

Thermal Explosion Hazards Investigation on 18650 Lithium-ion Battery Using Extend Volume Accelerating Rate Calorimeter

Zhao C.P.¹, Sun J.H.¹, Wang Q.S.^{1,2,*}

¹ State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, China

² Key Laboratory of Materials for Energy Conversion, Chinese Academy of Sciences (CAS), University of Science and Technology of China, China

*Corresponding author's email: pinew@ustc.edu.cn

ABSTRACT

With the increase of lithium-ion batteries energy density and capacity, the thermal explosion is becoming a significant issue that can't be ignored. In this work, one kind of commercial 18650 lithium-ion battery with different states of charge (SOCs) and cycling times is used to evaluate the thermal explosion hazards by a ramp heating method in an extend volume accelerating rate calorimeter (EV-ARC). Some thermal characteristic parameters are selected and analyzed from the experiment trails, such as the cell surface temperature, temperature raise rate, canister internal pressure and average canister temperature. The experiment results show that the maximum surface temperature of the battery and the maximum canister internal pressure increase with the increase of SOC when the thermal explosion occurs. The thermal energy released from the battery under different SOCs during thermal explosion is calculated using the initial and the maximum temperature on the battery and the canister surface. A fully charged fresh battery can release 61.7 kJ energy when it gets into thermal explosion, which could be converted to an explosion TNT-equivalent of 5.57 g. Compared with fresh batteries, aging batteries are more prone to get into thermal explosion and the thermal explosion hazards increase.

KEYWORDS: Lithium-ion battery, EV-ARC, thermal explosion, thermal runaway.

INSTRUCTION

As a new type of clean energy, lithium-ion battery has been widely used in electric vehicles filled for its high energy density and long-life span, but thermal runaway (TR) with fire or even explosion will occur under some abuse conditions such as overheating, overcharging, crush and short circuit [1-3]. Nowadays, with the decreasing numbers of basic units in the battery pack and the increasing vehicle energy density, the new generation lithium-ion batteries would have higher energy density and specific capacity. Once the battery with higher specific energy got into thermal explosion (TE), it would certainly cause more severe damage. Hence, it is very vital to conduct the study on the TE hazards of high specific energy lithium-ion battery.

The safety behaviors of lithium-ion battery is affected by electrode materials, SOCs, cycling times, etc. [4-14]. The safety rank of cathode materials is LiFePO_4 (LFP) > LiMnO_4 (LMO) > $\text{LiNi}_x\text{Co}_y\text{Mn}_z\text{O}_2$ (NCM) > LiCoO_2 (LCO) [4-7]. Furthermore, the charged cells are more dangerous than discharged cells [8, 9], meanwhile the cells at high SOCs would release more energy when it gets into TR [10-12]. Aging also play an important role in lithium-ion battery safety, the cell which cycled many times at specific temperatures usually has a reduced thermal stability [13], e.g. the aging cells create an additional decomposition reaction before the fresh cells under the same abuse conditions [14]. Liu et al. [11] investigated the thermally-induced failure of 18650 cells with a

Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9), pp. 891-901

Edited by Snegirev A., Liu N.A., Tamanini F., Bradley D., Molkov V., and Chaumeix N.

Published by Saint-Petersburg Polytechnic University Press

ISBN: 978-5-7422-6498-9 DOI: 10.18720/spbpu/2/k19-22

Copper Slug Battery Calorimetry, the results showed that for LCO, LFP and NCM cells, the LCO cells released the highest energy of 37 kJ/cell at 100% SOC. Besides, the combustible materials released from failure cells would translate into another fire and/or explosion if the ventilation was poor. Lu et al. [10] also calculated the energy released by 18650 LCO cell at 4.2 V. The released energy measured by vent size packet 2 (VSP2) with a customized stainless steel canister was converted to 1.77 g TNT-equivalent. Chen et al. [9] improved the TNT-equivalent method [10] for the conversion of battery TE energy, and they found that the TNT-equivalent mass for one 18650 LCO cell at 100% SOC was 1.9 g. However, in research [9] and [10] the thermal energy absorbed by the air and canister were ignored, and these two parts of energy were also ignored in our previous work [15]. Yayathi et al. [12] analyzed the energy distributions exhibited for runaway lithium-ion batteries by extend volume accelerating rate calorimeter (EV-ARC) with a sealed canister, and the energy absorbed by the canister was 45-55% of the total energy. Christopher et al. [16], explored the influence of cell sizes on thermal runaway energetics on cells from 3 to 50 Ah, and the results showed that the normalized total heat released is relatively constant over that cell size range and the normalized heating rate increased with the increase of cell sizes.

In this paper, one kind of 18650 NCM battery was tested by the EV-ARC with a sealed canister. The total energy released from the cells was calculated and the value was converted to a TNT-equivalent. The cell surface temperature (T_{surf}) and the canister internal pressure (P_{inter}) during the whole test were recorded. The effects of SOCs and cycling times on TE hazards of sample cells were also discussed.

