

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

185,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Battery Efficiency Measurement for Electrical Vehicle and Smart Grid Applications Using Isothermal Calorimeter: Method, Design, Theory and Results

Mohammad Rezwan Khan

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.75896>

Abstract

The chapter primarily explores the likelihood of heat measurement by means of the calorimeter in the lithium-ion battery cells for different applications. The presented focus applications are electrical vehicle and smart grid application. The efficiency parameter for battery cell is established using state of the art isothermal calorimeter by taking the consideration of heat related measurement. The calorimeter is principally used for the determination of the heat flux of the battery cell. The main target is to achieve the precision and accuracy of measurement of battery cell thermal performance. In this chapter, the assessment of battery efficiency parameter is proposed. A newly devised efficiency calculation methodology is projected and illustrated. The procedure ensures the precision and accurate measurement of heat flux measurement and turns into more comparable efficiency parameter. In addition, the issue is to investigate thermal sensitivity to factors that influence the energy storage system performance, i.e., current rate and temperature requirements. The results provide insight into the establishment of new key performance indicator (KPI) efficiency specification of the battery system. The usage of the calorimetric experiments is presented to predict the temperature distribution over a battery cell and an array of cells.

Keywords: battery systems, calorimeter, isothermal calorimeter, heat flux, efficiency, key performance indicator, electrical vehicle, smart grid, battery thermal management, heat generation, performance and battery behavior, key performance indicator (KPI)

1. Literature study

Sustainable low-carbon economy yet resource-efficient and competitive is a top-priority in the international community. Focusing on emissions, transport sectors, are some of the largest and

fastest-growing contributors to greenhouse gas (GHG). This is omnipresent in the whole world, where significant emissions reductions in transport and grid sectors, are needed to meet long-standing climate goals. Scientific studies have often directed to renewable energies coupled with batteries for cuts in GHG emissions [1, 2]. There is no doubt of the fact that adopting electric technologies in the transport industry, therefore, makes the highest potential since it is an achievable option in current status quo. There are however more technological as well as structural challenges to overcome [3].

There is no denying of the fact that battery technology, for instance, Lithium-ion battery technology offers great benefits in current energy scenario. However, an essential challenge is to safeguard working safety, reliability and cost, etc. State of the art lithium-ion batteries is prone to temperature related problems. In order for EVs like PHEVs, BEVs technologies to succeed in the marketplace, the strict requirement is placed on being very safe and reliable. Therefore, either the consequences of a heat-related hazard, for instance, thermal runaway or the severity of a thermal runaway reaction must be minimized under both normal operations and abusive conditions [4–6]. Undoubtedly, battery thermal management system (BTMS) is critical to the life and performance of electric-drive vehicles (EDVs) hybrids (HEVs), plug-in hybrids (PHEVs), and all-electric vehicles (EVs). The lithium-ion (Li-ion) batteries found in most of today's electric-drive vehicles are smaller and more lightweight than previous nickel-metal hydride (NiMH) technology, but they are also more sensitive to overheating, overcharging, and extreme spikes in temperature known as thermal runaway [7, 8]. A comparison is presented in **Table 1**.

In extreme instances, battery overheating can pose safety hazards, including fires. The important performance assessments factors are management system, the thermal behavior of the cell, battery lifespan, and safety of the energy storage system, as well as full integration into an application. While designing the thermal system EV and HEV performance and life-cycle cost are seriously affected by battery pack performance, i.e., the pack's operating temperature profile. The effect is mainly uneven temperature distribution [7, 9]. It may direct unbalanced modules and reduced performance in a battery pack [10]. Therefore, it is no surprise that manufacturers seek battery cells with a safe thermal profile so that modules operate within the desired range. Another important goal is that HEVs, PHEVs, and BEVs batteries need to operate at maximum efficiency to attain ultimate market penetration [4, 11, 12]. Though the performance is influenced by a wide range of driving conditions and climates, and through numerous charging cycles, high temperatures decrease battery life [13]. So, it increases battery replacement costs, while low temperatures diminish battery power and capacity, all of which impact required applications operational range, performance, and affordability. So, it is imperative to conduct the thermal management research and development (R&D) to optimize battery performance and extend the life of battery [14, 15]. Undeniably to become a recognized leader in battery research and development, thermal analysis and characterization specifically with calorimeter is necessary. Through calorimetric testing, it is necessary to evaluate the thermal performance of battery cells. Then the result is extending further to modules and packs by strict inspection [7, 16, 17].

Current battery breakthrough research is focused on reducing thermal barriers to achieve more uniform temperatures. One of the important attributes is being capable of precise thermal measurements with great accuracy. It should enable battery developers to predict thermal

Specifications	Non- lithium Batteries			Lithium Based Cells		
	Lead Acid (PbAc)	Nickel–cadmium (Ni Cd)	Nickel–metal hydride (NiMH)	Lithium cobalt oxide (LCO)	Lithium manganese oxide (LMO)	Lithium phosphate (LFP)
Specific energy (Wh/kg)	30-50	45-80	60-120	150-190	100-135	90-120
Internal resistance (mΩ)	<100	100-200	200-300	150-300	25-75	25-50
Cycle life' (80% DoD)	200-300	1000	300-500	500-1000	500-1000	1000-2000
Fast-charge time	8-16h	1h	2-4h	2-4h	1h or less	1h or less
Overcharge tolerance	High	Moderate	Low	Low	Low	Low
Self-discharge/ month (room temp)	5%	20%	30%	5-10%	2-10%	1-10%
Cell voltage (nominal)	2V	1.2V	1.2V	3.6V	3.8V	3.3V
Charge temperature	-20°C to 50°C	0°C to 45°C	0°C to 45°C	0°C to 45°C	0°C to 45°C	0°C to 45°C
Discharge temperature	-20°C to 50°C	0°C to 45°C	0°C to 45°C	0°C to 45°C	0°C to 45°C	0°C to 45°C
Commercialization year Since	Late 1800s	1950	1990	1991	1996	1999

Table 1. Common batteries used in electric vehicle and smart grid applications.

performance before installing batteries in vehicles [18]. Manufacturers use these metrics to compare battery performance to industry averages, troubleshoot thermal issues, and fine-tune their designs in successive iterations. The measuring principles might rely on precise measurement of energy storage devices' heat generation and efficiency under different states of charge, power profiles, and temperatures [19, 20]. In general, Calorimetry means the measurement of heat. Only one single energy (the internal energy) stored in the battery, which—only during an exchange—appears in a variety of energy forms such as heat energy. Accordingly, the form of energy known as heat can only be conceived as coupled with a change of energy. In other words, heat is the amount of energy exchanged within a given time interval in the form of heat flow from a battery specimen as measured by the calorimeter. The precise measurement of battery's heat capacity, the heat of fusion, the heat of reaction, and other caloric quantities is the foundations for progress in battery research and development. As a result, there is now an increasing interest in calorimetry as a very easy and powerful method for different kinds of investigation. Heat and temperature uniformity affect the battery application performance, lifecycle, and security [12, 21, 22].

Calorimeters are used for measuring the heat of chemical reactions or physical changes inside a battery cell or a module. The underlying techniques are based on measuring heat generated from the exothermic process, consumed from the endothermic process or simply dissipated by

a battery cell or module at controlled temperatures with a controlled environment. It provides an accurate assessment of heat-evolution and thermal foot-print of the battery cell or the pack [23–25]. A variety of calorimetry techniques are found to characterize energy storage systems. Accelerating rate calorimetry (ARC) is used to quantify calorific output and heating rates for runaway reactions in lithium-ion cells. It is used to evaluate materials and strategies to minimize the severity of these reactions. In addition, it is possible to understand better the degradation products, mechanisms, and potential hazards associated with degrading battery materials. Another technique is isothermal calorimetry used to measure cell or battery heat capacity and heat generation during charge/discharge profiles [26, 27]. This information retrieved from the calorimeter can be used to model, design, and test the performance of a battery's thermal management system. Through calorimetry, it is possible to determine the temperature at which lithium-ion cells, the quantity of energy released during the operation of the battery, the associated reaction speed. Isothermal battery calorimeters (IBCs) are capable of providing the precise thermal measurements needed for safer, longer-lasting, and more cost-effective electric vehicle (EV) batteries [28].

