American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-12, Issue-12, pp-26-32
www.ajer.org
Research Paper Open Access

Study on thermal analysis of lithium-ion battery modules using CFD analysis

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ABSTRACT : *Regulations on greenhouse gas emissions are expected to affect daily life in the near future, leading to changes in transportation modes such as cars and airplanes. It is predicted that the power source of transportation will change from fossil fuel combustion to electric power. The eco-friendly electric energy technology that enabled the practicalization of electric cars is rapidly spreading to the electric aircraft field because it does not affect air pollution and global warming. In order for an electric aircraft to be commercialized, it is necessary to design a battery pack that can implement the battery's optimal performance and durability by increasing energy density. In this study, the charging and discharging and thermal characteristics of lithium-ion batteries for electric aircraft were examined, and the basic analysis necessary for actual battery pack thermal management and optimal design was carried out. The temperature characteristics of lithium-ion batteries according to the discharge C-rate were found, and thermal analysis was performed to verify the validity of the simulation. This method can be commonly applied to various battery operating conditions, so it is expected to be effectively utilized in the basic design and development process for improving the thermal performance and durability of batteries.*

KEYWORDS *Li ion battery, battery module, thermal analysis, CFD, simulation*.

Date of Submission: 06-12-2023 Date of acceptance: 19-12-2023

I. INTRODUCTION

Global warming phenomenon is causing abnormal temperatures and natural disasters such as floods, heavy snow, and drought worldwide, and the resulting economic loss is estimated to be astronomical. Greenhouse gas regulations will also affect daily life in the near future, and it is expected that transportation modes such as cars and airplanes will change. Scientists predict that the power source of transportation will shift from fossil fuel combustion to electric power in the 21st century[1-3].

Emissions from international aviation are rapidly increasing, and these aircraft emissions have a significant impact on climate change, such as ozone and contrail formation. In response, various approaches are being proposed to include international aviation and maritime transport in the post-2012 climate policy. Although the current impact of air transport on environmental pollution is estimated to be around 3%, the direct influence on the atmosphere at high altitudes makes the actual environmental pollution impact very high, such as ozone layer destruction.

As urban and highway surface transportation networks become increasingly congested and saturated, and as the situation worsens with the huge cost of expanding ground transportation networks, social needs for three-dimensional air transport, that is, personal air vehicles (PAV), are increasing.

The eco-friendly electric energy technology that enabled the practical application of electric vehicles is rapidly spreading to the electric aviation domain, without causing air pollution and global warming. The speed of electric aircraft is approaching that of conventional small gasoline-engine aircraft, and the low noise, fuel economy, and simplified maintenance are expected to greatly expand the future electric aviation industry.

However, the range of electric aircraft is increasing, but the flight time is still limited. This is because the battery is heavier than the gasoline thrust engine. In the case of cars, it is possible to compensate for this by adding batteries, but adding batteries to increase the range of electric aircraft is not a practical method since it increases the weight of the aircraft.

For the technical advancement and commercialization of electric vehicles, high-energy-density, high-power-density batteries are required as fundamental solutions. Various types of batteries have been considered as alternatives for automotive power sources, and lithium-ion batteries are considered to have the most competitive advantage due to their small size, high efficiency, long life, low self-discharge rate, and low electrical resistance. To be mass-produced and applied as an electric power source, long-term stability during operation of the system used, as well as safety issues and additional improvements in performance and efficiency are required simultaneously. Therefore, battery management technology to effectively solve this is emerging as a key research issue, and active technological development efforts are being undertaken[4-6].

The current mobile IT devices and electric vehicle (EV) lithium-ion batteries have an energy density of up to 250 Wh/kg, approaching the theoretical energy density. To develop high-energy-density lithium-ion batteries, research on next-generation batteries, such as lithium-metal-based batteries with high theoretical capacity, is needed.

In the case of electric aircraft, the battery's discharge capacity is the most significant problem. The design of the battery system needs to focus on increasing the energy density rather than the output characteristics required by the system.