EXPERIMENTAL SETUP

A series of tests were carried out by the EV-ARC (THT Inc. England) [17] with a sealed stainless canister. The canister mass is 0.7 kg with a specific heat capacity of 0.5 kJ/(kg·K). There are 6 ports on the canister and the internal volume is 292 ml. One port is designed for the introduction of the thermocouple into the canister and one 1/16" port is to connect the pressure measurement line, the other 4 1/8" ports could be used for voltage monitoring wires, gas flushing, nitrogen inerting or for additional thermocouples. In our tests these four ports were tightened with plugs and the canister is initially filled with air [18]. To ensure the canister with leakage during the tests, the thermocouple port was sealed with epoxy (Araldite 2014-1) and the hole in the middle of the canister was sealed with a viton O-ring. Three thermocouples were set at different positions on the canister surface to get an average temperature.

A ramp heating method was used to induce the sample cells to get into TE. Compared with common EV-ARC tests, in this mode the "Start Temperature" value was set to 300 °C and the EV-ARC would overheat the sample until it got into TE. The advantage of this "ramp heating method" is that it can greatly reduce the duration time of the test (about 70-90 min for per test) and at the same time the TE onset temperature (T_0), the max cell surface temperature (T_{max}), the max canister internal pressure (P_{max}) and the average canister temperature (T_{avg}) could be picked up from the experiment trails. The battery explosion heat could be calculated using these data. However, the experiment results couldn't be used to estimate the exothermic onset temperature and the apparent kinetic parameters of the sample cells.

Figure 1a shows the picture of the sample cell located in the canister before tightening the lid and Fig. 1b shows the final test apparatus in the EV-ARC. In order to ensure reproducibility, at least 2 tests were conducted under each operating condition.

Figure 2 shows the picture of pre- and post-tests sample cell. The jelly roll was ejected from the can when the cell got into TE. The test sample is a commercial 18650 lithium-ion cell with 2000 mAh capacity, the cathode and anode materials are Li (Ni_{0.5}Mn_{0.2}Co_{0.3}) O₂ and graphite, respectively. The

operating voltage range is from 2.75 V to 4.2 V. In this work, the SOC of fresh cells were 25, 35, 50, 65, 75, 85, and 100%. And before being charged to the special SOC with a rate of 0.5 C, the fresh cells were cycled 3 times with 0.5 C at ambient temperature (25 °C). For the aging cells, they were cycled with 1 C at ambient temperature with 100, 200, 300 and 400 times and were finally fully charged with 0.5 C.



Fig. 1. The illustration of the canister (a) [15] and the final test apparatus in the EV-ARC (b).



Fig. 2. The picture of the sample cells before and after the EV-ARC test. After the test the cell can ruptured and some broken electrodes ejected from the cell.

RESULTS AND DISCUSSION

The initial temperature of thermal explosion

According to Fig. 3a, the whole experimental progress could be divided into 3 stages with 2 critical temperatures (T_{vent} and T_0) [19, 20].

Stage 1: The T_{surf} and the T_{avg} rises slowly, as shown in Fig. 4. The rise rate of T_{surf} is also relatively moderate. In stage 1, the battery capacity starts to fade that is caused by the fact that lithium-ion deintercalated from anode [21, 22]. Then the solid electrolyte interface (SEI) starts to decompose. Without the protection of SEI the anode begins to react with the electrolyte to release some heat [23, 24]. When the temperature continues to get higher, the separator starts to melt, thus making some micro short circuit points appear. Although the separator melting reduces the temperature rise rate, soon an accelerating process appears because of the micro internal short circuit [25].

Stage 2: When the cell surface temperature gets to $T_{vent} = 176$ °C, a temperature rise rate reduce and a small pressure rise can be observed as shown in Fig. 3. At T_{vent} , the cell safety valve opens and some gas leak from the cell to reduce the cell internal pressure. In stage 2, the internal short circuit

continues and the cathode begins to react with the electrolyte [2, 3]. Besides, the temperature rise rate is significantly higher than that in stage 1.

Stage 3: When the cell surface temperature gets to $T_0=234\text{ }^\circ\text{C}$, the temperature growth rate increases rapidly and a significant pressure rise can be observed as shown in Fig. 3b. In Fig. 4, the cell surface temperature begins to rise exponentially, thus meaning the sample gets into TE. So, T_0 was defined as the initial temperature of TE in this paper.

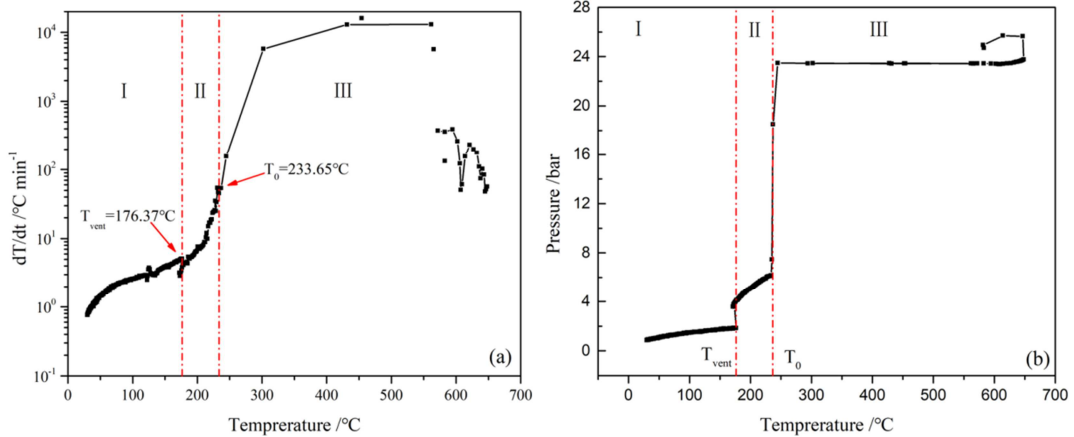


Fig. 3. The test data profiles of fresh cell at 75% SOC: (a) cell surface temperature rise rate versus cell surface temperature; (b) canister internal pressure versus cell surface temperature.