Development of precisely calibrated battery systems relies on accurate calorimetric measurements of heat generated by battery cell or modules during the full range of charge/discharge cycles. Moreover, it is important of the determination of whether the heat is generated electrochemically or resistively. The calorimeter must determine the heat levels and battery energy efficiency with greater accuracy. Additionally, it should provide precise measurements through complete thermal isolation to ensure the heat measured is entirely from the battery cell. Besides, it is needed to analyze heat loads generated by complete battery systems [24, 25, 29, 30]. Three typical calorimeter configurations are presented in **Table 2**.

The evolution of surface temperature distribution and the heat flux of the battery cell is measured 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.

Specifications	Units	IBC 284 (Cell)	Module IBC	Large-Volume IBC (Pack)
Maximum Voltage	Volts (V)	50	500	600
Sustained Maximum Current	Amps (A)	250	250	450
Excursion Currents	Amps (A)	300	300	1,000
Volume	Litre (L)	9.4	14.7	96
Maximum Dimensions	(cm)	20.3 x 20.3 x 15.2	35 x 21 x 20	60 x 40 x 40
Operating Temperature	(°C)	-30 to 60	-30 to 60	-40 to 100
Maximum Constant Heat Generation	Watt (W)	50	150	4,000

Table 2. Commercial calorimeter configurations used for EV and smart grid application.

Consequently, using the heat generation result, the important performance constituent, i.e., key performance indicator (KPI) 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 (1°C , 2°C , 4°C , 8°C). There is a significant change in heat generation level in both charge and discharge events on decreasing temperature and increasing C-rate. The heat flux magnitude level change is non-linear at different temperature and current rate. This nonlinear heat flux is responsible for the corresponding nonlinear change of efficiency in different C-rate at a particular temperature. The results lead to a deeper understanding of the efficiency and heat generation behavior of the specific battery cell. Additionally, the result of the research can be incorporated in constructing a precise datasheet of a specific type of battery cell which can assist the researchers, engineers, and different stakeholders to enhance diverse aspects of battery research [29, 31]. Inevitably identifying and understanding those behaviors and performance indicators are critical to ensuring the proper operation of the battery [29, 31]. The knowledge of the individual cell heat generation can give a good indication of the behavior inside a pack.

Therefore, it is evident that understanding the temperature gradients, its evolution and finding key performance indicator (KPI), i.e., efficiency of the battery is very important. It assists in choosing the required efficient battery cell for a specific application. This can provide very valuable information on the characteristics of the battery. Furthermore, the results can be used to build a thermal model. Moreover, the research can assist in the process of design selection from different cooling options. Additionally, it can lead to choosing the optimal battery cell for desired application from diverse options to choose the optimum battery. The specific method and the use of the method are presented in the subsequent sections of this chapter.

2. Underlying physics and methodology development

2.1. Physics behind isothermal battery calorimetry

The term isothermal refers to a fixed temperature in equilibrium thermodynamics. Strictly speaking, the temperature of isothermal calorimeters must be kept constant in every part and every moment. But in such a case, no heat transport would occur since heat only can flow when a temperature gradient (difference) exists. Therefore, at least the battery sample temperature must be dissimilar from the (isothermal) calorimeter temperature. Hence, it is more quasi-isothermal rather than only isothermal. Furthermore, the heat produced during a reaction inside a battery cell in such a calorimeter must be compensated for immediately in one way or the other. There are two possibilities to compensate for the heat produced by the battery sample [26, 27, 32]. The heat released from a battery sample during a process flows into the calorimeter and would cause a temperature change of the latter as a measuring effect; this thermal effect is continuously suppressed by compensating the respective heat flow. The methods of compensation include the use of “latent heat” caused by a phase transition, thermoelectric effects, heats of chemical reactions, a change in the pressure of an ideal gas [33], and heat exchange with a liquid [34].

2.1.1. *Summary of measuring principles*

Measurement of the heat exchanged while a battery in operation by compensation, that is, suppression of any temperature change of the calorimeter caused by the thermal effect of the battery sample. The underlying compensation principle is:

- By endothermic effect
- By exothermic effect
- Phase transition (solid-liquid; liquid-gaseous, liquid-solid, gaseous-liquid, etc.
- Electric cooling (Peltier effect)
- Electric heating (Joule effect)

2.1.2. *The isothermal condition*

In calorimeters operating isothermally, the surroundings and the measuring system always have the same constant temperature. Consequently, isothermal operation necessitates a compensation of the heat flow released from the battery sample. This can be achieved by a phase transition (passive measuring system) or by thermoelectric effects (active measuring system). There are no truly isothermal conditions in the measuring system of a compensation calorimeter, least of all in the battery sample. Constant temperature in time and space cannot be expected because any heat transport from the battery sample to the substance undergoing transition would be impossible in the absence of temperature differences. Similar considerations apply to calorimeters involving electric compensation about the heat transport between the battery sample, the temperature sensor, and the heater or the cooler. The magnitude of the temperature difference depends on the quantity of heat delivered per time unit by the battery sample surface, the thermal conductivities of the substances that surround the battery sample (vessel materials), and their geometry. In calorimeters involving electric compensation, the insulation of the temperature sensors and of the heating or cooling elements causes additional local temperature differences. Despite these limitations, the designation “isothermal” is commonly used with regard to calorimeters. Calorimetric measurement and data processing (evaluation), as well as calorimeter control, are nowadays carried out electronically and with the help of a computer. In most cases, the computer ultimately presents the result of the measurement graphically for the sake of clarity and in order to make any change of test values readily visible [23, 35, 36]. The heat produced (or consumed) brings about a change of temperature, which in turn causes a heat flow and other effects. A sensor (thermometer) located within or outside the reaction vessel detects a temperature change that occurs with some time lag relative to the reaction proper and can be only loosely correlated with the course of the chemical reaction because of the uncontrollable character of such phenomena as diffusion, convection, and heat conduction in the liquid. However, if sufficient time is allowed for all equalization processes to go to completion, it becomes evident that the overall temperature change is closely related to the overall heat of reaction [23–26, 30].

2.2. The methodology

The research associates with the determination of heat generation and efficiency of a battery cell using an experimental approach. It is accomplished through applying a full charge and discharge current at different rates in diverse temperatures. During the experiment, the principal thermal features of the battery cell are measured simultaneously. Those are battery cell raw heat flux (measured using isothermal calorimeter) and surface temperature (measured using contact thermocouples) at different spots. Those are simultaneously measured to track the thermal gradients on the surface of the battery as well as to track the heat generation rate. Calorimetric measurement represents the global heat generation inside the cell at the given current profile. By using this calorimetric raw heat flux data, the quantity of the battery heat generation is determined. To accomplish this, a suitable range of raw heat flux is carefully chosen. The next procedure is to select the best baseline type. It is needed for finding the enclosed heat flux area. Then using computational software, the actual heat generation is determined. Afterwards, using the electrical energy input (area enclosed by electric power versus time curve) and calorimetric heat dissipation data (area enclosed by heat flux versus time curve), the efficiency of the battery cell is calculated at the corresponding operating condition. Simultaneously, the maximal increase in the battery temperature inside cell surface is measured for different current rates on the battery cell surface [5, 6]. The calorimetric data is used to model the cooling effect inside a battery cell and an array of cells inside a pack.

