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Research Article

Experimental Study of Air-Cooling System for Thermal Runaway Prevention of Nickel-Manganese-Cobalt Oxide (NMC) Battery Cells in Electric Vehicles

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Abstract:
Battery thermal runaway (BTR) is a critical safety concern in electric vehicles (EVs), where heat generated within the battery can spread to adjacent cells, potentially causing explosions. This study investigates 18650-type NMC cylindrical cells to develop strategies for preventing battery fires linked to internal short circuits (ISCs) and self-heating, which can lead to BTR. We analyzed the impacts of battery surface temperature, blower speed, and cooling duration on preventing BTR. An air-cooling system was utilized to maintain surface temperatures at 90 ℃, 95 ℃ and 100 ℃, with air velocities at 1.92 m/s and cooling times of 5, 10, and 15 minutes. While BTR occurred with insufficient cooling time, cells cooled for at least 10 minutes at 90 ℃ and 95 ℃ showed no BTR signs. Importantly, at 100 ℃, no ISCs were observed after 15 minutes of cooling, demonstrating the effectiveness of proper cooling in preventing BTR.

Keywords: *Battery thermal runaway, Air-cooling system, Internal Short Circuit, Cooling-time, Electric vehicle*

1. Introduction

Global temperature is currently rising, melting polar ice, and raising sea levels, with increased greenhouse gas effects. These problems are caused by global warming. At this present, the primary source of these pollutants is internal combustion engines, and much air pollution is emitted. Therefore, development of low-emission engines is being done. Alternative vehicles, such as electric vehicles (EVs), are more popular. EVs are widely used today because of their low maintenance, no need for fossil fuel, convenience, and no emissions. However, internal combustion engines are still more popular as electric vehicles have limited driving range, battery capacity, and risk battery explosion. Lithium-ion batteries (LIB) are widely used in electric vehicles because of their high energy density, long life cycle, and high-power density. The most common batteries used in EVs are Nickel Manganese Cobalt (NMC) and Lithium Ferro Phosphate (LFP) types. NMC batteries have less thermal runaway resistance than LFPs. High-efficiency electric vehicles have greater power requirements. Batteries need to be connected in parallel and series to form battery packs that may accumulate heat and risk thermal runaway. Thermal runaway is exacerbated by three types of abuse, mechanical, electrical, and thermal abuse. Battery thermal runaway occurs resulting from abuse which may end in a battery fire and explosion. Wang et al. studied thermal runaway mechanisms and chain reactions [1]. Thermal runaway is a serious problem that needs significant study. Zhang et al. studied thermal runaway suppression using various extinguishing agents in open space [2]. Much research was done on ways to prevent thermal runaway using strategies such as air cooling [3,4], water cooling [5], and phase change materials (PCMs) [6], among other approaches. Presently, thermal runaway is a main problem of the battery that many researchers are interested. Liu et al. [7] studied the effect of pressure on thermal runaway.

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They found that the high ambient pressure could lead to the severer thermal runaway. Yuan et al. [8] studied the vented gases from lithium-ion cells during the TR processes.They found the gases that released from the cells are CO, CO_2, H_2, CH_4, C_2H_2, C_2H_4, C_2H_6. The thermal runaway behavior with different percentages of State of Charge (SOC) was studied by Huang et al. [9] and Yi X [10]. The batteries with more SOCs and greater thermal runaway severity were found. The past research of cooling system was also studied to exhibit thermal runaway such as air-cooling system by Wang et al. [11], liquid-cooling system by Tousi et al. [12], heat pipe-cooling system by Zhang et al. [13] and phase-changed material-cooling system by Jiang et al. [14] and Zhang et al. [15].

However, when redundant heat was not removed. The increasing of temperature may cause the thermal decomposition inside the battery. When thermal runaway of LIB occurred the high amount of non-condensed gas and vapors was produced inside the battery by self-heating reaction causing vent gases and explosion because of high pressure. The suitable condition for store the LIB at maximum temperature of less than 40°C and the difference of temperature of less than 5°C for long life span and cycle. The thermal runaway in battery has the parameters that can be used for the safety signal such as temperature, voltage, gas venting to specify the stage of battery thermal runaway. This signal can be used for triggering the safety system. The cell arrangement of battery module also the significant thing that affect the severity of thermal runaway. It depends on the battery design and operating parameters. Huang et al [16]. and Weng et al [17]. was studying the cell arrangement found that the lengthwise of thermal runaway propagation was faster than the transversal due to the small area of heating transfer. So, this experiment, we decide to use the lengthwise to heating the battery. There are several works that have been done in thermal runaway suppression such as water, water mist, extinguishing agents etc. Sun et al. [18] studied suppressing thermal runaway using HFC-227ea and $C_6F_{12}O$ in confined space chamber. The results of this study show that HFC-227ea and C_6F1_2O can suppress the open flame in confined space chamber. On the other hand, these two agents cannot suppress the thermal runaway in battery because of the cooling effect of these two agents not enough to heat transfer that generated from the cell that thermal runaway occurred transfer to another cell. Thus, HFC-227ea and C_6F1_2O cannot suppress thermal runaway but $C_6F_{12}O$ can prolong the propagation time.