INFLUENCE OF THE SOC ON THERMAL EXPLOSION HAZARD OF FRESH CELLS

Transient data was collected throughout each test for T_{surf} , T_{avg} and P_{inter} . All tests were conducted when the T_{surf} reached $30\text{ }^\circ\text{C}$. Figure 4 shows the temperature (both T_{surf} and T_{avg}) and P_{inter} profiles for 4 picked tests. Noting that the O-ring would get damaged when the pressure exceeds about 24 bar, so the peak pressure for high SOC (75, 85, and 100%) samples got down in several minutes rather than maintained for stable value, as shown in Fig. 4. All peak temperatures and pressures are marked in each figure. The trend of three curves of each test is consistent as shown in Fig. 4; T_{surf} is lower than T_{avg} until the sample gets T_0 , then T_{surf} goes up exponentially and there is also a rapid increase for P_{inter} . T_0 is a critical point between T_{surf} and T_{avg} . Before this point, the canister is heated directly by the EV-ARC and then the cell is heated by the hot canister, so the T_{avg} is higher than the T_{surf} . After this point, there is a series of violent exothermic reactions happening in the cell [2, 3], which release amount of energy to make the cell and canister temperature rise instantly. The P_{inter} has two jumps during the entire experiment: (1) The cell safety valve opens to release a bit of gas and energy, which makes the pressure rise slightly by about 1.46 bar (an average value for 15 tests). This slight ejection also causes the cell surface temperature to decrease slightly, but it rebounds quickly; (2) The cell gets into TE, a large amount of gas, tiny solids and energy are ejected from the cell to make the pressure increase significantly. Besides, some energy is absorbed by the canister, causing a sharp temperature jump of the canister.

Figure 5 shows the change curves of T_{surf} and P_{inter} with time under different SOC. It can be observed that, overall, the time from cell started to be heated to TE (t_{TE}) increases as its SOC decreasing, and 100% SOC is about 13 min earlier than 25% SOC. Meanwhile, when a cell gets into TE, the higher the SOC is, the higher the maximum cell surface temperature and the canister internal pressure is. In Fig. 5, the maximum pressure is 36.2 bar at $682\text{ }^\circ\text{C}$ of 100% SOC, while for 25% SOC it's 14.2 bar at $476\text{ }^\circ\text{C}$.

The critical statistics of fresh cells is summarized in Table 1. When the battery gets into TE, overall, the maximum temperature and the maximum pressure increase with the increase of SOC, but the initial temperature/pressure of vent and TE varied little from 25 to 100% SOC, while in high SOC's (75, 85, and 100%) these values get a little lower. It's probably caused by the experimental errors. The mass loss at 100 and 85% SOC are higher than other conditions, the quality of the loss includes electrolyte solution and some electrode materials. T_{max} increases with the increase of SOC as shown in Fig. 6, and the value between 25 and 35% SOC is very close as well as for 75 and 85% SOC.