2.3. Calorimetric experimental steps

Obtaining reliable experimental results needs painstaking preparation stages. Those are discussed in the subsequent subsection.

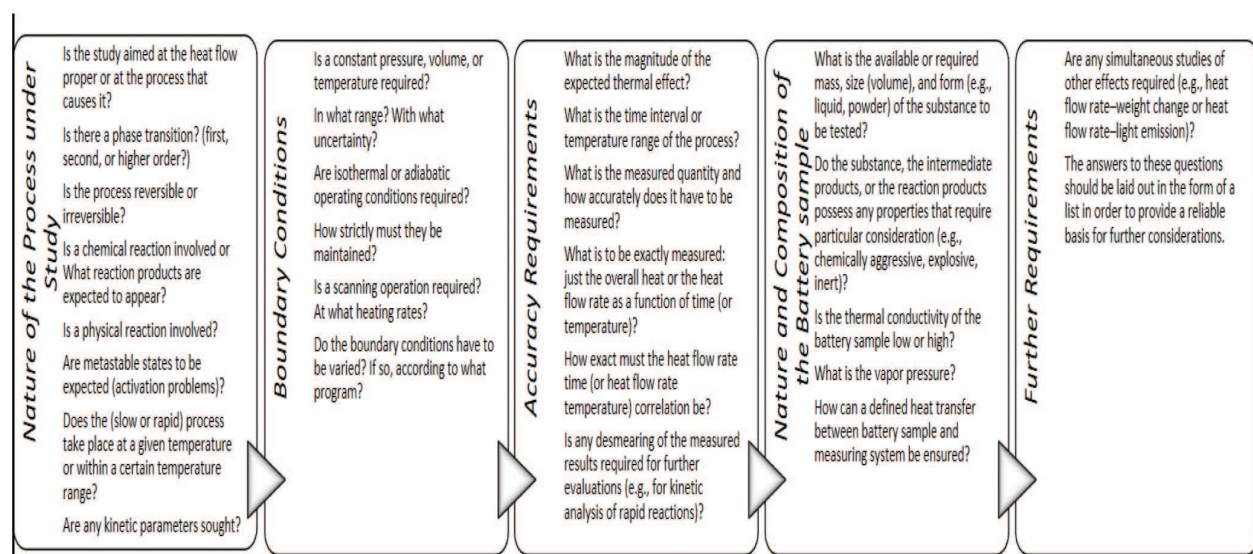


Figure 1. Selection of a suitable calorimeter using the queries.

2.3.1. Definition of the problem to be investigated

Calorimetric procedures provide valuable information toward an understanding of processes where the enthalpy remains constant (i.e., there is no exchange of heat), but one of the derivatives of enthalpy with regard to temperature (e.g., the first derivative—the heat capacity) undergoes a change during the process. The answers to these questions should be laid out in the form of a list in order to provide a reliable basis for further considerations as presented in **Figure 1**.

2.3.2. Calorimeter requirements

The requirements with regard to a calorimeter can be derived on the basis of the analysis of the measuring problem.

- Find the necessary operating conditions: isothermal, adiabatic
- Define the temperature range
- Find the required heating rate
- Determine boundary conditions: a constant pressure, constant volume, gas flow rate, and so on
- Find the required noise and accuracy level
- Determine the safety and security risk level

3. Calorimetric measurement

3.1. Calibration and setup of the experiment

Before starting an experiment, the calorimeter must be carefully calibrated. The calibration should be verified from time to time (depending on the stability of the instrument). In case of higher accuracy demands, such verification is to be recommended before and after every experiment to be on the safe side regarding the reliability of the calorimetric results. After the insertion of the battery sample into the calorimeter, enough time must be given to the instrument to come to a stable state and thermal equilibrium before the measurement can be started. Proper measurement parameters must be chosen: in the case of calorimetry, the initial temperature and the heat flux measurements have come to steady-state conditions (by putting the machine in idle condition for sufficient time) before the event to be investigated starts. The quantities temperature, time, and heat flow rate, must be measured and stored for later analysis. Additionally, the analog-to-digital converter must have the proper resolution and precision to fulfill the uncertainty demands of the measurement [28]. The battery cell temperature measurement system is made of five type K thermocouples. The Isothermal Battery Calorimeter Netzsch™ IBC 284 is a robust instrument designed for the accurate measurement of heat flux generated by batteries while in operation. It has an operating span of -30°C to $+60^{\circ}\text{C}$.

A mixture of 50% ethylene glycol and 50% deionized water (EG/W) is used inside the bath. It ensures the isothermal environment inside the bath. The following **Table 3** lists the specification of the calorimeter.

The instrument is semi-automated. Most of the operations are controlled manually from the front panel of LabVIEW-based data acquisition system. It has a heat sensing range from 100 mW to 50 W. It should be noted that the calorimeter has high thermal inertia. It limits the calorimeter’s heating or cooling rate. A maximum of 5 K per hour rate can be reached. For instance, when starting from 25°C, for an experiment to be run at 40°C, so it may take minimum 3 h to reach temperature equilibrium. Image of the calorimeter are shown in **Figure 2** [29, 31].

Attribute	Limit	Attribute	Limit
Temperature range	-30°C to +60°C	Maximum battery size	305 [mm] x 203.2 [mm] x 152.4 [mm]
Isothermal bath stability	±0.01°C	Baseline noise	5 mW
Heating / Cooling rate	5°C / hour	Baseline stability	30 mW
Refrigerated Recirculation	Built-in to unit	Maximum power	50 W
Thermal fluid	Ethylene glycol / deionized water	Maximum current	250A
Operational mode	Isothermal for measurement of battery enthalpic and entropic changes, efficiency, lifetime and performance	Maximum voltage	50V

Table 3. Netzsch™ IBC 284 calorimeter specification.



Figure 2. Netzsch™ IBC 284 isothermal calorimeter used in the chapter for measuring the thermal behavior of battery cells.

The calibration factor for heat or heat flow rate must be determined or verified. The measured temperature is checked in a variety of ways depending on the calorimeter, and the same applies to the information on temperature fluctuations. Heat flows are invariably associated with a temperature gradient whose magnitude must be taken into account in order to be able to analyze the accuracy of temperature measurement. The determination or checking of the calibration factor usually takes place through the release of a definite amount of heat in an electric heater (resistor). The test measurements are made to find the repeatability and the accuracy of the calorimeter [28]. The specific calibration is carried out using the precision resistance. It is provided with the calorimeter instrument. It is accomplished by applying three different Joule effect pulses. The goal of this particular calibration is to calibrate the heat flux measurement as closely as possible to the known amount of heat flux generation. Joule effect calibration is found in **Figure 3** [29, 31].

In the current experimental condition, a particular precision resistance is used. It generates a 50 mV voltage for 300 A current and having a resistance value of 0.167 m Ω . Calibration of the calorimeter is accomplished by applying a controlled electrical current to this accurate resistance located inside the calorimeter chamber. The power of the different Joule effect pulses, applied in the precision resistance placed inside calorimeter chamber, is adapted for the measuring range of the instrument (100 mW to 50 W). The calibration is also performed at many different temperatures (-30°C , 0°C , $+30^{\circ}\text{C}$ or $+60^{\circ}\text{C}$) [29, 31]. The standard calibration is comprised of three successive Joule effect pulses at different levels of power 100 mW, 1 W, and 10 W. The goal of this particular calibration would be to obtain the exact calibration coefficient for the specific temperature of the experiment. From different calibration points, various calibration coefficients are calculated. Consequently, a calibration polynomial can be generated as shown in **Figure 4**.