Phase Change Material (PCM) is a new material that using in this kind of work, so, this PCM need the further research for using to avoiding thermal runaway. Phase Change Material (PCM) is one of the ways in avoiding thermal runaway. Zhang et al. [19] studied avoiding thermal runaway by simulation methods using PCM and liquid-cooling system. In this study aim to prevent thermal runaway from cell 1 spread to cell 2. This simulation consists of two cell of batteries and three systems. The system (1) is PCM buffer, (2) Liquid cooling system, (3) PCM and liquid cooling system. The results of this studied shown that system (1), Thermal runaway occurred on cell 1. The temperature rapidly increases to 886°C then the heat transfer through the PCM buffer to cell 2 thus this system cannot prevent thermal runaway spread. In system (2), Thermal runaway occurred on cell 1. Then, the rapidly heat transfer from cell 1 to cell 2. Thus, this system cannot prevent thermal runaway spread. In the system (3) combined of PCM and liquid cooling system. Thermal runaway occurred on cell 1. The heat passing through PCM buffer and aluminum plate and transferred to the cooling water causing the heat that transferred to cell 2 is not enough to make the cell 2 occurring in thermal runaway. Thus, system (3) can prevent thermal runaway spread from cell 1 to cell 2. In kind of water suppression, Water is widely used agent for fire extinguishing due to very high specific heat capacity. Zhang et al. [20] was found that water spray can suppressing the battery fire and reducing surface temperature. The effectively temperature range of 130 ℃ - 150 ℃ can suppress thermal runaway by spray duration of 5 s, but above the 170 ℃ is not enough. If the surface temperature is more than 170 ℃, it is requiring the minimum spray duration of 20 s. Additionally, water spray affects the venting gases that released from battery. When applied the water spray, the concentration of CO_2 decreased. On the other hand, the concentration of CO, HF, and H_2 increased. Sun et al. using the water spray as fire extinguish agent in confined space. The water spray in this experiment shows the best performance of the cooling effect which can suppress thermal runaway propagation. On the other hand, HFC-227ea and C_6F1_2O cannot suppress. Zhang et al. [21] studied about combined the gas and water mist to study suppression effect of combination. It was found that using only water mist is hardly to suppress the thermal runaway propagation. On the other hand, CO_2 can prolong the propagation, C_6F1_2O can suppress the propagation suddenly, HFC-227ea cannot suppress the open flame. The combination of C_6F1_2O and water mist show the best extinguishing agents and cooling effect in this experiment. The second-best agent is CO_2 and water mist, it has a good cooling effect.

Recently, there are many studies related to thermal runaway behaviors, mechanisms, and preventions. A comprehensive review of the thermal runaway processes, thermal runaway initiation mechanisms, thermal runaway propagation, and the characterization of vented gases during the thermal runaway process were summarized [22]. The prevention methods such as liquid-cooling system and thermal battery management system (BTMS). The effected parameters and integrated battery cooling strategy for EV were also studied to reduce the target battery temperature [23]. The effectiveness of the proposed model was also verified by experimental data. The new technology of liquid cooling plate provided a heating solution for batteries in cold temperatures was investigated [24]. The efficiency of the mini-channel cooling plate could be significantly improved by a new approach for Lithium-ion battery thermal management with streamline shape mini channel cooling plates [25]. Recently, the external short circuit (ESC) behavior was studied by electro-thermal coupling model of lithium-ion batteries [26]. The behaviors of battery thermal runaway consist of ISC stage, vented gas stage and explosion. Even the thermal runway could be quenched by cooling system, however the activated the internal short circuit (ISC) stage could bring about the explosion stage. Following the referenced studies, the cooling system for prevention of ISC stage affected the battery thermal runaway was rarely investigated.

Consequently, this work aims to study the prevention for ISC stage of 18650-type NMC battery thermal runaway or explosions using an air-cooling system. It focuses on the critical battery temperature as the external heating which can damage the battery separator, causing it to short circuit, leading to thermal runaway and eventually an explosion. The air-cooling system with cooling-time is conducted with consideration of critical battery temperature. This research is to study the NMC battery temperature, the air-cooling system, variation of cooling-time and battery voltage drops to exhibit the ISC stage of NMC battery thermal runaway. This study is expected to apply for battery thermal management system of EV. The air velocity of this experiment was fixed at 1.92 m/s due to experimental constraint and equipment. The air source in this experiment is compressor, we choose the speed number 1 that have velocity of 1.92 m/s. Other high speed than number 1, also can prevent ISC from battery because of high velocity can cause the case of force air convection and cannot study thermal runaway behavior.