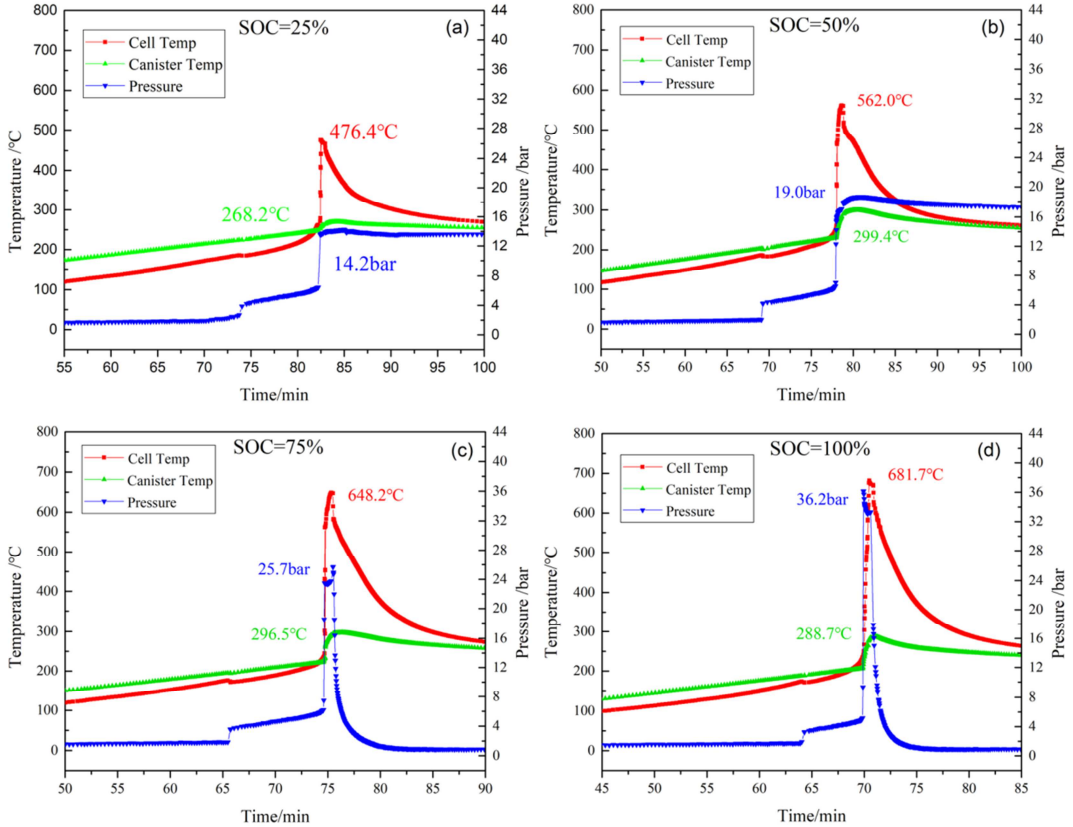


Fig. 4. The sample data of typical operating conditions: fresh cell at 25, 50, 75, and 100% SOC.

The pressure increase trend is more obvious and regular. As shown in Fig. 6, the pressure values could be approximated as an arithmetic progression with a tolerance of 3 from 25 to 85% SOC until it suddenly rises at 100% SOC. The pressure value at 100% SOC is about 1.3 times of the value at 85% SOC, and about 2.5 times of the value at 25% SOC. This may be caused by the violent internal reaction of 100% SOC, which caused more flammable gas releasing and at high SOC's even a gas explosion [26] would occur in the canister. Besides, the cell doesn't go to TE at 0% SOC and some electrolyte solution released from the cell was found on the bottom of the canister, Wu et al. [27] had confirmed this point in their research.

Table 2 shows the state of health (SOH) of these aging cells, the capacity loss is not obvious when cycle times is less than 300. When the cells are cycled 400 times, the capacity decreases to less than 80%, which can be regarded as scrap [24, 28]. Compared with fresh cells (0.5 C, 3 cycles at ambient temperature), the t_{TE} of aging cells are advanced, and the more cycles the cell has, the easier the cells get into TE. In Fig. 7, both the peak temperature and peak pressure of fresh cells and aging

cells are close, but the aging cells are more prone to get into TE. For 400-cycles-cell, the t_{TE} is about 15 min ahead of fresh cells. 100, 200 and 300-cycles-cells have similar capacity fade and thermal profiles. Although their capacity fade is not obvious, the t_{TE} is still shorter than fresh cells. This may be caused by some irreversible changes, including active material loss, electrolyte reduction and lithium deposition [13, 14, 29].

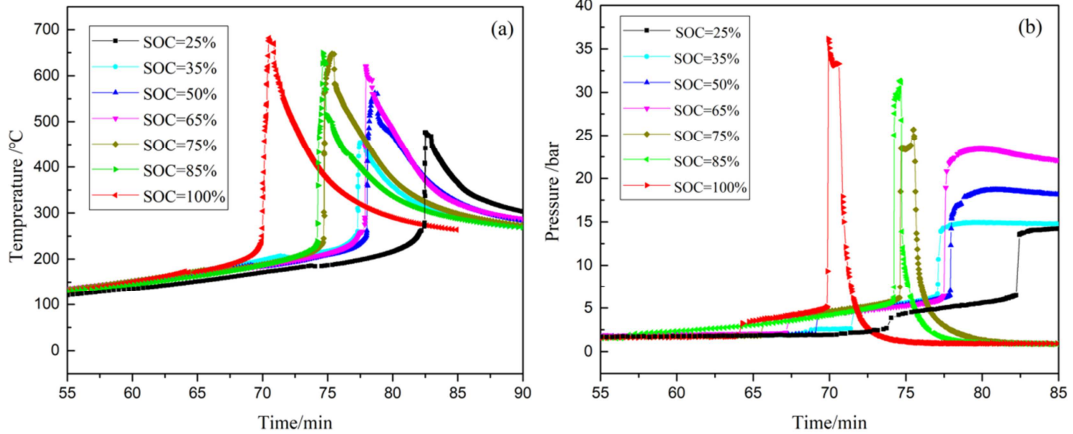


Fig. 5. The test data profiles of fresh cells at different SOC: (a) the comparison cell surface temperature; (b) the comparison of canister internal pressure.

Table 1. Summary of the experimental data from the fresh cells

SOC, %	Mass, g	Loss mass, g ^c	Vent ^b		Start of TE		Thermal Explosion	
			T_{vent} , °C	P_{vent} , bar	T_0 , °C	P_0 , bar	T_{max} , °C	P_{max} , bar
25	44.16	6.98	197.0	2.4	265.5	6.8	454.2	14.4
35 ^d	43.62	8.99	191.3	2.0	251.5	6.1	462.8	15.0
50	44.00	6.33	185.5	1.9	246.2	6.2	528.7	18.2
65 ^d	42.98	7.26	184.3	1.9	267.2	5.8	632.9	20.5
75	43.56	7.87	167.1	1.6	248.8	5.6	687.6	23.3
85	43.91	10.45	177.2	1.7	247.5	5.8	689.5	27.0
100	44.05	12.88	169.4	1.5	237.3	4.6	727.6	36.3

^a All calculations were the average of two tests except 100% SOC, in this condition there were 3 tests.

^b T is the cell surface temperature, P is the canister internal pressure, 1 bar = 100000 Pa.