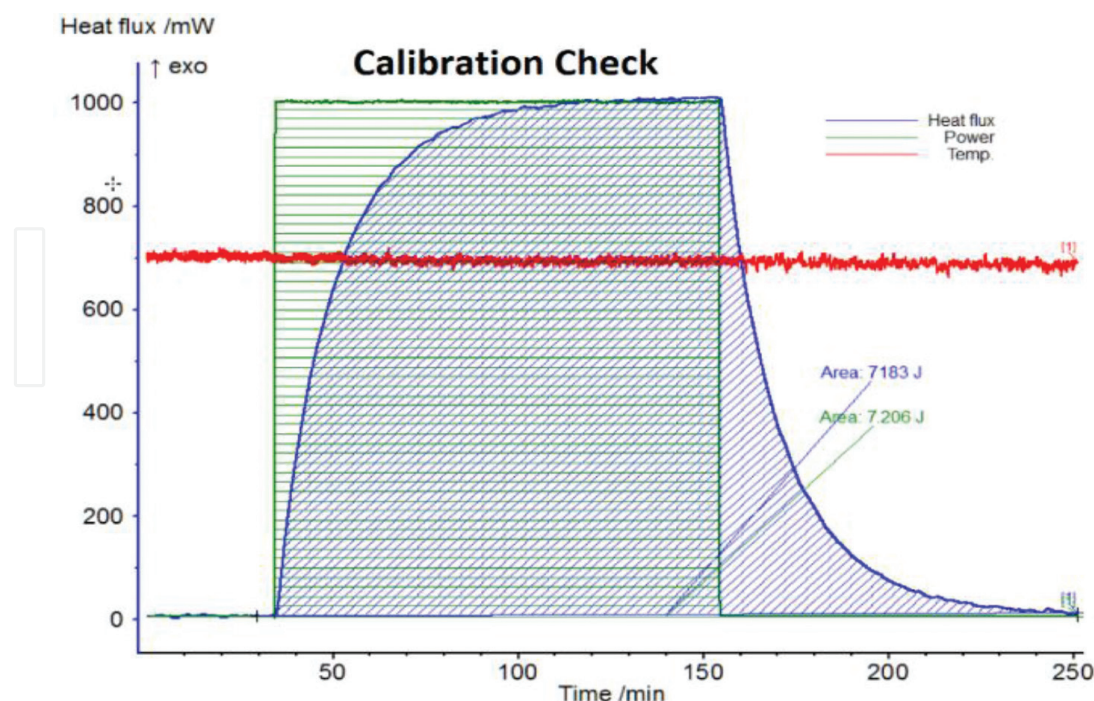


Figure 3. Joule effect calibration graphs [29, 31].

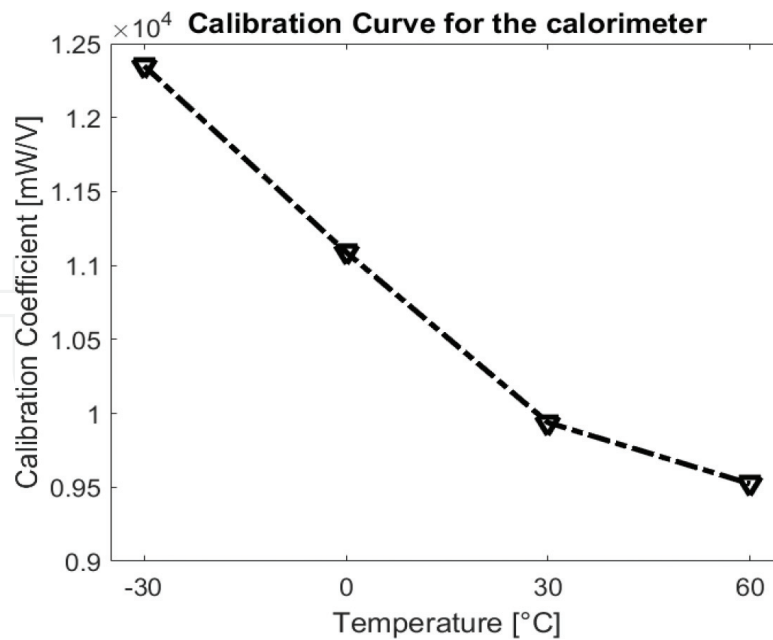


Figure 4. Calibration curve of the calorimeter [29, 31].

Most of the experiments need to be run at temperatures other than the temperatures (-30°C , 0°C , $+30^{\circ}\text{C}$ or $+60^{\circ}\text{C}$) that the calorimeter was calibrated. In that case, to obtain a good accuracy, a calibration polynomial is used. The polynomial is used for interpolating the coefficient on the intermediate temperature levels. It should be noted that using the calibration polynomial for calculating the calibration coefficient at the particular temperature may lead to an error of less than 1. The resulting calibration polynomial equation expresses the calibration coefficient as a function of temperature (in $^{\circ}\text{C}$) as shown in Eq. (1):

$$\text{Calibration coefficient } (T) = 0.0039T^3 + 0.0594T^2 - 43.709T + 11090 \quad (1)$$

3.2. Battery calorimetric experiment

The inert gas atmosphere is maintained inside the calorimeter chamber. To achieve excellent temperature homogeneity (inside the isothermal bath), constant stirring is needed in the experimental condition. Before electrically connecting the battery sample inside the calorimeter, the battery cell sample needs to be prepared. To be tested, the battery sample needs to be equipped with two wires for powering purpose and two wires for sensing. The thermal contact between the battery sample and the calorimeter is the most important factor for obtaining the accurate data. This ensures efficient heat transfer between the battery itself and the bottom plate of the calorimeter. It is to be noted that the thermoelectric sensors are located underneath of the battery chamber. After performing the calibration and experimental conditioning, the battery sample is electrically connected with battery cycler. The experiment is repeated at different temperature at the different current rate. After acquiring the data, NetzschTM Proteus[®] Software and hand optimized Matlab[®] script is used for the thermal analysis. After selecting the proper baseline and the range, using the computational software, the enclosed area is found (refer to **Figure 5**) which represents the heat flux area [29, 31].

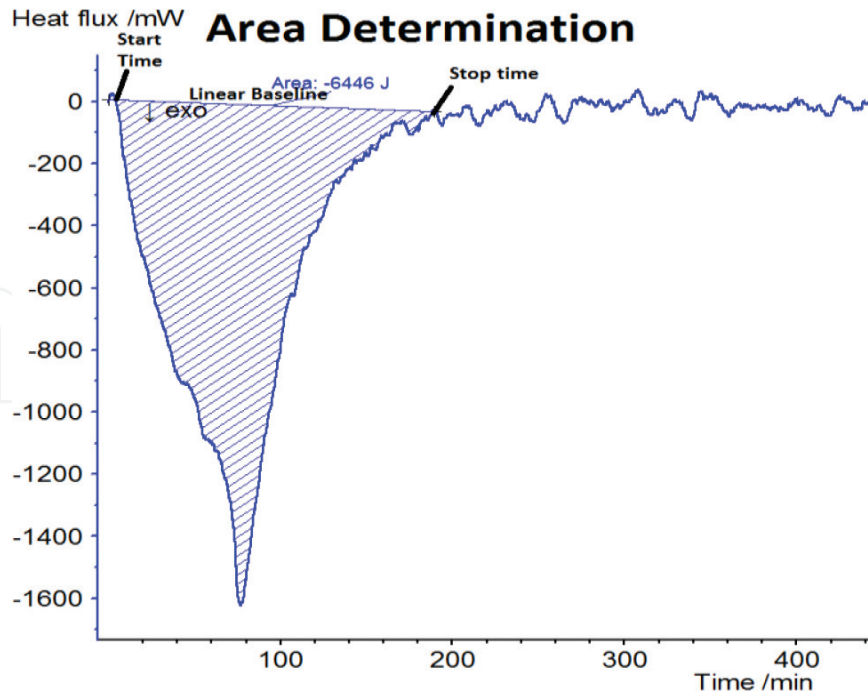


Figure 5. The determination area of the heat flux [29, 31].

