an enormous impact on the life time profiling of a battery cell. Using this established methodology, the extensive full lifetime profile of a battery cell for instance: efficiency, heat generation at different current rates, temperatures (representing the diverse operating condition of charge and discharge) in different lifecycle states can be found. Using these established profiling methodology, the extensive full lifetime modelling can be accomplished. The results will lead to a more profound understanding the efficiency and heat generation behavior of the specific battery cell for a particular application.

TABLE I. SUMMARY OF THE CALORIMETRIC RESULT

Temperature	Event	Discharge					Charge				
	Current Rate	***1C***	***2C***	***4C***	***8C***	***10C(max)***	***1C***	***2C***	***4C***	***8C***	***10C(max)***
-5°C	Heat Generation (mW)	462.054	759.989	21870.818	73932	93549.163	1486.301	5039.613	14931.753	30968.705	20934.790
	Total energy Loss (J)	6349	9302	13972	10928	9095	4348	8504	13627	17695	16687
	Efficiency (%)	92.42	87.75	77.73	59.62	53.63	94.93	91.12	85.67	80.49	78.17
10°C	Heat Generation (mW)	347.907	663.854	15585.385	57166.196	241.015	901.148	2527.652	12492.603	38128.072	40231.541
	Total energy Loss (J)	5093	7727	12343	16178	16139	2387	6903	11880	20208	14564
	Efficiency (%)	94.91	91.56	85.01	70.50	65.87	96.92	93.60	88.89	80.90	80.76
25°C	Heat Generation (mW)	1006.671	3104.462	10363.16	38006.21	49501.34	994.34	2373.	8262.227	28384.583	46800
	Total energy Loss (J)	3989	5828	9308	15623	15893	4389	5043	8834	15992	16081
	Efficiency (%)	96.45	94.49	90.44	81.42	78.62	96.52	95.73	92.43	86.3	85.13
40°C	Heat Generation (mW)	261.114	3004.222	10043.835	36380.693	50921	559.537	2048.821	7565.513	27379.734	36380.693
	Total energy Loss (J)	3932	6111	9944	18700	20674	2216	4753	8980	17085	16700
	Efficiency (%)	96.67	94.59	90.88	86.68	78.70	98.01	96.20	92.85	86.43	84.68