^c Pre-test and post-test mass were measured to determine the overall mass loss of the cells.

^d These data come from our previous work [15].

Table 2. The state of health (SOH) of ageing cells

Numbers	Initial capacity, mAh	Remained capacity, mAh	SOH
Fresh	-	-	100%
100	2010	2000	99.5%
200	2100	2000	95.2%
300	2040	1972	96.7%
400	1925	1574	79.2%

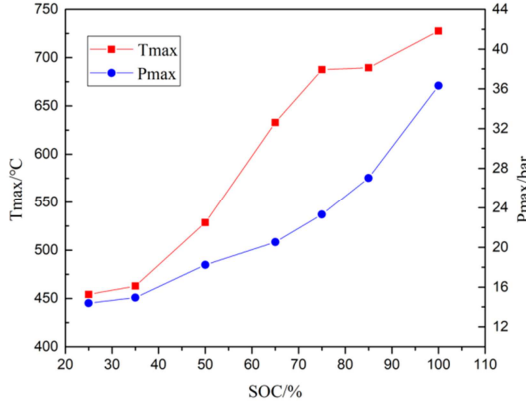


Fig. 6. The maximum battery surface temperature and the pick pressure of fresh cells.

INFLUENCE OF CYCLE TIMES ON THE THERMAL EXPLOSION HAZARD OF CELLS

Table 3 shows the average of the two experiment results. Except for the T_0 and T_{max} , the other key experimental values are very close. The 400-cycles-cell shows the lowest T_0 , 205 °C, which is about 32 °C lower than the fresh cells. The fresh cells show the highest T_{max} , 728 °C, while the T_{max} of 400-cycles-cell is only 552 °C, but still higher than 100-cycles-cell, which has the highest external pressure, 36.9 bar.

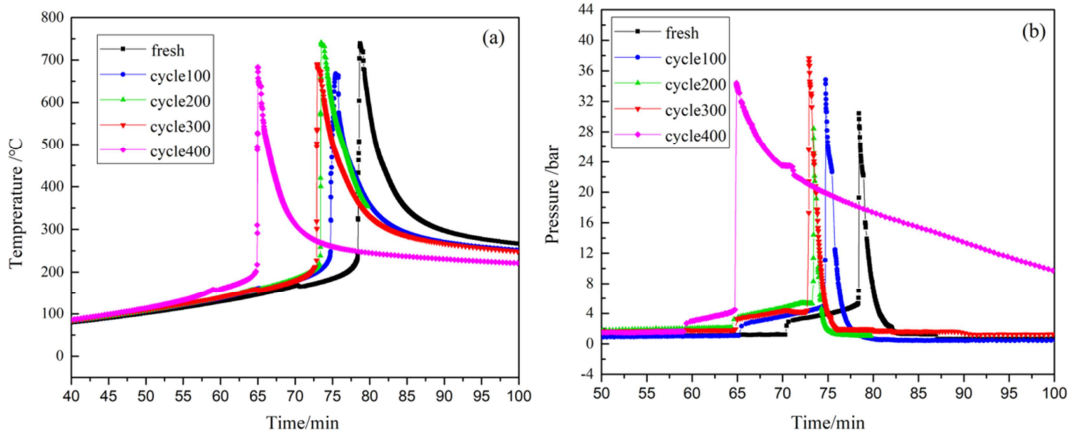


Fig. 7. The test data profiles of aging cells at 100% SOC: (a) the comparison of cell surface temperature; (b) the comparison of canister internal pressure.

Table 3. Summary of the experimental data from the aging cells

Cycle	Mass, g	Loss mass, g	Vent		Start of TE		Thermal Explosion	
			T_{vents} , °C	P_{vents} , bar	T_0 , °C	P_0 , bar	T_{max} , °C	P_{max} , bar
Fresh	44.05	12.88	169.4	1.48	237.3	4.51	727.6	36.33
100	44.24	13.11	158.8	1.16	228.1	4.84	534.8	39.31
200	43.69	14.42	161.5	1.98	219.7	5.43	635.8	34.08
300	43.65	15.09	159.0	1.92	220.3	4.65	699.3	35.87
400	43.23	14.20	156.7	1.36	205.0	4.68	551.7	36.63

ENERGY CALCULATION AND CONVERSION

By knowing the mass, the specific heat capacity and the transient temperature profiles, the total energy released from batteries during the TE can be calculated. The total energy is a combination of the energy which raises the cell temperature and the canister temperature, we ignore the energy raising canister internal gas temperature because it is difficult to calculate and the value is very small [8, 12]. The calculation method is shown in Eq. (1)

$$\Delta H = C_p m (T_{\max} - T_0), \quad (1)$$

where ΔH is the energy (kJ), C_p is the specific heat capacity (kJ/(kg·K)), m is the mass of sample cell or canister (kg), T_{\max} is the maximum temperature of the cell surface and canister surface (the average value) (°C), T_0 is the initial temperature of cell surface and canister surface (°C). Note that the temperature of canister is an average of three data and the C_p of sample cell is measured by the EV-ARC, which is 1.06 kJ/(kg·K), for canister C_p is 0.5 kJ/(kg·K). In order to get a more intuitive interpretation of the energy released from the cells, we use the TNT-equivalent method to convert the thermal energy to TNT-equivalent [10]. The conversion method is shown in Eq. (2) [9]