This study aims to prevent the internal short circuit (ISC) stage of thermal runaway or explosions in 18650-type NMC batteries by utilizing an air-cooling system. The focus is on the critical battery temperature, where external heating can damage the battery separator, triggering a short circuit, thermal runaway, and potentially an explosion. The air-cooling system was evaluated with varying cooling times, taking the critical battery temperature into account.
The research investigates NMC battery temperature behavior, the effects of the air-cooling system, variations in cooling time, and battery voltage drops to characterize the ISC stage of thermal runaway. The findings are intended to inform the development of thermal management systems for electric vehicle batteries. In this experiment, the air velocity was fixed at 1.92 m/s due to equipment limitations. The air source was a compressor set to speed level 1, which provided the desired velocity of 1.92 m/s. Higher speeds were avoided, as increased air velocity could induce forced air convection, which might prevent ISC entirely, making it difficult to study thermal runaway behavior effectively.

2. Experimental Setup

This research focuses on preventing thermal runaway in 18650-type NMC batteries used in electric vehicles. To achieve this, an experimental study was conducted to analyze the battery's behavior, with specific details provided in Table 1. Figure 1 illustrates a schematic diagram of the air-cooling system, which includes a cooling box, rotameter, and air source. The chamber is connected to a steel pipe at the bottom, positioned at the same level as the battery, allowing air to flow into the chamber through the pipe and distribute around the battery before exiting through the top. In this experiment, the chamber was designed as an open space. To investigate thermal runaway and its prevention, the experiment utilized an NMC battery placed on a heating pad equipped with a temperature controller and a data acquisition system, as shown in Fig. 2. The experimental setup focused on examining the effects of a cooling system on mitigating thermal runaway. The 18650 cylindrical NMC battery was mounted onto a heater plate, with its temperature (Tb) controlled by a temperature controller. Three K-type thermocouples were installed to monitor the battery's temperature, while voltage measurements were taken by connecting the anode and cathode to the data acquisition system to track the thermal runaway stage Battery temperatures under the air-cooling system were monitored over time. In this study, a fully charged (100% SOC) 18650 NMC cylindrical battery was fitted with thermocouples at the top, middle, and bottom positions. The battery was heated to target temperatures of 90°C, 95°C and 100°C, after which the cooling system was operated for durations of 5, 10 and 15 minutes. The suitable battery temperatures and cooling times for preventing thermal runaway were determined experimentally, as summarized in Table 2.

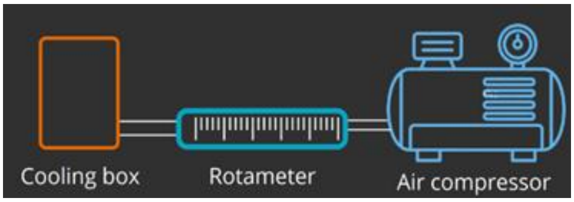


Fig. 1. Schematic diagram of the air-cooling system used in the current study.

Table 1: Specific information of Lithium-ion battery in this experimental.

Parameters	Specification
Cathode	NMC ($LiNiMnCoO_2$)
Nominal capacity (mAh)	2900
Nominal voltage (V)	3.6
Charge voltage (V)	4.2
Discharge cut-off voltage (V)	2.5
Geometry (mm)	Height: 64.85± 0.25, Diameter: 18.35± 0.15
Weight (g)	≤ 48

Table 2: Experimental conditions for prevention of 18650-type NMC lithium-ion battery thermal runaway.

T_b (°C)	Cooling system		Cooling-time		
	on	off	5 mins	10 mins	15 mins
90	•				
90		•	•		
90		•		•	
90		•			•
95	•				
95		•	•		
95		•		•	
95		•			•
100	•				
100		•	•		
100		•		•	
100		•			•

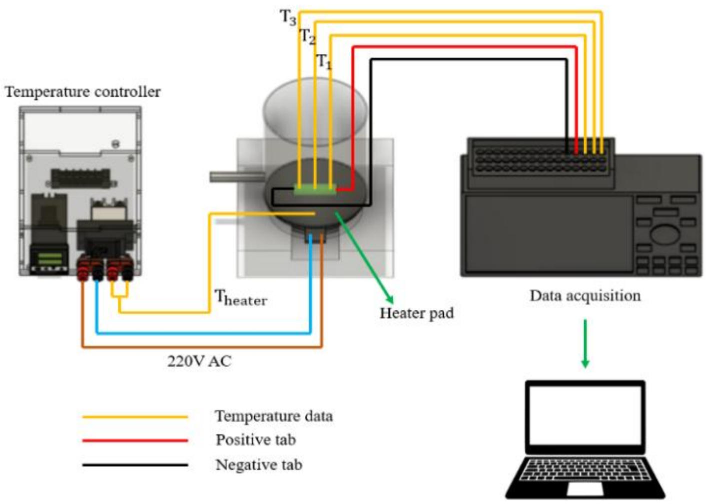
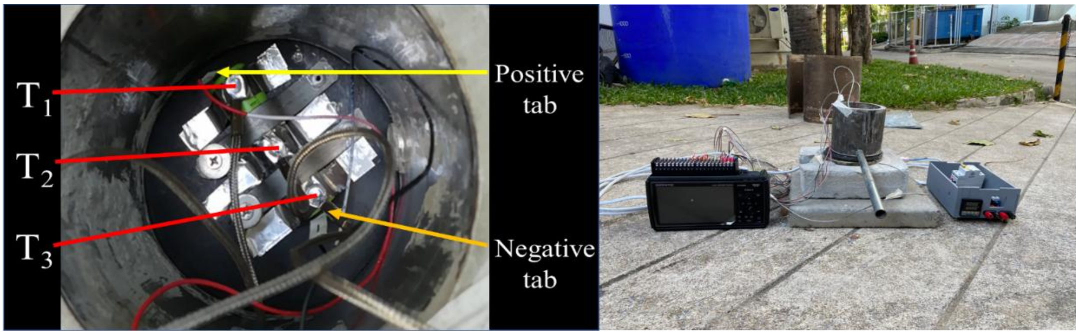


Fig. 2. The experimental setup.