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 [29, 31]. The value is used to determine the total heat loss by the battery cell on the defined operation. The heat generation can be found by Eq. (2):

$$\text{Heat generation} = \frac{\text{Heat Flux-Area}}{t_f - t_s} \quad (2)$$

The next step is to calculate battery efficiency. It is achieved by determining the absolute power area, i.e., input absorbed power during discharge or extracted output power while in experimental (i.e., charge or discharge) operation. Heat flux area is subtracted from the absolute electrical power area and normalized 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 normalized by the electrical input [29, 31]. More specifically, Eq. (3) is used for determining the efficiency:

$$\eta = \frac{\text{Absolute Power Area} - \text{Heat Flux Area}}{\text{Absolute Power Area}} \quad (3)$$

3.3. Evaluation of the measurement

Data analysis from the measured calorimetric data has multiple facets and approaches, encompassing diverse techniques under a variety of names in battery domain. The crucial point is to distinguish between real effects coming from the battery sample itself and artifacts produced

Attribute	Test at 0°C				Test at 25°C			
	Discharge	Charge	Discharge	Charge	Discharge	Charge	Discharge	Charge
Heat Generation (mW)	3961.415	1423.189	4005.315	1489.725	1498.498	1069.493	1521.143	1071.65
Total energy Loss (J)	14898.213	10664.569	14810.35	11201.158	6437	4721	6501	4734
Efficiency (%)	88.71	92.85	88.59	92.48	94.25	96.25	94.5	96.01
Maximum temperature increase (°C)	3.9	3.7	2.2	2.04	2.3	2.1	1.9	1.8

Table 4. The complete calorimetric analysis at different temperatures and different operating conditions [29].

by the apparatus or by the environment (temperature and line voltage fluctuations, electronic and computer problems). Real battery sample effects such as transitions and reactions are, as a rule, repeatable, whereas artifacts caused by environmental influences occur almost accidentally. It is helpful to decrease the noise by averaging several measurements; this will improve the signal-to-noise ratio. It should be mentioned that changes in the heat transfer condition between the battery sample and the calorimeter (e.g., by vibrations or bumps of the calorimeter or surroundings) produce peaks in the heat flux signal. The same is true if the battery sample moves inside the calorimeter chamber. The summary of analysis is tabulated in **Table 4**,

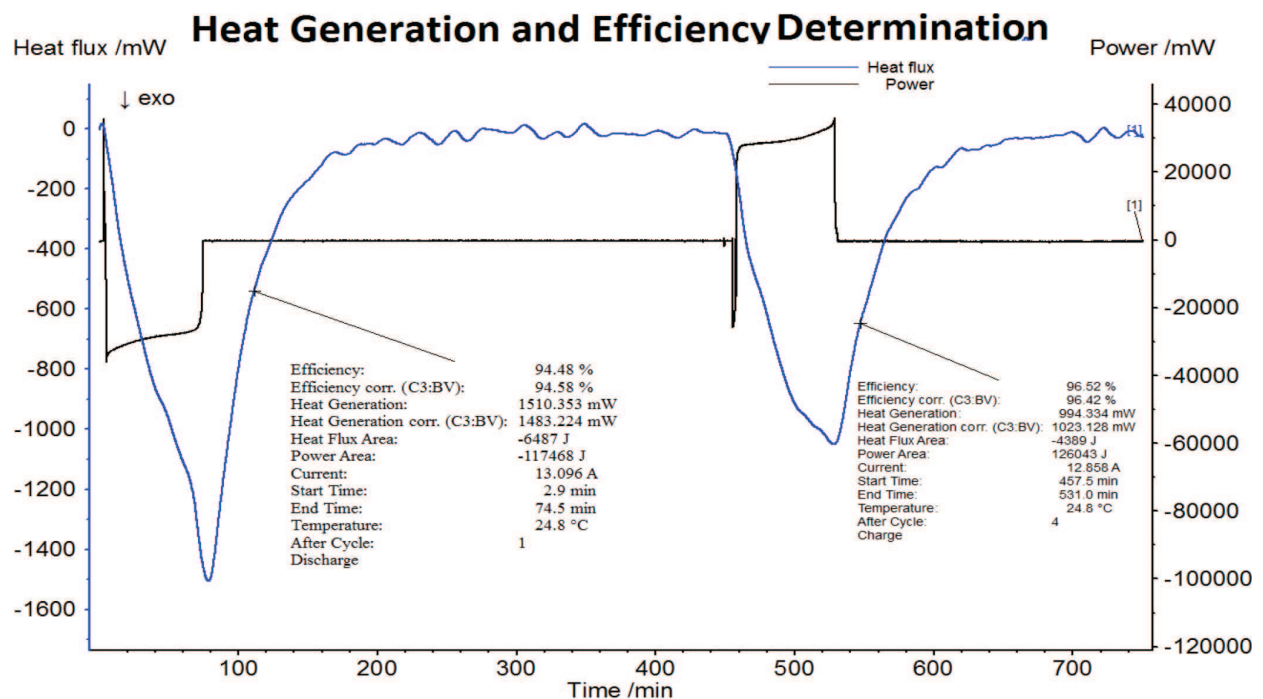


Figure 6. A complete analysis of LTO battery cell heat generation using isothermal calorimeter [29].

and complete analysis is shown in **Figure 6**. To show the variability among the same experiments, two results are presented [29, 31].

The above procedures are repeated at different temperature levels by applying a diverse current charge and discharge pulses. The associated calibration factors for the specific temperatures corresponding to the research are shown in the following **Figure 7**.

The effect of charge-discharge events in different temperature at the different current rate is tabulated in **Table 5**.

The heat flux change level is non-linear. This nonlinear heat flux is responsible for the non-linear change of efficiency in different C-rate in particular. Battery cell efficiency is a key performance indicator. It can assist to choose the best design parameter efficiency among