$$W = \frac{\eta \Delta H}{H_{TNT}^{1/3}}, \quad (2)$$

where W is the TNT-equivalent (g TNT), η is the empirical mass of TNT (1-15 mass%, in general) and in this study we take 15% [9], H_{TNT} is the explosive heat of TNT, for which a typical value is 4.437 kJ/g. The amount of gas produced from the cell is calculated using the ideal gas law and the pressure data, note that we replace the gas temperature with the T_{surf} for there is only one thermocouple port on the canister. The estimate method is shown in Eq. (3) [19, 30]

$$n = \frac{pV}{RT} - n_0 = \frac{pV}{RT} - \frac{p_0V}{RT_0}, \quad (3)$$

where P is the recorded pressure (Pa), $V = 2.92 \times 10^{-4} \text{ m}^3$ is the canister internal volume, T is the cell surface temperature (K), $R = 8.314 \text{ J/(mol·K)}$ is the ideal gas constant. The calculation results are shown in Table 4. For fresh cells, the total energy released from the cells increases with the increase of SOC, and the average 100% SOC energy release is 61.72 kJ, which is equivalent to 5.57 g TNT. Furthermore, 116.6 mmol gas is released by the cell during the whole test. For aging cells, over all, the total thermal energy is lower than fresh cells at 100% SOC, which is close to fresh cells at 75 and 85% SOC. However, the 400-cycles-cell releases 148 mmol gas and there is only 72.3 mmol and 92.3 mmol for 75 and 85% SOC. The total energy released from 300-cycles-cell is higher than other aging cells, the value is 56.5 kJ which is close to fresh cells at 100% SOC. In this situation the cell is at the junction of capacity fade and thermal stability decreasing. Although the electrochemical energy stored in the cell body is the same as fresh cells, the internal state is similar to 400-cycles-cell. So, the 300-cycles-cell releases much more thermal energy while it still maintains the similar thermal profiles to 100 and 200-cycles-cell.

Figure 8 shows the energy distribution and the normalized θ [12]. The fresh cells at 100% SOC release the highest energy and the thermal energy absorbed by the canister is the 54-69% of the total energy in all experiments. For fresh cells, the normalized θ decreases with the increase of SOC, but for the aging cells it increases with the increase of cycle numbers. This ratio indicates that the thermal energy caused by cell thermal explosion is higher than the electrochemical energy stored in the cell.

Table 4. Characteristic calculated average values in the thermal-explosion experiments

Item	Cell energy, kJ	Canister energy, kJ	Total energy, kJ	Electrochemical Energy ^b , kJ	W, g TNT	θ^a	N, mmol
Fresh-25%	8.84	12.49	21.33	6.51	1.92	3.28	53.73
Fresh-35%	9.77	14.74	24.51	9.13	2.21	2.69	56.66
Fresh-50%	13.17	18.59	31.76	13.25	2.86	2.40	64.75
Fresh-65%	16.63	22.53	39.16	17.41	3.53	2.25	65.23
Fresh-75%	20.26	28.88	49.15	20.08	4.43	2.45	72.29
Fresh-85%	20.58	25.88	46.45	22.81	4.19	2.04	92.28
Fresh-100%	22.91	38.80	61.72	27.57	5.57	2.24	116.6
Cyc-100	14.36	31.90	46.27	27.59	4.17	1.68	165.0
Cyc-200	19.28	29.74	49.01	27.81	4.42	1.76	122.1
Cyc-300	22.16	34.37	56.53	27.47	5.10	2.06	113.7
Cyc-400	15.77	30.37	46.14	22.24	4.16	2.07	148.2

^a The dimensionless θ factor is the total calculated energy released to the electrochemical energy ratio.

^b The cell electrochemical energy was obtained from the battery test system.

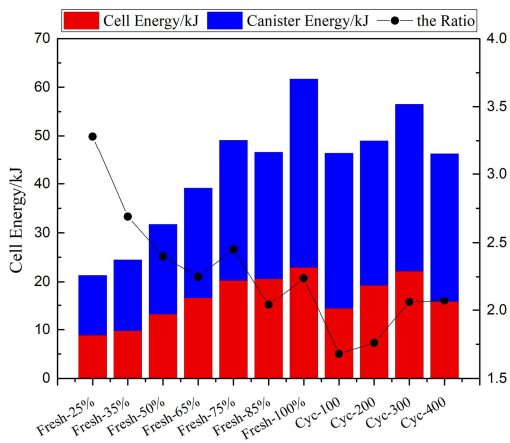


Fig. 8. Comparison of the energy distribution and the ratio (θ).

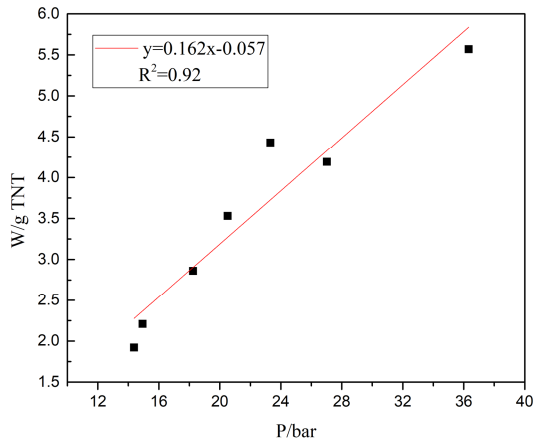


Fig. 9. The explosion equivalent versus the peak canister internal pressure.