3. Research methodology

3.1 Air cooling system

The thermal runaway behavior of NMC cylindrical battery cells without an air-cooling system was investigated using an experimental apparatus. The battery was placed in an open chamber with three thermocouples attached to measure surface temperatures. To ensure accuracy and minimize temperature measurement errors, the thermocouples were mounted directly on the battery's surface. According to the experiment, the highest temperature during the internal short circuit (ISC) point was recorded at the middle surface (110°C), as shown in Fig. 4. This temperature aligns closely with the 110–120°C range reported in the reference study [27], validating the results of the current study. Voltage measurements were taken at the positive and negative tabs, as shown in Fig. 3(a), while Fig. 3(b) provides an overview of the experimental setup. Thermocouples were positioned at specific points on the battery: T_1 on the positive tab side, T_2 on the middle surface, and T_3 on the negative tab side, as illustrated in Fig. 4. The thermocouples were installed on the side opposite the heater pad to account for the battery's thermal conductivity and ensure that the recorded temperatures reflected the battery's actual state rather than the heater's temperature. The target temperature was defined as the value to which the heater pad would raise the battery's temperature before holding it steady at that level. Once the temperature was stabilized, the cooling system was activated, as selected from Experiment 4.1. To study battery behavior, the cooling system was triggered before the ISC occurred, reducing the temperature from the ISC point (110°C) to 90°C, 95°C and 100°C. The highest recorded temperature among T_1, T_2, and T_3 was used to determine when to initiate cooling.



(a) (b)

Fig. 3. (a) Position of thermocouples on the battery. (b) Experimental setup.

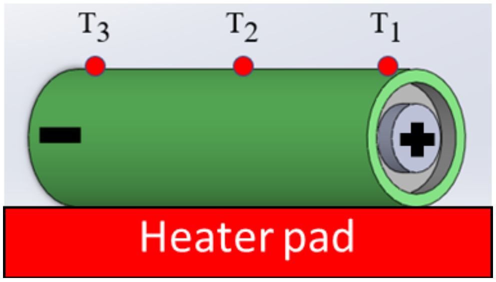


Fig. 4. Thermocouples arrangement.

3.2 Heat generation

To design a cooling system, it is necessary to determine the amount of heat generated by Eq. (1). Following the heat generation equation, it is calculated by mass (M) and heat capacity (C_p) integrated with temperature different. This amount of heat generation was applied to heat up battery.

$$\Delta Q = M \cdot \int_{T_1}^{T_2} c_p(T) \cdot dT \quad (1)$$

3.3 Convection heat transfer

Convection heat transfer is the rate of heat transferred by natural or force convection sources such as blower. Convection heat transfer is analyzed by temperature difference between surface (T_s) and ambient (T_∞), surface area (As) and heat transfer coefficient (h) as shown in Eq. (2). Heat transfer coefficient is determined by media fluid property. Equation 3 shows the heat transfer coefficient of cylindrical shape is obtained by Nusselt number (Nu_{cyl}), tube diameter (D) and thermal conductivity (k) which Nu_{cyl} is a function of Reynold's number (Re) and Prandtl number (Pr). Where Re could be calculated by fluid properties of velocity (v), tube diameter (D) and dynamic viscosity (ν) as shown in Eq. (4).

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \quad (W) \tag{2}$$

$$Nu_{cyl} = \frac{hD}{k} = 0.3 + \frac{0.62\,Re^{1/2}Pr^{1/3}}{[1+(0.4/Pr)^{2/3}]^{1/4}}\left[1+\left(\frac{Re}{282{,}000}\right)^{\frac{5}{8}}\right]^{4/5} \tag{3}$$

$$Re = \frac{VD}{\nu} \tag{4}$$

4. Results and discussions

4.1 Thermal runaway behavior of NMC 18650-type battery

Following the experimental setup, NMC 18650-type battery was tested to achieve the critical battery temperature which leaded to battery thermal runaway (BTR). Figure 5 shows thermal runaway behavior of 18650-type NMC batteries which was heated up by heater at almost same temperature T_1, T_2 and T_3. Then the battery temperature and voltage were measured for stage I, II and III. The results show 110°C of battery temperature was observed at stage II as the critical battery temperature. According the BTR, three steps of voltage drop at stage II shows the internal short circuit (ISC) stage, gas venting stage and thermal runaway stage, respectively. The fluctuated voltage and was diminished at a surface temperature of around 125°C when the battery reached a gas venting stage, resulting in a white smoke discharge from inside the battery. Then, the voltage dropped to 0 V and the surface temperature sharply increased due to an open flame followed by an explosion.

