A comparative study of Li-ion batteries thermal behavior with different geometries,capacities,cathode materials

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Abstract

Li-ion batteries are nowadays widely used in electric vehicles, portable devices and smart grids. They are commercialized in different geometries, capacities and serval technologies depending on users' requirements. During operating time, heat is generated inside Li-ion batteries due to chemical reactions which causes temperature rise. Non-controllable thermal behavior of these batteries may lead to the deterioration of their performance and may also cause a thermal runaway. In this study, A comparison of the thermal behavior of five li-ion batteries is performed. Used batteries are: LFP (lithium iron phosphate) prismatic (72Ah,60Ah,20Ah), NMC (Nickel Manganese Cobalt) prismatic (53Ah) and NMC cylindrical (3Ah). All batteries are tested under different climate conditions (0°C,10°C,20°C,30°C) and consecutive charge/discharge cycles were applied. The application of consecutive charge/discharge cycles aims to describe the temperature profiles and difference with the ambient in quasi-stationary regime. Constant current was used during each charge/discharge cycle, maximum and minimum voltage recommended by manufactures were chosen as cut-off voltage. T-type thermocouples are used to measure the temperature. The results show a 'V' shape during a cycle in quasi-stationary regime for all tested batteries. Moreover, the temperature difference increases for decreasing ambient temperature. The batteries specific heat capacity and thermal conductivities were experimentally measured. The results show a linear increase of the specific heat capacity for increasing ambient temperature while no dependency of thermal conductivity to ambient temperature was observed.

Keywords: Li-ion batteries, Battery surface temperature, Charge/Discharge cycle.

I. INTRODUCTION

Recently, many studies have been focusing on enhancing the efficiency of the use of electric energy storage systems and electric engines used in transport sector [1,2]. these studies aim to introduce novel solutions based on clean energies sources to ensure reducing the world global emissions of CO_2 of which 24% is caused by transport sector [3] and to limit the dependency of this sector to fossil fuels [4]. One of the markets which is strongly progressing in last decades is the Li-ion batteries industries. Many electric vehicles and hybrid electric vehicles are using Li-ion batteries as energy source systems such as Nissan Leaf and Mitsubishi iMiev [5]. Nevertheless, many technical issues may damage the Li-ion batteries and lead to their ignition [6]. The thermal behavior of Li-ion batteries depends on many factors such as applied current, climate conditions and the used chemistries. Arsri et al. [7] proved in their study the obtention of higher battery temperature for higher discharge current. Furthermore, Schuster et al. [8] experimentally studied the effect of increasing charge and discharge from 5A to 40A on a 40Ah battery. The measured battery temperature rise was from 3°C to 11°K for a half cycle. Moreover, Panchal et al. [9] tested a 20Ah battery under different discharge current (1C and 3C) for different external ambient conditions (5°C,15°C,25°C,35°C). Their results show when increasing ambient temperature from 5°C to 35°C the battery average surface temperature rise from 10.1°C to 35.9°C for an applied current of 1C. While, for an applied current of 3C, the average surface temperature rises from 15.7°C to 40.3°C. In another side, the effect of battery internal chemistry on its thermal behavior was also studied by several researchers, Goutam et al. [10] studied the temperature profile for three different commercialized pouch batteries (20Ah NMC type, 14Ah LFP, 5Ah LTO). Same current rates were applied. The result show higher obtained temperature during charge compared to discharge. Moreover, NMC battery type temperature was the highest compared to the two other tested batteries.

The studies performed on batteries thermal behavior are supplied by the characterization batteries thermal parameters as they explain the thermal behavior. Madani et al. [11] reviewed experimental and analytical methods to determine internal resistance and entropic heat coefficient reacting inside the battery and affecting internal heat generation amounts and also battery specific heat and thermal conductivity. Murashko et al. [12] proposed a novel method to determine the specific heat of a pouch LTO battery cell. Results show no dependency of the specific heat to the battery SOC. Loges et al. [13] experimentally studied 7 commercialized cells manufactured with different chemistries. The results show a linear increase of specific heat capacity with ambient temperature. Moreover, a slight dependence to SOC lower than 2.5%. Al-zareer et al. [14] proposed a novel method to characterize the specific heat and thermal conductivities of three cylindrical batteries of different chemistries (NCA, NMC, LCO). Experimental measurements of voltage and temperature was used to determine battery internal heat

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generation and the inverse method was applied to determine the thermal properties. The obtained results show a specific heat of (1046 J. Kg^{-1}. K^{-1}, 1002J.Kg^{-1}. K^{-1}, 958.2J. Kg^{-1}. K^{-1}) for respectively the (NMC, LCO, NCA) batteries.