According to Table 1 and 4, the total energy increases with the increase of SOC, but the regularity of the maximum surface temperature is not very clear, which is related to the accuracy of the thermocouple and the calorimeter. On the contrary, the peak pressure has the similar variation tendency to the total energy released from the fresh cells. Figure 9 shows the relationship between peak pressure and explosion heat equivalent. It can be seen that the explosion heat equivalent is a linear function of peak pressure, that is, the greater the external pressure, the higher the explosion heat equivalent of the battery, and the higher the thermal explosion hazards, which is more convenient and intuitive than calculating the total energy released from the batteries.

CONCLUSIONS

The thermal explosion hazards of a commercial 18650 NCM cell at various SOCs and cycle numbers were studied by extend volume calorimeter with a ramp heating method. In this study, both

fresh cells and aging cells were charged to specific SOCs, and then put into the EV-ARC to be heated until they got into thermal explosion. A sealed canister was designed to measure the external pressure and the considerable energy released from a thermal runaway battery. The experimental results indicated that the thermal explosion hazards of 18650 lithium-ion battery increase with the increase of SOCs and cycle numbers. For fresh cells, the cells at 100% SOC released the highest thermal energy of 61.7 kJ (equivalent to 5.57 g TNT), the highest runaway temperature of 728 °C, the highest peak pressure of 36.3 bar and the most gas of 116.6 mmol. For aging cells, the time from started to be heated to thermal explosion decreased with the increase of cycle numbers, and the time for 400-cycles-cell was about 15 min ahead of fresh cells at 100% SOC, besides, the 400-cycles-cell had the lowest initial temperature at 205 °C, which was 32 °C lower than that of fresh cells with the same SOC. For fresh cells, the peak pressure showed a much more similar tendency to the total energy released from the cells at different SOCs, so it could be used as one of the judge standard of the thermal explosion hazards that the higher the peak pressure, the higher the thermal explosion hazards.

ACKNOWLEDGEMENT

This work was supported by the National Key R&D Program of China (No.2016YFB0100305), the National Natural Science Foundation of China (No. 51674228), the External Cooperation Program of BIC, CAS (No. 211134KYSB20150004) and the Fundamental Research Funds for the Central Universities (No. WK2320000038). Dr. Q.S Wang is supported by Youth Innovation Promotion Association CAS (No.2013286).

REFERENCE

- [1] S.-i. Tobishima, J.-i. Yamaki, A Consideration of Lithium Cell Safety, *J. Power Sources* 81-82 (1999) 882-886.
- [2] Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, C. Chen, Thermal Runaway Caused Fire and Explosion of Lithium Ion Battery, *J. Power Sources* 208 (2012) 210-224.
- [3] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, X. He, Thermal Runaway Mechanism of Lithium Ion Battery for Electric Vehicles: A Review, *Energy Storage Mater.* 10 (2018) 246-267.
- [4] J. Jiang, J.R. Dahn, ARC Studies of the Thermal Stability of Three Different Cathode Materials: LiCoO₂; Li[Ni_{0.1}Co_{0.8}Mn_{0.1}]O₂; and LiFePO₄, In LiPF₆ and LiBoB EC/DEC Electrolytes, *Electrochem. Commun.* 6 (2004) 39-43.
- [5] Y. Wang, J. Jiang, J.R. Dahn, The Reactivity of Delithiated Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O₂, Li(Ni_{0.8}Co_{0.15}Al_{0.05})O₂ or LiCoO₂ with Non-aqueous Electrolyte, *Electrochem. Commun.* 9 (2007) 2534-2540.
- [6] T.M. Bandhauer, S. Garimella, T.F. Fuller, A Critical Review of Thermal Issues in Lithium-Ion Batteries, *J. Electrochem. Soc.* 158 (2011) R1-R25.
- [7] C.-Y. Jhu, Y.-W. Wang, C.-Y. Wen, C.-M. Shu, Thermal Runaway Potential of LiCoO₂ and Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O₂ Batteries Determined with Adiabatic Calorimetry Methodology, *Appl. Energy* 100 (2012) 127-131.
- [8] C.Y. Jhu, Y.W. Wang, C.M. Shu, J.C. Chang, H.C. Wu, Thermal Explosion Hazards on 18650 Lithium Ion Batteries with a VSP2 Adiabatic Calorimeter, *J. Hazard. Mater.* 192 (2011) 99-107.
- [9] W.-C. Chen, Y.-W. Wang, C.-M. Shu, Adiabatic Calorimetry Test of the Reaction Kinetics and Self-heating Model for 18650 Li-ion Cells in Various States of Charge, *J. Power Sources* 318 (2016) 200-209.
- [10] T.-Y. Lu, C.-C. Chiang, S.-H. Wu, K.-C. Chen, S.-J. Lin, C.-Y. Wen, C.-M. Shu, Thermal Hazard Evaluations of 18650 Lithium-ion Batteries by an Adiabatic Calorimeter, *J. Therm. Anal. Calorim.* 114 (2013) 1083-1088.