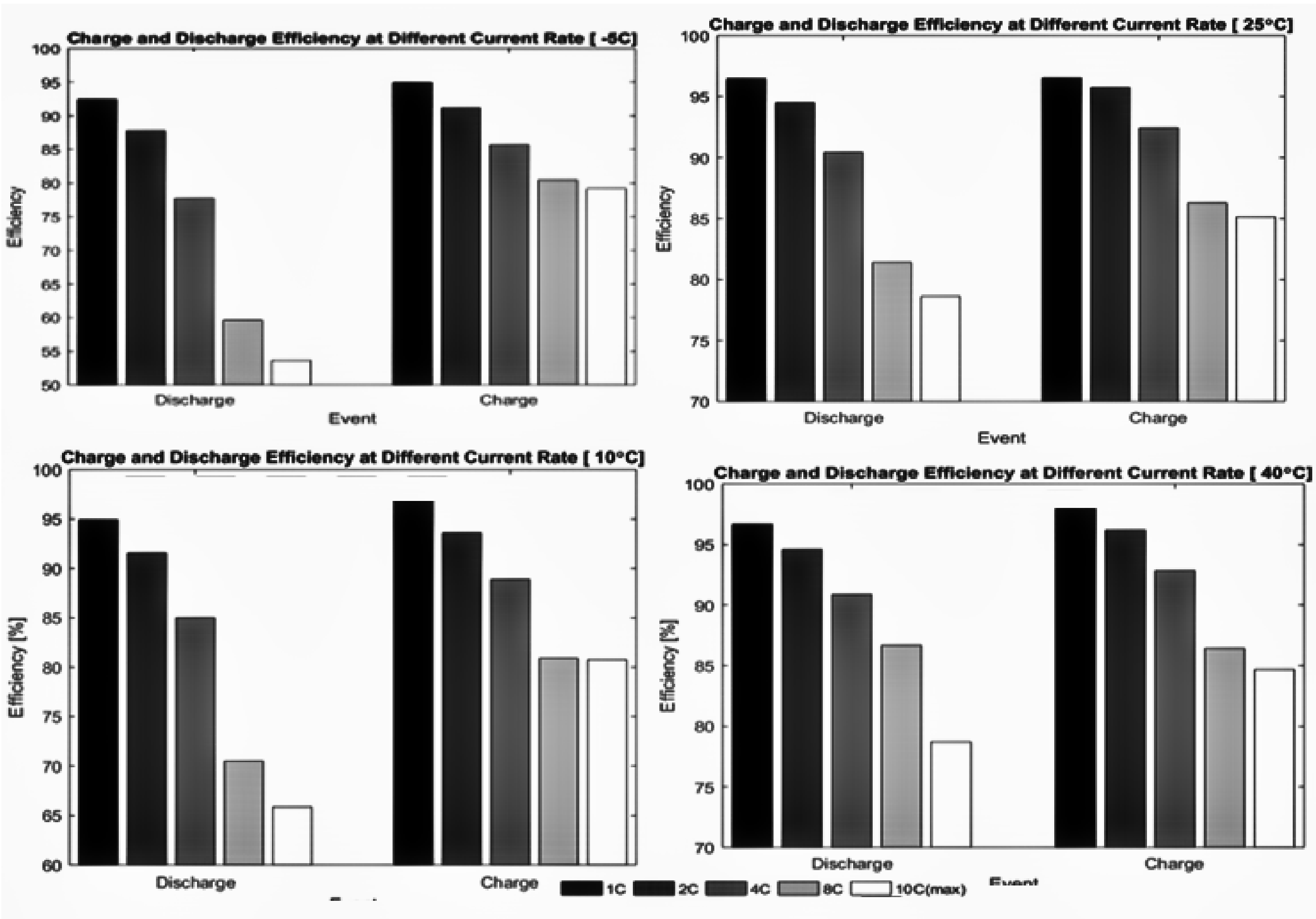

Fig. 7. Comparison of Charge and Discharge efficiency at a different temperature.

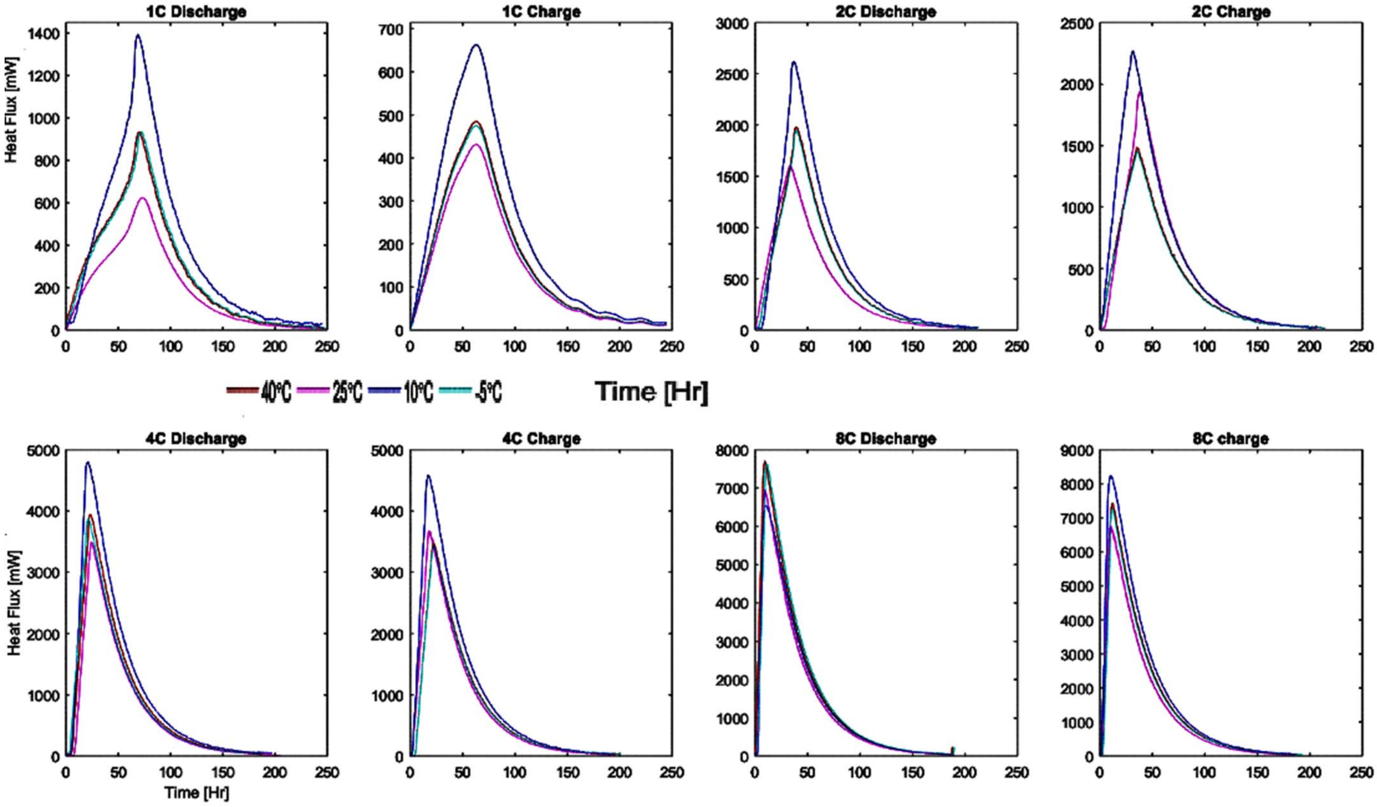

Fig. 8. Comparison of Charge and Discharge Heat Flux at different temperatures.

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