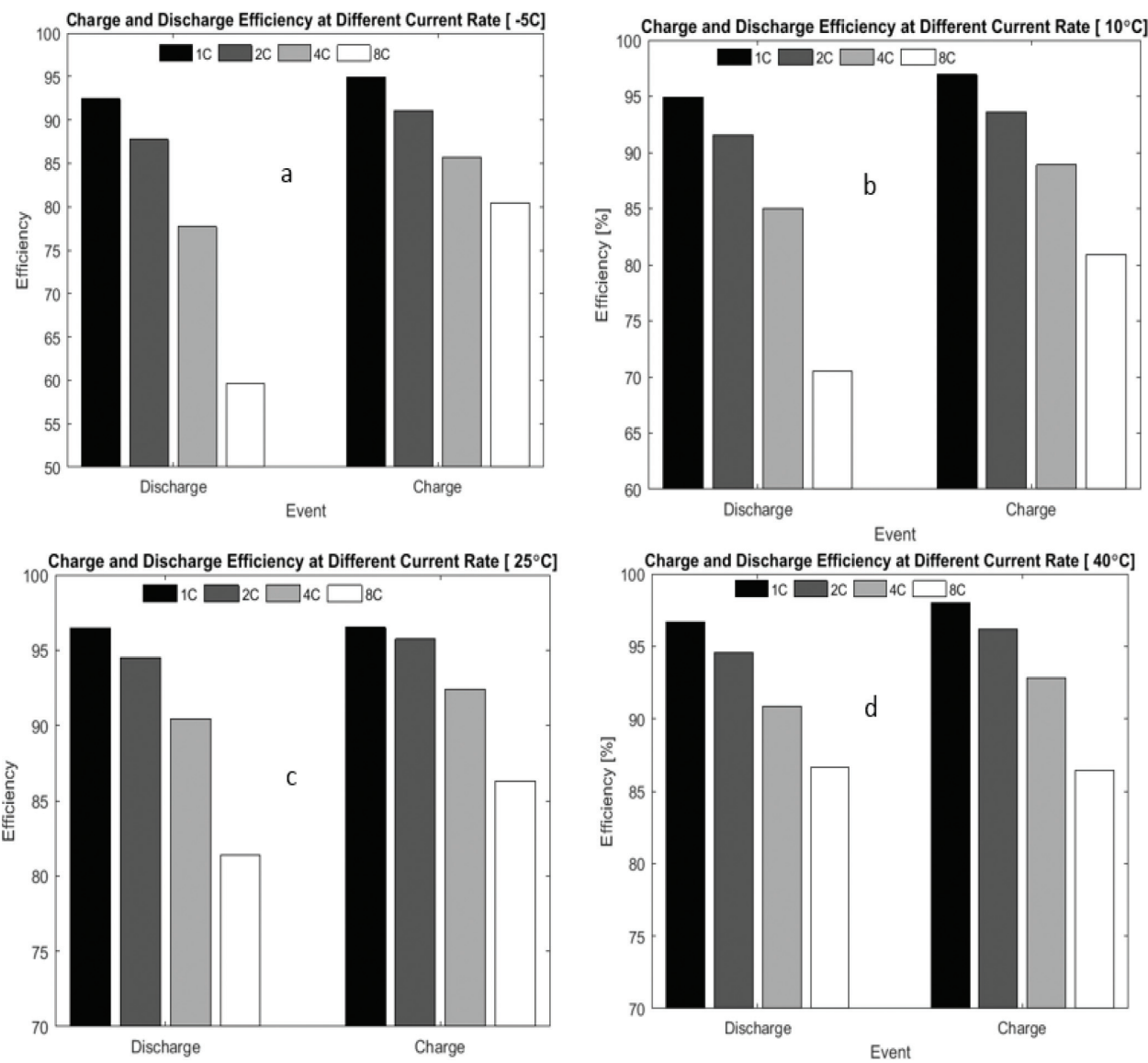


Figure 7. Comparison of charge and discharge efficiency at different temperature: [a] 5°C charge, [b] 10°C discharge, [c] 25°C discharge, and [d] 40°C charge [37, 38].

Temperature	Event	Discharge				Charge			
		1C	2C	4C	8C	1C	2C	4C	8C
-5°C	Current Rate								
	Heat Generation (mW)	1739	5000	15601	26333	4364	4463	12600	25134
	Total energy Loss (J)	6408	9331	14041	10902	4348	8543	13684	17795
	Efficiency (%)	92.42	87.75	78.26	59.83	95.01	91.23	85.64	79.98
10°C	Heat Generation (mW)	1352	3669	11825	38402	870	3270	10609	25461
	Total energy Loss (J)	5202	7883	12488	16129	2424	6908	11967	20318
	Efficiency (%)	94.82	91.55	85.30	80.86	96.90	93.74	88.89	81.16
25°C	Heat Generation (mW)	939	2666	8066	21427	994.34	2068	3449	18721
	Total energy Loss (J)	4007	5840	9389	15623	5027	5043	8888	16063
	Efficiency (%)	96.42	94.46	90.43	81.45	95.79	92.32	92.43	86.29
40°C	Heat Generation (mW)	839	2510	7192	19148	574	1825	6330	23247
	Total energy Loss (J)	3918	6116	10098	17923	2261	4831	9078	17157
	Efficiency (%)	96.39	94.67	90.77	82.22	97.98	96.12	92.73	86.27

Table 5. Battery calorimetric result summary [37, 38].

different battery cell options. 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 [29, 31].

4. Model development using calorimeter data

The calorimetric data can be used for battery cell and pack model development—using physical, mathematical relationships to represent logically. As such, the model can facilitate understanding a battery system's behavior without actually testing the system in the real world. A good paradigm is the temperature development inside a battery cell and the heat condition inside an array of battery cells. Useful insights about different decisions in the design could be derived without actually building the system. The model can be used to train personnel using a virtual environment that would otherwise be difficult or expensive to produce the battery thermal management system.

4.1. Cell model

A computationally efficient electro-thermal li-ion model can be developed using the calorimetric data. The model assimilates the main design parameters of the battery cell (sizes, materials, and parameters, etc.) and relevant physics (heat transfer and computational fluid dynamics (CFD)). The battery geometry is generated suitably for further analysis. The numerical problem

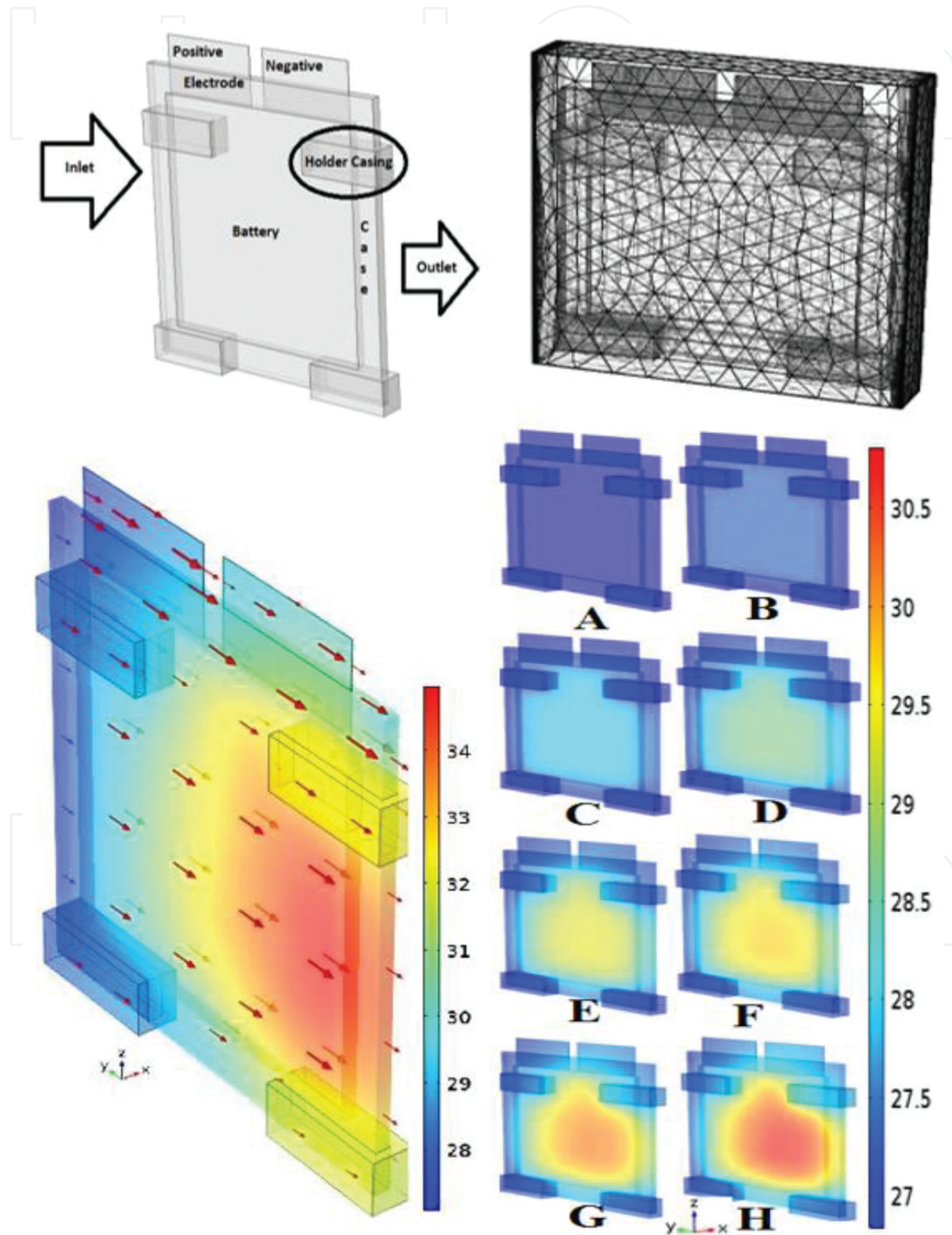


Figure 8. Battery cell modeling using the calorimeter data [39]. Transient simulation results of the battery pack with a cell with 1C discharge with 1m/s air flux and 27°C initial temperature in alphabetic caption order. There is significant temperature gradient with the time evolution. (A) 0 sec (B) 7 min 30 Sec (C) 15 min (D) 22 min 30 Sec (E) 30 min (F) 37 min 30 Sec (G) 45 min 30 Sec (H) 60 min.