In the present paper, both a thermal behavior study and thermal parameters characterization were performed for different applied ambient temperature. Consecutive charge discharge cycles were applied on five li-ion batteries tested on a climate chamber to ensure same climate conditions. The effect of ambient temperature on batteries thermal behavior was investigated then measurements of battery thermal parameters were carried out to explain the thermal behavior.

II. Experimental setup

The charge and discharge experimental cycles were conducted using Chroma 17020 test bench. It is equipped with 8 charge/discharge chains with a maximum power and current of (1200W,60A) in each chain. Figure 1 illustrates the used test bench and the five Li-ion batteries tested in this research. Moreover, Table 1 summarize the tested batteries. Two different batteries chemistries were chosen LFP and NMC, this choice is justified by their wide use as energy storage systems in electric vehicles. All batteries were tested under their 1C-rate and consecutive charge discharge cycles were applied. The voltage cut-off of each battery is determined by the recommendation of its manufacture. T-type thermocouples were inserted in each battery and an average battery surface temperature is then determined to enable the comparison with other batteries. The chroma 17020 was connected to Battery pro graphical interface permitting the system control and data acquisition. To ensure same climate condition all batteries were tested inside a climatic chamber Weiss Technik. 4 different temperature (0°C,10°C,20°C,30°C) were tested to enable performing a comparative study of the effect of climate conditions on tested batteries thermal behavior.

Figure 1. Experimental setup and tested batteries inside the climate chamber

Table 1. Tested batteries.

Cathode material	Geometry	Capacity (Ah)	Voltage range (V)
LFP	Prismatic	72	(2.6-3.6)
LFP	Prismatic	60	(2.6-3.6)
LFP	Prismatic	20	(2.7-3.7)
NMC	Prismatic	53	(2.9-4.3)
NMC	Cylindrical	3	(2.6-4.1)

The measurement of batteries specific heat capacity and thermal conductivities were performed using a heat flow meter (Net-zsch HFM446) illustrated in Figure 2 this test bench gives the possibility to test samples with a maximum size of (203 mm, 203mm, 51mm). and applied temperature range varies from -20°C to 90°C. A high accuracy of measurement is ensured by the used heat flow meter lower than 2% as given by its manufacture.

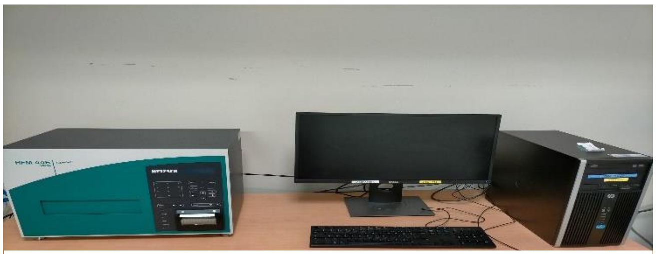

Figure 2. Heat Flow Mete test bench

III. Results analysis

A. Consecutive charge/discharge cycles

Figure 3 illustrates the results of the average temperature measured on battery surface for four batteries (LFP 72 Ah, LFP20 Ah, NMC 53 Ah, NMC 3Ah) and each battery was tested for different ambient temperatures (30°C,20°C,20°C,0°C). 1C-rate was applied on each battery and consecutive charge/discharge cycles were performed. the purpose is to characterize thermal regimes existing for all tested batteries. During the first charge cycle, the temperature of the 20Ah LFP battery rise strongly until attending a temperature of 5°C then the measured temperature is quietly constant during the rest of the test. Moreover, the temperature of the 72Ah battery rise strongly during all first charge cycle time and reaches a temperature of 19°C. Furthermore, the temperature of the 3Ah battery rise slightly first during the first charge cycle, then it decreases slightly. The temperature of the 53 Ah NMC battery rises strongly during the first half of the first charge cycle then slightly decreases until reaching 34°C in the end of the cycle. The batteries temperature rises during operating time because heat is generated inside them. Two main heat types could be defined. Reversible heat which depends to battery entropy and irreversible heat which is related to the battery internal resistance and proportional to the square of current [15]. The obtained experimental results show for the tested batteries the existence of a transient thermal regime in the first charge cycle followed by a quasi-stationary regime. This regime is characterized by a non-constant temperature during either charge or discharge cycle in a side and in another side the temperature profile is repetitive in each cycle. This phenomenon is due to the amount of internal heat generated in each cycle which could be considered approximately equals as same charge and discharge current are applied. Furthermore, this variation of temperature profile in the quasi-stationary regime is caused by the variation of battery entropy for each state of charge.