- [11] X. Liu, Z. Wu, S.I. Stoliarov, M. Denlinger, A. Masias, K. Snyder, Heat Release During Thermally-induced Failure of a Lithium Ion Battery: Impact of Cathode Composition, *Fire Saf. J.* 85 (2016) 10-22.
- [12] S. Yayathi, W. Walker, D. Doughty, H. Ardebili, Energy Distributions Exhibited During Thermal Runaway of Commercial Lithium Ion Batteries Used for Human Spaceflight Applications, *J. Power Sources* 329 (2016) 197-206.
- [13] M. Börner, A. Friesen, M. Grützke, Y.P. Stenzel, G. Brunklaus, J. Haetge, S. Nowak, F.M. Schappacher, M. Winter, Correlation of Aging and Thermal Stability of Commercial 18650-type Lithium Ion Batteries, *J. Power Sources* 342 (2017) 382-392.
- [14] A. Friesen, F. Horsthemke, X. Monnighoff, G. Brunklaus, R. Krafft, M. Borner, T. Risthaus, M. Winter, F.M. Schappacher, Impact of Cycling at Low Temperatures on the Safety Behavior of 18650-type Lithium Ion Cells: Combined Study of Mechanical and Thermal Abuse Testing Accompanied by Post-mortem Analysis, *J. Power Sources* 334 (2016) 1-11.
- [15] C. Zhao, Q. Wang, Y. Yu, Thermal Explosion Hazards of Lithium-ion Batteries in Hermetic Space, *Energy Storage Sci. Technol.* 7 (2018) 424-430.
- [16] C. Orendorff, J. Lamb, L.A. Steele, S.W. Spangler, J. Langendorf, Quantification of Lithium-ion Thermal Runaway Energetics, Report No. SAND2016-0486, Sandia National Lab., 2016.
- [17] Thermal Hazard Technology. <http://www.thermalhazardtechnology.com/downloads>.
- [18] S. Koch, A. Fill, K.P. Birke, Comprehensive Gas Analysis on Large Scale Automotive Lithium-ion Cells in Thermal Runaway, *J. Power Sources*, 398 (2018) 106-112.
- [19] A.W. Golubkov, D. Fuchs, J. Wagner, H. Wiltsche, C. Stangl, G. Fauler, G. Voitic, A. Thaler, V. Hacker, Thermal-runaway Experiments on Consumer Li-ion Batteries with Metal-oxide and Olivin-type Cathodes, *RSC Adv* 4 (2014) 3633-3642.
- [20] M. Lammer, A. Koenigseder, V. Hacker, Holistic Methodology for Characterisation of the Thermally Induced Failure of Commercially Available 18650 Lithium Ion Cells, *Rsc Adv.* 7 (2017) 24425-24429.
- [21] K. Takei, K. Kumai, Y. Kobayashi, H. Miyashiro, N. Terada, T. Iwahori, Tanaka, Cycle Life Estimation of Lithium Secondary Battery by Extrapolation Method and Accelerated Aging Test, *J. Power Sources* 97-98 (2001) 697-701.
- [22] X. Han, M. Ouyang, L. Lu, J. Li, Y. Zheng, Z. Li, A Comparative Study of Commercial Lithium Ion Battery Cycle Life in Electrical Vehicle: Aging Mechanism Identification, *J. Power Sources* 251 (2014) 38-54.
- [23] P. Biensan, B. Simon, J.P. Peres, A.d. Guibert, M. Broussely, J.M. Bodet, On Safety of Lithium-ion Cells, *J. Power Sources* 81-82 (1999) 906-912.
- [24] M. Fleischhammer, T. Waldmann, G. Bisle, B.-I. Hogg, M. Wohlfahrt-Mehrens, Interaction of Cyclic Ageing at High-rate and Low Temperatures and Safety in Lithium-ion Batteries, *J. Power Sources* 274 (2015) 432-439.
- [25] X. Feng, M. Fang, X. He, M. Ouyang, L. Lu, H. Wang, M. Zhang, Thermal Runaway Features of Large Format Prismatic Lithium Ion Battery Using Extended Volume Accelerating Rate Calorimetry, *J. Power Sources* 255 (2014) 294-301.
- [26] F. Larsson, S. Bertilsson, M. Furlani, I. Albinsson, B.-E. Mellander, Gas Explosions and Thermal Runaways During External Heating Abuse of Commercial Lithium-ion Graphite-LiCoO₂ Cells at Different Levels of Ageing, *J. Power Sources* 373 (2018) 220-231.
- [27] T. Wu, H. Chen, Q. Wang, J. Sun, Comparison Analysis on the Thermal Runaway of Lithium-ion Battery Under Two Heating Modes, *J. Hazard Mater.* 344 (2017) 733-741.
- [28] W. He, N. Williard, M. Osterman, M. Pecht, Prognostics of Lithium-ion Batteries Based on Dempster-Shafer theory and the Bayesian Monte Carlo Method, *J. Power Sources* 196 (2011) 10314-10321.
- [29] T. Waldmann, M. Wilka, M. Kasper, M. Fleischhammer, M. Wohlfahrt-Mehrens, Temperature Dependent Ageing Mechanisms in Lithium-ion Batteries – A Post-Mortem Study, *J. Power Sources* 262 (2014) 129-135.
- [30] P. Huang, P. Ping, K. Li, H. Chen, Q. Wang, J. Wen, J. Sun, Experimental and Modeling Analysis of Thermal Runaway Propagation Over the Large Format Energy Storage Battery Module with Li₄Ti₅O₁₂ Anode, *Appl. Energy* 183 (2016) 659-673.