of the thermal steady state problem with cooling is solved by considering the heat generation as measured by a calorimeter. The method of cooling is through an air medium. The amount of heat source generation is measured by an isothermal calorimeter. When the battery is functioning, it releases a finite, uniform and constant quantity of heat energy. There is an unhindered circulation of the heat in 3d (longitudinal (x), lateral (y) and normal (z) directions). The outcome of the model simulation is the determination of temperature distribution [39]. The model details are explained in [39] and the results are presented on **Figure 8**.

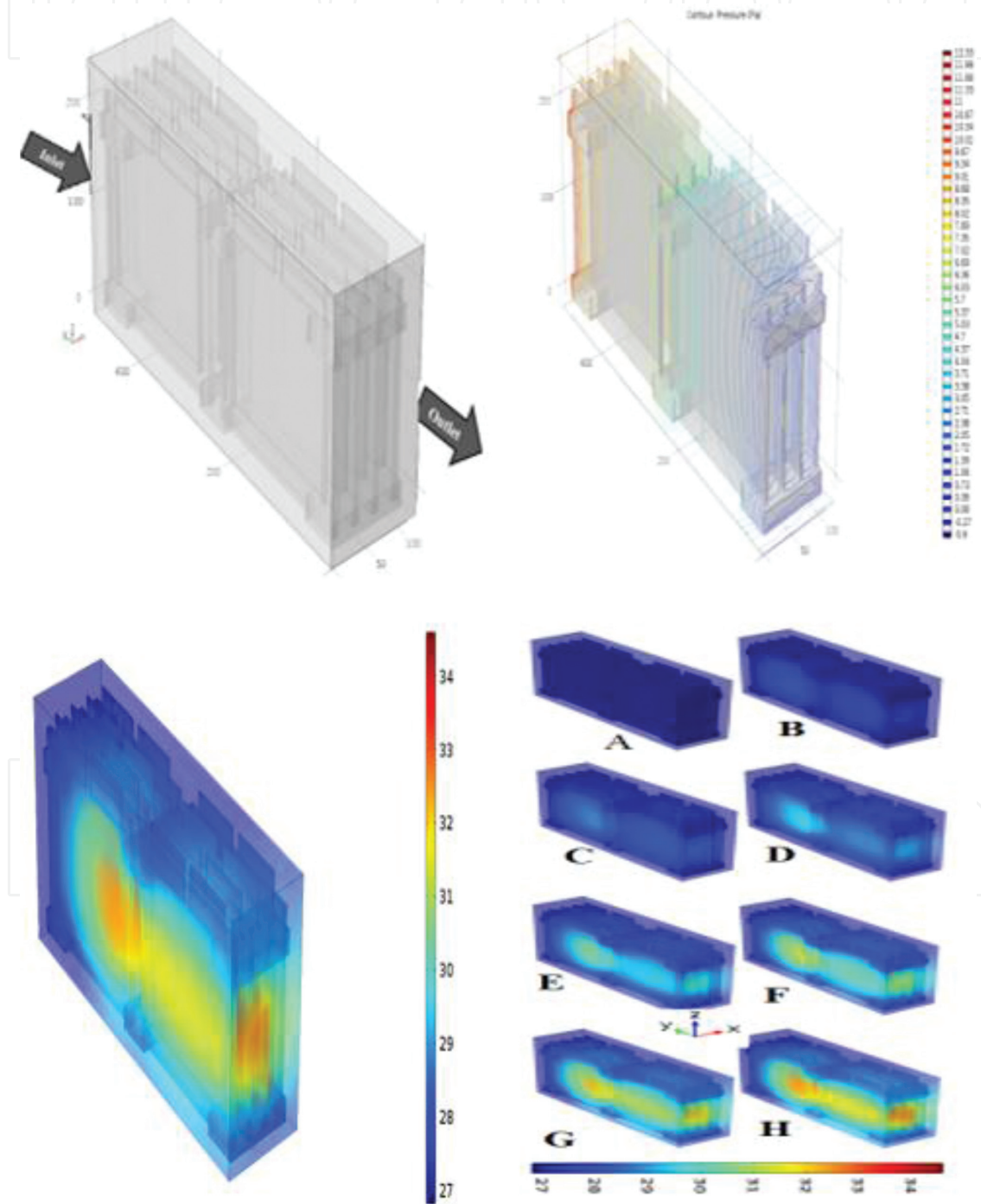


Figure 9. Battery pack model development using calorimeter data [40]. Transient simulation results of the battery pack with a cell with 4C discharge in alphabetic caption order. There is a significant temperature gradient with the time evolution. (A) 0 sec (B) 1 min 52 Sec (C) 3 min 44 Sec (D) 5 min 36 Sec (E) 7 min 28 Sec (F) 9 min 20 Sec (G) 11 min 20 Sec (H) 15 min.

4.2. Pack model

The battery pack made of eight large-size is studied having the 13 Ah nominal capacity. The model integrates the necessary parameters of the battery pack (cell dimensions, configurations, and orientations, associated materials, pack dimensions and configurations) and relevant physics (heat transfer (HT) and (CFD)). The battery cell and pack geometry are analyzed extensively and generated for further investigation using computer-aided design(CAD) tools. The input parameters are provided. The steady state and the time-dependent thermal problem of the battery pack are solved. The numerical solution considers the heat generation in the battery cell. The amount of heat generation is found by an isothermal calorimeter. The battery cells in the pack have direct exposure to cooling medium air. When the battery is operational, it suddenly releases a finite, consistent and constant quantity of heat energy in the homogeneous carrier fluid air. There is an unobstructed propagation of the heat energy in the longitudinal (x), lateral (y) and normal (z) directions. It is combined with the laminar fluid flow of the system to integrate the fluid flow with the current heat transfer phenomena [40]. The effect is the determination of temperature distribution as presented in **Figure 9**. The model details are explained in [40].

5. Conclusions

The calorimetric experiments are used to determine efficiency and heat generation of the battery cell. The key performance indicators (KPI) is found in the battery cell. It is found that the magnitude of heat generation is associated with the corresponding current rate (charge or discharge). This fact is used for thermal modeling. The heat generation in function of battery current rate can be used as input (heat source) of the model. Using the developed methodology, large battery cells can be tested safely and efficiently. The experimental platform has a direct impact on the lifetime profiling of a battery cell. Utilizing the developed methodology, the extensive full lifetime profile of a battery cell (e.g., efficiency, heat generation, temperatures and different state of charge level, etc.) in different lifecycle states, i.e., aging levels (new or old battery cell) can be found. The increasing heat loss is responsible for the decrease in efficiency. The effect of charge-discharge events on heat generation and efficiency has nonlinear effects in different temperature. The experimental technique is a very precise determination to profile the battery cell characteristics. The developed data can be used to predict the thermal behavior of the battery cell and pack by using corresponding cell and pack level.