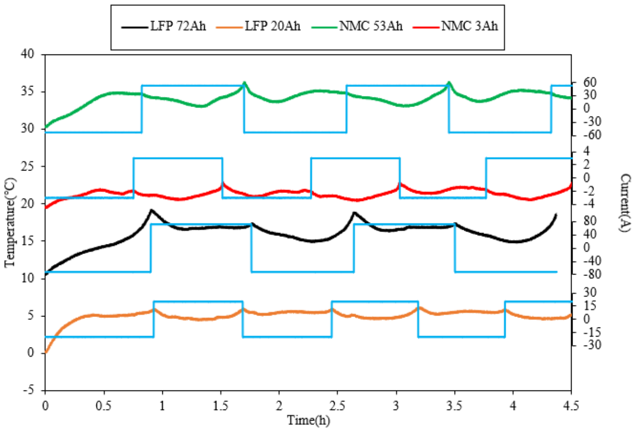

Figure 3. consecutive charge/discharge cycles applied for different ambient temperature and different battery chemistries.

thermal behavior

The effect of ambient temperature on battery temperature during quasi-stationary regime for 60Ah battery is presented in Figure 4 Same temperature profile was obtained for all tested ambient temperatures. The results show lower battery surface temperature rise for higher ambient temperature. In the beginning of charge cycle temperature decreases slightly then increases until the end of the cycle. Temperatures in the starting instant of the charge cycle obtained for ambient temperature of (0°C, 10°C, 20°C and 30°C) are respectively (6.87°C ,6.08°C, 4.36°C and 3.43°C) while in the end of the cycle are (6.40°C,5.36°C, 4.32°C and 3.31°C). The temperature profile in discharge cycle has same “V” shape profile as charge cycle. Nevertheless, the minimal temperature rise obtained in discharge cycle is slightly lower than the obtained in charge cycle. This is caused mainly by the difference of entropy coefficient during charge and discharge cycle [16].

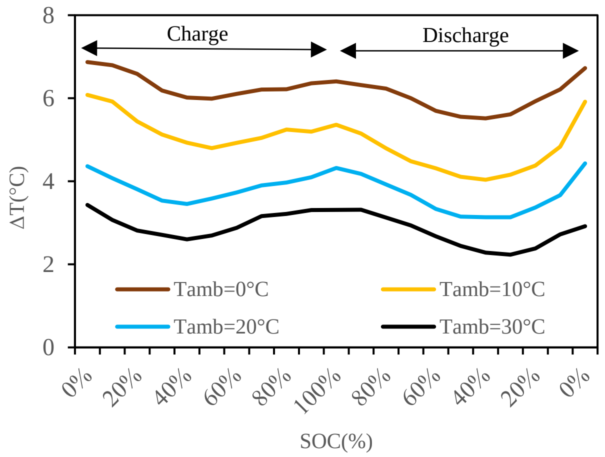

Figure 4. Effect of temperature on 60Ah battery temperature rise.

A comparison of temperature profile for three different batteries (NMC 53Ah, LFP 20Ah, NMC 3Ah) tested under a temperature of 10°C is shown if Figure 5. the decrease of temperature in the beginning charge cycle is related directly to the endothermic part of the entropic heat coefficient for a SOC of charge lower than 40% followed by an exothermic stage [17]. The slight difference between temperature profile in charge and discharge cycles is due mainly to the difference between the entropic coefficient during charge and discharge studied for three different batteries’ chemistries (NCA, LCO, LFP) in [18]. their results prove a hysteresis of the entropy coefficient and higher entropy during charge compared to discharge which explain our experimental results showing the difference in temperature profile. Moreover, even though all the three batteries were tested under 1C-rates different temperature rise were obtained. This is justified by the difference of applied current on each battery. The NMC 53Ah battery’s temperature is the highest as the applied current for this battery is the highest.