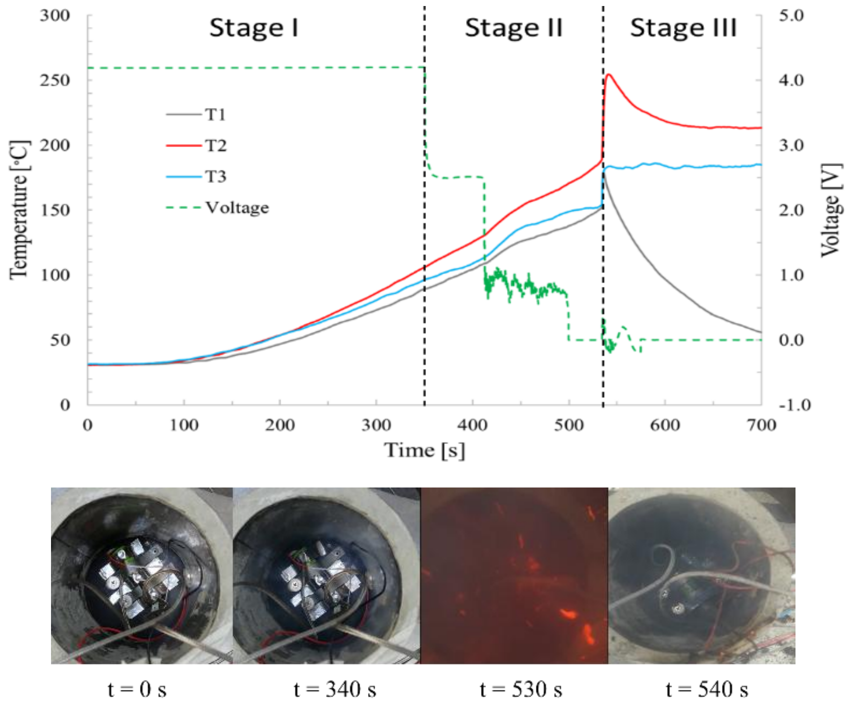


Fig. 5. Thermal runaway behavior of 18650-type NMC batteries.

4.2 Heating without air-cooling system

In the without air cooling and with an air cooling, the experiment will classify into 3. A is the experiment that have target temperature at 90°C, B is 95°C and C is 100°C. To study the heat that generated by battery can reach ISC or not.

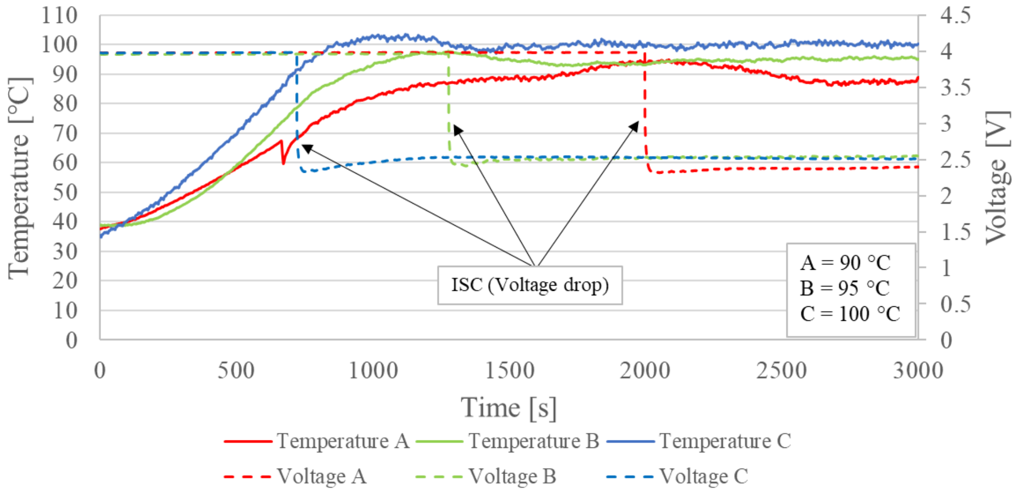


Fig. 6. NMC 18650-type battery behavior without air cooling at 90°C, 95°C and 100°C of battery surface temperatures.