Author details

Mohammad Rezwan Khan

Address all correspondence to: rezwankhn@gmail.com

Department of Energy Technology, Aalborg University, Aalborg, Denmark

References

- [1] IEA. Harnessing Variable Renewables: A Guide to the Balancing Challenge. Paris Cedex, France: International Energy Agency (IEA); 2011
- [2] Inage S. Modelling Load Shifting Using Electric Vehicles in a Smart Grid Environment. Paris Cedex, France: International Energy Agency (IEA); 2010
- [3] EPRI. Electricity Energy Storage Technology Options A White Paper Primer on Applications, Costs, and Benefits, USA: Electric Power Research Institute (EPRI); 2010
- [4] Khan M, Swierczynski M, Kær S. Towards an ultimate battery thermal management system: A review. *Batteries*. 2017;**3**(1):9
- [5] Khan MR, Mulder G, Van Mierlo J. An online framework for state of charge determination of battery systems using combined system identification approach. *Journal of Power Sources*. 2014;**246**:629-641
- [6] Khan MR et al. The integration and control of multifunctional stationary PV-battery systems in smart distribution grid. In: EU PVSEC The 28th European Photovoltaic Solar Energy Conference and Exhibition. Paris, Germany: WIP Wirtschaft und Infrastruktur GmbH & Co Planungs KG; 2013
- [7] Bandhauer TM, Garimella S, Fuller TF. A critical review of thermal issues in lithium-ion batteries. *Journal of the Electrochemical Society*. 2011;**158**(3):R1-R25
- [8] Culpin B. Thermal runaway in valve-regulated lead-acid cells and the effect of separator structure. *Journal of Power Sources*. 2004;**133**(1):79-86
- [9] Rao ZH, Wang SF. A review of power battery thermal energy management. *Renewable & Sustainable Energy Reviews*. 2011;**15**(9):4554-4571
- [10] Deng F et al. Fault detection and localization method for modular multilevel converters. *IEEE Transactions on Power Electronics*. 2015;**30**(5):2721-2732
- [11] Khan MR, Andreasen SJ, Kær SK. Novel battery thermal management system for greater lifetime ratifying current quality and safety standard. In: *Battery Connections*. UK, USA: Don Cleary Publishing, Institute of Electrical and Electronics Engineers (IEEE); 2014. pp. 6-10
- [12] Khan MR, Nielsen MP, Kær SK. Feasibility study and techno-economic optimization model for battery thermal management system. In: *Proceedings of the 55th Conference on Simulation and Modelling (SIMS 55), Modelling, Simulation and Optimization*. Aalborg: Linköping University Library; 2014. Sweden
- [13] Khan MR et al. Behavior patterns, origin of problems and solutions regarding hysteresis phenomena in complex battery systems. In: Dias JC, editor. *Hysteresis: Types, Applications and Behavior Patterns in Complex Systems*. Nova Science Publishers; 2014. pp. 215-226

- [14] Alaoui C. Solid-state thermal management for lithium-ion EV batteries. *IEEE Transactions on Vehicular Technology*. 2013;**62**(1):98-107
- [15] Newman J et al. Modeling of lithium-ion batteries. *Journal of Power Sources*. 2003;**119**: 838-843
- [16] Committee, SBSS. SAE J 2929 Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-Based Rechargeable Cells. 2013
- [17] Kim GH et al. Multi-domain modeling of lithium-ion batteries encompassing multi-physics in varied length scales. *Journal of the Electrochemical Society*. 2011;**158**(8):A955-A969
- [18] Swierczynski M et al. Investigation of multidimensional electrothermal impedance spectroscopy measurement on lithium ion battery cell. *ECS Transactions*. 2015;**70**(1):305-310
- [19] Gi-Heon K, Pesaran A, Spotnitz R. A three-dimensional thermal abuse model for lithium-ion cells. *Journal of Power Sources*. 2007;**170**(2):476-489
- [20] Pesaran AA, Keyser K. Thermal characteristics of selected EV and HEV batteries. In: 16th Annual Battery Conference: Applications and Advances. Long Beach, USA: IEEE; 2001
- [21] Hémery C-V et al. Experimental performances of a battery thermal management system using a phase change material. *Journal of Power Sources*. 2014;**270**:349-358
- [22] Yu K et al. Thermal analysis and two-directional air flow thermal management for lithium-ion battery pack. *Journal of Power Sources*. 2014;**270**:193-200
- [23] Downie LE et al. The impact of electrolyte additives determined using isothermal microcalorimetry. *ECS Electrochemistry Letters*. 2013;**2**(10):A106-A109
- [24] Krause LJ, Jensen LD, Dahn JR. Measurement of parasitic reactions in li ion cells by electrochemical calorimetry. *Journal of the Electrochemical Society*. 2012;**159**(7):A937-A943
- [25] Schmidt AP et al. Experiment-driven electrochemical modeling and systematic parameterization for a lithium-ion battery cell. *Journal of Power Sources*. 2010;**195**(15):5071-5080
- [26] Kobayashi Y et al. Precise electrochemical calorimetry of LiCoO₂/graphite lithium-ion cell: Understanding thermal behavior and estimation of degradation mechanism. *Journal of the Electrochemical Society*. 2002;**149**(8):A978-A982
- [27] Guldbæk Karlsen L, Villadsen J. Isothermal reaction calorimeters—I. A literature review. *Chemical Engineering Science*. 1987;**42**(5):1153-1164
- [28] Stefan Mathias Sarge GWHH, Hemminger W. *Calorimetry: Fundamentals, Instrumentation and Applications*. USA: Wiley; 2014
- [29] Khan MR, Swierczynski MJ, Kær SK. Determination of the behavior and performance of commercial Li-Ion pouch cells by means of isothermal calorimeter. In: 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER), USA: Institute of Electrical and Electronics Engineers (IEEE); 2016

- [30] Subramanian VR, Boovaragavan V, Diwakar VD. Toward real-time simulation of physics based lithium-ion battery models. *Electrochemical and Solid State Letters*. 2007; **10**(11):A255-A260
- [31] Khan MR, Kaer SK. Investigation of battery heat generation and key performance indicator efficiency using isothermal calorimeter. In: 2016 IEEE Vehicle Power and Propulsion Conference (VPPC), USA: IEEE; 2016
- [32] Pals CR, Newman J. Thermal modeling of the lithium/polymer battery. 2. Temperature profiles in a cell stack. *Journal of the Electrochemical Society*. 1995; **142**(10):3282-3288
- [33] Minassian LT, Milliou F. An isothermal calorimeter with pneumatic compensation-principles and application. *Journal of Physics E: Scientific Instruments*. 1983; **16**(5):450
- [34] Regensass W. Thermoanalytische methoden in der chemischen verfahrensentwicklung. *Thermochimica Acta*. 1977; **20**(1):65-79
- [35] Thomas KE, Newman J. Thermal modeling of porous insertion electrodes. *Journal of the Electrochemical Society*. 2003; **150**(2):A176-A192
- [36] Pals CR, Newman J. Thermal modeling of the lithium/polymer battery. 1. Discharge behavior of a single-cell. *Journal of the Electrochemical Society*. 1995; **142**(10):3274-3281
- [37] Khan MR. Thermal Management of Battery Systems in EV and Smart Grid Application. LAP Lambert Academic Publishing; 2017. p. 84
- [38] Khan MR. Thermal management of battery systems in electric vehicle and smart grid application. In: Department of Energy Technology. Aalborg University: Aalborg Universitetsforlag; 2016
- [39] Khan MR, Kær SK. Multiphysics based thermal modeling of a pouch lithium-ion battery cell for the development of pack level thermal management system. In: 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER), USA: Institute of Electrical and Electronics Engineers (IEEE); 2016
- [40] Khan MR, Kaer SK. Three dimensional thermal modeling of li-ion battery pack based on multiphysics and calorimetric measurement. In: 2016 IEEE Vehicle Power and Propulsion Conference (VPPC), USA: Institute of Electrical and Electronics Engineers (IEEE); 2016