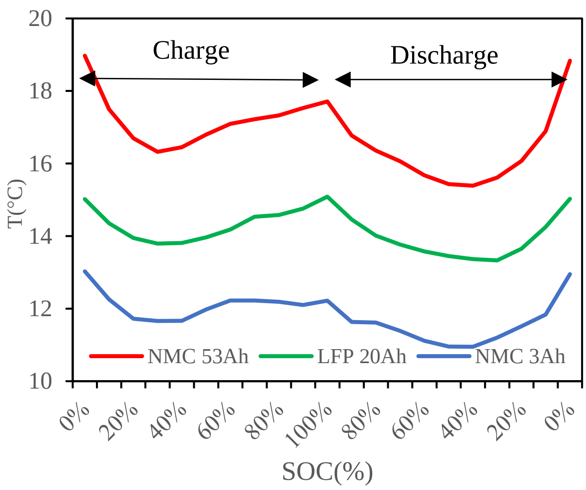

Figure 5. Comparison of temperature profile of different batteries in quasi-stationary regime Tamb=10°C.

Figure 6 illustrates the maximum temperature rise obtained for the five tested batteries and for 4 different applied ambient temperature (0°C,10°C,20°C,30C). For all tested batteries the temperature shows strong dependency to ambient temperature. The temperature of batteries rises basically due to internal heat generation, as the applied current is same in all ambient temperature for each battery. The dependency of battery temperature to environmental temperature could be explained by a change in the battery thermal properties. The internal resistance of battery tested by Wu et al. [19] was found to be dependent to ambient temperature. It decreases for increasing ambient temperature, this decrease is about 25% for an applied temperature ranging from 0°C to 25°C. The effect of ambient temperature was investigated on the battery entropy. The experimental study conducted by Bazinski et al. [20] show no dependency of the battery entropy to the ambient temperature. Additionally, the temperature obtained for the three LFP batteries was higher for higher battery capacities. Besides, the temperature of the NMC 53Ah battery was found to be higher than tested LFP batteries even if the ones who have higher capacity. This is due mainly to the strong thermal stability of LFP batteries comparing to NMC batteries [21].

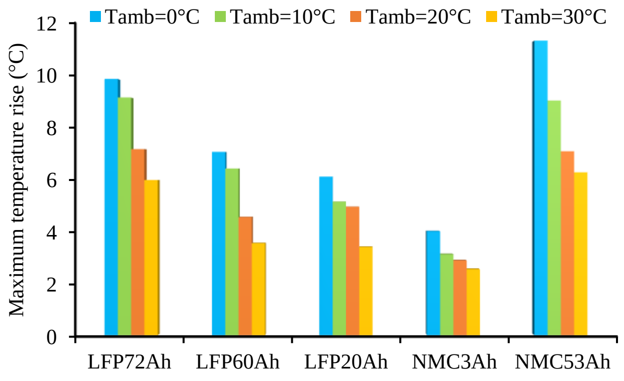

Figure 6. Different batteries maximum temperature rise for different ambient temperatures.

C. Measurement of specific heat capacity

In the previous section, five li-ion batteries thermal behavior was investigated for different climate conditions. A strong dependency of battery temperature to climate conditions was proven. This dependency is justified by the dependency of battery thermal parameters to environmental conditions. In this section the specific heat is measured for three batteries (LFP 60Ah, LFP 72Ah, NMC 53Ah). Figure 7 presents the applied cycles of temperature on each battery using the HFM 446 heat flow meter. Same applied battery thermal behavior ambient temperatures were applied to measure the battery specific heat capacity.

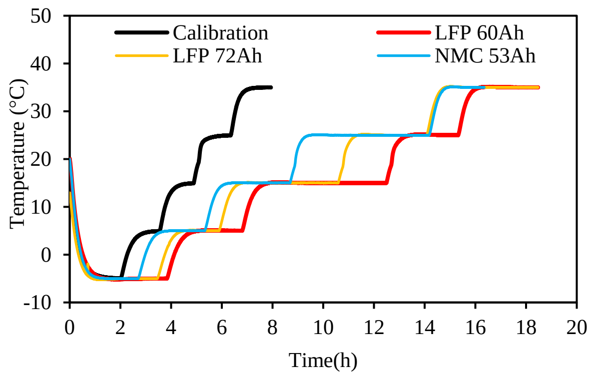

Figure 7. applied cycles to measure batteries specific heat capacity.