As the critical battery temperature was observed at 110°C, the heater temperature was controlled under the conditions of 90°C, 95°C and 100°C without air-cooling system. The battery was heated with a heating pad controlled using a temperature controller. When the battery temperature increased to a target value at 90°C, 95°C and 100°C, all NMC batteries were damaged due to ISC stage leading to BTR stage. Figure 6 NMC 18650-type battery behavior without air cooling at 90°C, 95°C and 100°C of battery surface temperatures. The results show the voltage drops of internal short circuit stage at 90°C, 95°C and 100°C of battery temperature was observed at 2000 sec, 1300 sec and 650 sec, respectively. As the target temperatures, the battery cooled by the ambient air or natural convection was not enough to exhibit an internal short circuit and subsequent thermal runaway due to great amounts of heat generated by internal chemical reactions. After maintaining the target temperature before reaching the ISC point, the battery begins to generate heat internally due to chemical reactions caused by operating at high temperatures. At this stage, temperature and voltage monitoring can help identify early warning signs of potential issues with the battery. Both parameters serve as critical safety indicators for battery health, especially on a larger scale. Thermal runaway (TR) can be triggered by three main types of abuse: thermal, mechanical, and electrical. This study focuses on thermal abuse, as it is a significant factor in battery safety. When the battery reaches Stage II of TR due to thermal abuse and experiences simultaneous mechanical or electrical abuse—such as a crash or penetration—the thermal runaway reaction can accelerate significantly. It is essential to ensure that the battery operates within its normal working temperature range of 0–50°C. Temperatures exceeding 50°C require increased caution to mitigate the risk of ISC and chain reactions. For batteries larger than the 18650 type, additional considerations arise. Larger sizes, higher energy densities, and greater states of charge (SOC) increase the intensity of fires or explosions during TR. Higher battery temperatures also require longer cooling times to prevent ISC. At elevated operating temperatures, battery performance diminishes, and after ISC occurs, voltage typically drops to half of the full charge before eventually reaching 0 V, rendering the battery inoperable. At this stage, cooling is no longer effective, and immediate suppression measures are required to prevent dangerous outcomes.

4.3 Heating with air-cooling system

In this case the experiment will classify into 3. A is the experiment that have target temperature (temperature that cooling system operate) at 90°C, B is 95°C and C is 100°C.

4.3.1 Air-cooling system operated for 5-minute of cooling-time

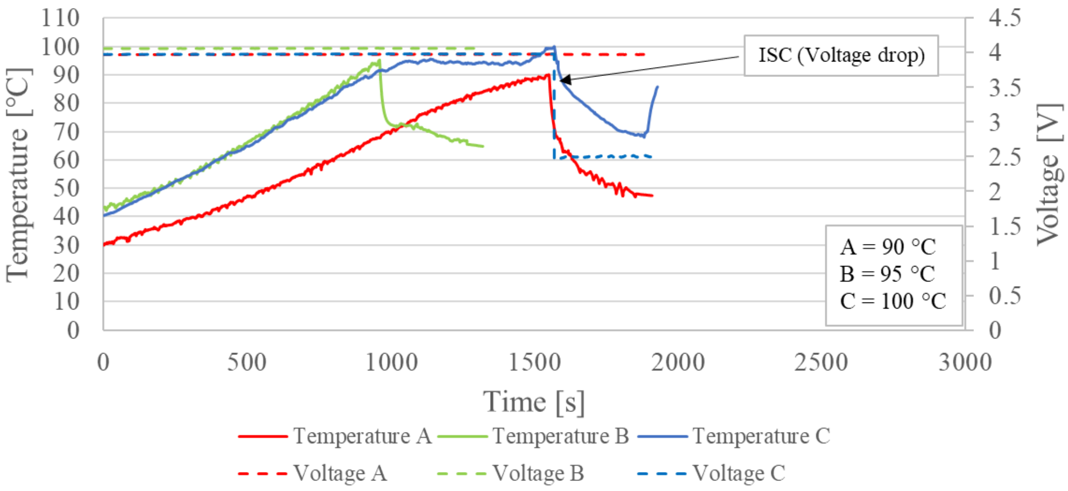


Fig. 7. NMC 18650-type battery behavior with an air-cooling system operated for 5-minutes of cooling-time at various surface temperatures.

As the natural convection was not enough to decrease battery temperature under critical temperature, the air-cooling system operated with a fan at air speed of 1.92 m/s to prevent ISC stage. Figure 7 shows NMC 18650-type battery behavior with an air-cooling system operated for 5-minutes of cooling-time at various surface temperatures of 90°C, 95°C and 100°C. When the battery was treated by 90°C and 95°C with 5-minutes of air-cooling-time, the battery temperature continuously decreased closed to 40°C whereas battery could active due to constant high voltage. When the battery was treated by 100°C with 5-minutes of air-cooling-time, the battery temperature decreased as a short time and continuously increased higher 80°C whereas battery was damaged due to voltage drop. As this results, 5-minutes of air-cooling-time for 90°C and 95°C of battery temperature could prevent the ISC stage and BTR due to proper convection heat transfer. However, the continuous increase of temperature at 100°C of battery temperature with 5-minutes of air-cooling was shown due to accumulation of energy from the heating pad and chemical reactions inside the battery resulting in an internal short circuit. In case of 5-minutes of air-cooling-time, an internal short circuit stage could be prevented not exceed 95°C of battery temperature.

4.3.2 Air-cooling system operated for 10-minute of cooling-time

As 5-minutes of air-cooling-time with cooling system, an ISC stage of battery thermal runaway could not prevent exceed 95°C of battery temperature owing to insufficient convection heat transfer. Following the same process with variation of cooling-time of 10 minutes, to decrease battery temperature under critical temperature, the air-cooling system operated with a fan at air speed of 1.92 m/s to prevent ISC stage. Figure 8 shows NMC 18650-type battery behavior with an air-cooling system operated for 10-minutes of cooling- time at various surface temperatures of 90°C, 95°C, and 100°C. When the battery was treated by 90°C and 95°C with 10-minutes of air-cooling-time, the battery temperature quickly decreased closed to 40°C whereas battery could work due to consistent high voltage. When the battery was heated by 100°C with 10-minutes of air-cooling-time, the battery temperature decreased as a short time and continuously increased less 70°C whereas battery was damaged due to voltage drop. Comparison between 5-minutes of air-cooling-time with cooling system, lower battery temperature and prevention of ISC stage was achieved by air-cooling system with 10-minutes of air-cooling-time for 90°C and 95°C of battery temperature. As this results, 10-minutes of air-cooling-time for 90°C and 95°C of battery temperature could prevent the ISC stage and BTR due to proper convection heat transfer. Nevertheless, the continuous increase of temperature at 100°C of battery temperature with 10-minutes of air-cooling was shown due to accumulation of energy from the heat source and chemical reactions inside the battery resulting in an internal short circuit. Even 10-minutes of air-cooling-time and decrease of battery temperature were observed, the voltage drop was shown and affected an internal short circuit stage for exceed 95°C of battery temperature.

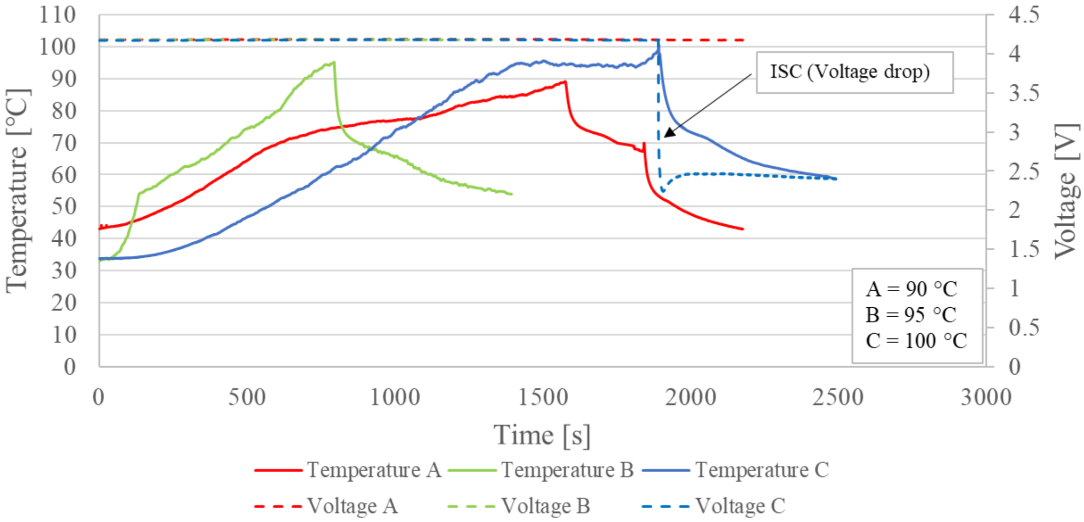


Fig. 8. NMC 18650-type battery behavior with an air-cooling system operated for 10-minutes of cooling-time at various surface temperatures.

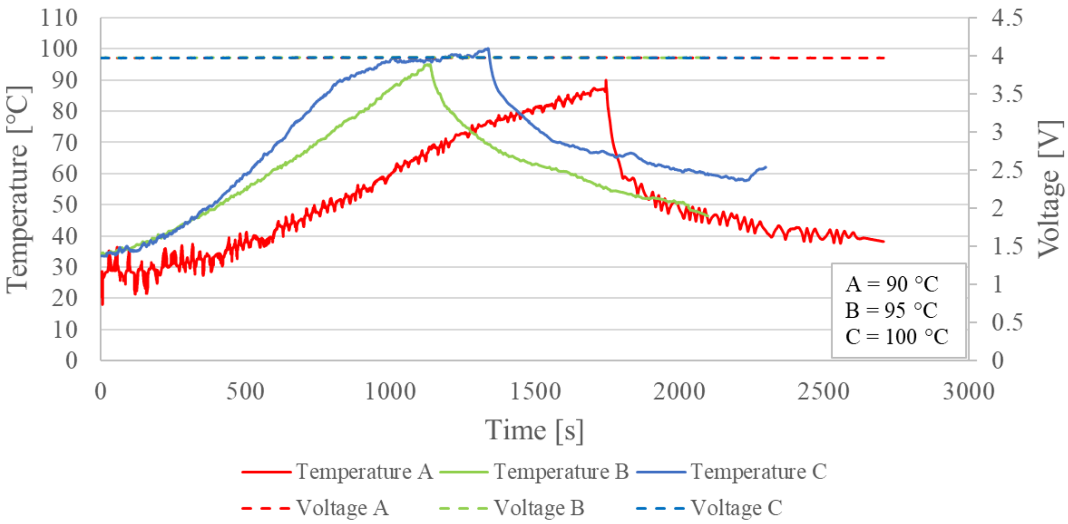


Fig. 9. NMC 18650-type battery behavior with an air-cooling system operated for 15-minutes of cooling-time at various surface temperatures.