The results shown in Figure 8 present the specific heat capacity of three batteries versus temperature. A linear increase of the specific heat is obtained for increasing temperature. This result may give an appropriate explanation to the thermal behavior. For higher applied environmental temperature, the battery heat store capacity rise. Lower heat is dissipated via battery surface which explains the lower temperature rise.

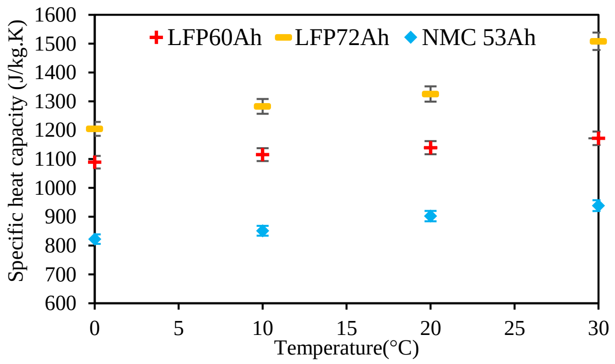

Figure 8. Measured specific heat capacity versus temperature.

D. Measurement of thermal conductivity

In this section, the thermal conductivity of tested batteries is discussed. The effect of temperature on battery thermal conductivity is illustrated in Figure 9 Three ambient temperatures were applied (10°C, 20°C, 30°C). Obtained experimental result show no dependency of thermal conductivity to ambient temperature.

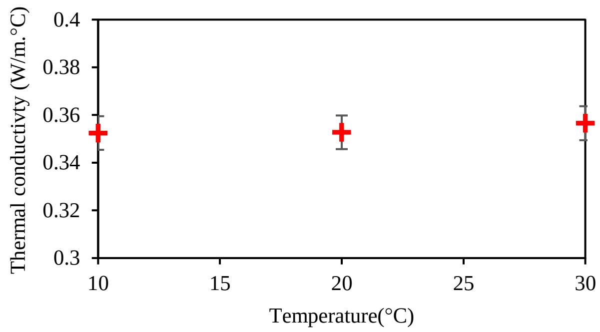

Figure 9. Measured thermal conductivity of the 60Ah LFP battery.

Figure 10 shows the results of the thermal conductivity measurement for three batteries under a temperature of 20°C. The LFP 60Ah has a low thermal conductivity comparing to the LFP 72Ah and NMC 53Ah. This is due basically to the effect of external shell which is made from plastic material.

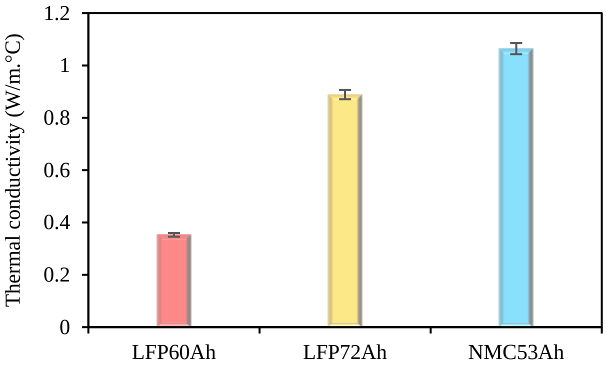

Figure 10. Comparison of the measured thermal conductivity of different batteries.

IV. Conclusion

The thermal behavior of five li-ion batteries is investigated for different ambient temperatures. The chemistries of the used batteries are LFP/graphite and NMC/graphite, two geometries were chosen prismatic and cylindrical. Each battery was tested under 1C rate and consecutive charge and discharge cycles were applied in similar climate conditions in each test to enable an accurate comparison of the results. During operating time, the temperature of all batteries rises due to internal heat generation. It reaches after cycling a quasi-stationary state in which the temperature is not constant, but it presents a repetitive profile in each one of the charge and discharge cycles. The profile of temperature in quasi-stationary regime has a “V” shape due to the strong dependency of the battery entropy to the SOC. The battery temperature depends strongly to applied climate conditions, Lower battery temperature rise is measured for higher ambient temperature. This phenomenon is due mainly to the influence of ambient temperature on the internal chemical compositions of batteries which causes a change of battery thermal parameters. Finally, the battery specific heat capacity and thermal conductivity were experimentally measured. Obtained results show a linear increase of battery specific heat capacity for increasing applied temperature while no dependency of thermal conductivity to the ambient conditions was noticed.

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