4.3 Air-cooling system operated for 15-minute of cooling-time

For both 5-minutes and 10-minutes of air-cooling-time with cooling system, an ISC stage were observed, and the battery thermal runaway could be not prevented exceed 95°C of battery temperature because of less convection heat transfer. Following the same process with variation of cooling-time of 15 minutes, to decrease battery temperature under critical temperature, the air-cooling system operated with a fan at air speed of 1.92 m/s to prevent ISC stage. Figure 9 shows NMC 18650-type battery behavior with an air-cooling system operated for 15-minutes of cooling-time at various surface temperatures of 90°C, 95°C and 100°C. When the battery was treated by 90°C, 95°C and 100°C with 15-minutes of air-cooling-time, the battery temperature quickly decreased closed to 40°C-60°C. Moreover, all batteries were not damaged because all voltages were not dropped and consistent high voltage. Even the battery was heated by 100°C, air-cooling system with 15-minutes of air-cooling time affected the decrease of battery temperature less 60°C whereas battery was not also damaged due to consistent high voltage. As this results, 15-minutes of air-cooling-time for all 90°C, 95°C and 100°C of battery temperature could prevent the ISC stage and BTR due to suitable enough convection heat transfer. Comparison between 5-minutes and 10-minutes of air-cooling-time with cooling system, the prevention of ISC stage was achieved by air-cooling system with 15-minutes of air-cooling-time for 90°C, 95°C and 100°C of battery temperature. Table 3 shows thermal runaway phenomena observed with and without an air-cooling system for 18650-type NMC lithium-ion batteries. The summarized results of ISC stage, vented gas stage and explosion stage by various heated battery temperature (90°C, 95°C and 100°C) with cooling system at air speed of 1.92 m/s and variation of cooling-time (5 mins, 10 mins and 15 mins)

Table 3: Thermal runaway phenomena observed with and without an air-cooling system for 18650-type NMC lithium-ion batteries.

T_b (°C)	Cooling system		Cooling-time			Thermal runaway phenomena		
	on	off	5 mins	10 mins	15 mins	ISC	Vented gas	Explosion
90		●				√	√	√
90	●		●			×		
90	●			●		×		
90	●				●	×		
95		●				√	√	√
95	●		●			×		
95	●			●		×		
95	●				●	×		
100		●				√	√	√
100	●		●			√	√	√
100	●			●		√	√	√
100	●				●	×		

6. Conclusions

Preventing thermal runaway (TR) involves different strategies depending on the stage of TR. Early intervention focuses on preventing internal short circuits (ISC) to halt chain reactions, while once TR reaches Stage II, suppression techniques like inert gases or water are needed. This study explored the relationship between battery temperature and ISC prevention, aiming to prevent temperature increases that could lead to Stage II of TR. For 18650-type NMC cells, the critical temperature was found to be 110°C, beyond which TR occurs. Experiments were carried out in Thailand's typical temperatures (35–40°C), using an open-space chamber to reduce explosion risks. Heating the batteries to target temperatures (90°C–110°C) took 700–2000 seconds, depending on the target, and cooling was tested with airflow rates of 1.92 m/s for 5, 10, and 15 minutes. Without cooling, batteries exceeding 110°C experienced ISC, resulting in gas emissions and fires. At temperatures of 90°C and 95°C, the air-cooling system successfully delayed or prevented TR. For batteries at 100°C, at least 15 minutes of cooling was needed to significantly reduce the risk of TR. Results showed that maintaining temperatures 10–15°C below the critical threshold required at least 5 minutes of cooling to prevent TR. Integrating cooling systems, such as air or water, into battery packs can enhance safety by keeping battery temperatures within safe limits. These systems could also identify the heat source in case of malfunctions, whether from the battery cells, wires, or the battery management system (BMS). For heat related to wires or BMS, inert gases could suppress fires, while cooling with air or water can prevent ISC in battery cells. If ISC cannot be prevented, water suppression could reduce risks. In the future, all-solid-state batteries, with their wide temperature range and non-combustible electrolytes, could offer safer alternatives, though more research is needed for their widespread use.

Nomenclature

A_s	Surface area [m^2]
c_p	Specific heat [$J \cdot kg^{-1} \cdot K^{-1}$]
D	Diameter [m]
h	Convection heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$]
k	Thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]
M	Mass [kg]
Nu_{cyl}	Nusselt number for cylindrical [-]
Pr	Prandtl Number [-]

Q	Amount of heat [W]
$\dot{Q}_{conv}$	Convection heat transfer rate [W]
Re	Reynolds number [-]
T	Temperature [°C]
T_b	Battery temperature [°C]
T_s	Surface temperature [°C]
T_∞	Free – steam temperature [°C]
t	Time [minute]
V	Velocity [m/s]
ν	Kinematic viscosity [$m^2 \cdot s^{-1}$]

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