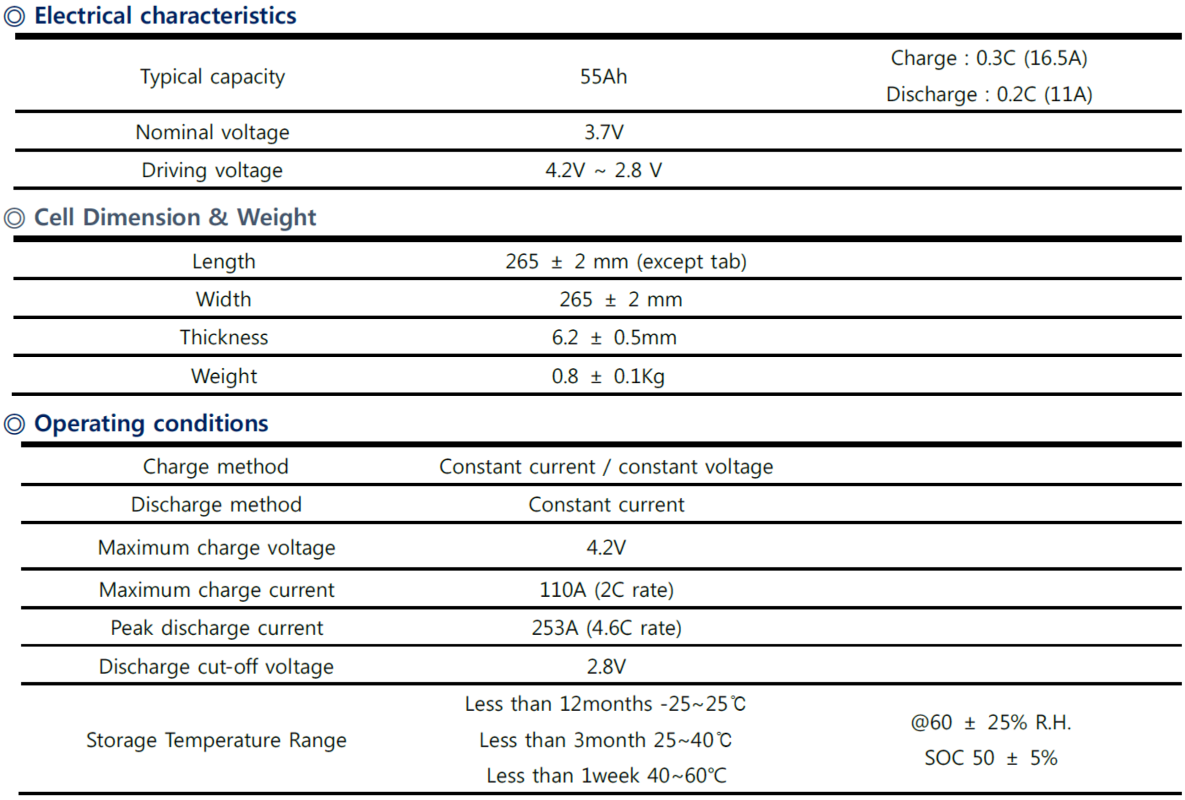
Lithium-ion batteries are known to have an appropriate operating temperature of 15-35°C, but thermal stability problems arise due to heat generation from internal reactions and electrical resistance during charging and discharging. In addition, to meet the requirements of electric aircraft, several unit batteries are connected in series, which can cause problems such as short circuits and thermal runaway. If abnormal temperatures occur during charging and discharging, voltage differences between the batteries can increase, shortening the life of the battery and causing problems such as imbalance. To achieve optimal performance and durability at the appropriate temperature for the battery pack, it is essential to apply a battery pack thermal management system[7-10].

In this study, the electrochemical and thermal characteristics of the lithium-ion battery were obtained for use in electric aircraft. The discharge-C-rate and temperature characteristics of the lithium-ion battery were investigated, and thermal analysis was conducted to confirm the validity of the simulation.

II. CONFIGURATION OF A LITHIUM ION BATTERY BASED MODULE

In this study, a 55 Ah class pouch-type lithium-ion battery was used, supplied by the manufacturer, and the general information and electrochemical performance of the unit cell is shown in the table 1 and Table 2, respectively.

Table 1. General information of 55 Ah pouch type lithium ion battery.



◎ Electrical characteristics

Typical capacity	55Ah	Charge : 0.3C (16.5A) Discharge : 0.2C (11A)
Nominal voltage	3.7V	
Driving voltage	4.2V ~ 2.8 V	

◎ Cell Dimension & Weight

Length	265 ± 2 mm (except tab)
Width	265 ± 2 mm
Thickness	6.2 ± 0.5mm
Weight	0.8 ± 0.1Kg

◎ Operating conditions

Charge method	Constant current / constant voltage	
Discharge method	Constant current	
Maximum charge voltage	4.2V	
Maximum charge current	110A (2C rate)	
Peak discharge current	253A (4.6C rate)	
Discharge cut-off voltage	2.8V	
Storage Temperature Range	Less than 12months -25~25℃ Less than 3month 25~40℃ Less than 1week 40~60℃	@60 ± 25% R.H. SOC 50 ± 5%

Table 2. Electrical performance of 55 Ah pouch type lithium ion battery.

Item	Criteria		Testing condition		
Outside Appearance	No abnormal strain, Deformation nor damage		Visual check		
External Dimension	According to the attached drawing				
Discharge			Various temperature for 1Hr after standard charging		
Discharge Rate	1.0C	2.0C	3.0C	4C	4.6C
Capacity (%)	99%	98%	97%	95%	94%
Initial internal Impedance	Less than 0.7mΩ		Measure by alternate current within 6hr after charge(23±3℃)		
Cycle Life	Above 80%		Carry out 400cycles charging/discharging Condition ▣ Charge(CC) : 1C to 4.2V ▣ Rest time between charge/discharge : 1hr ▣ Discharge(CC) : 1C to 2.8V ▣ Temperature : 23±3℃		
Storage performance	Above 90%		After full charge at 23±3℃, then leave 1month. After storage, measure discharge capacity at(23±3℃)		

To increase the range of electric aircraft, a high energy density of the battery is required, and for take-off and landing, a high output performance of the battery is needed. However, the energy density and output performance of batteries are typically in a trade-off relationship. The energy density of lithium-ion batteries is primarily determined by the amount of lithium ions that can be reversibly stored by the cathode and anode materials. So, active research on materials that can reversibly store more lithium ions is being carried out. Recently, for vehicle use, research to increase the amount of Ni is being actively conducted. In addition to high energy density, to satisfy high-rate discharge, long life, and other high-performance factors, it is necessary to use high-performance materials such as high-capacity active materials (Nickel-rich) and high-conductivity conductive materials and optimize the battery design. In this study, the lithium-ion battery used was manufactured for application to a personal air vehicle, and it can be confirmed in Figure 1 below that the discharge capacity is maintained even under high-rate discharge.

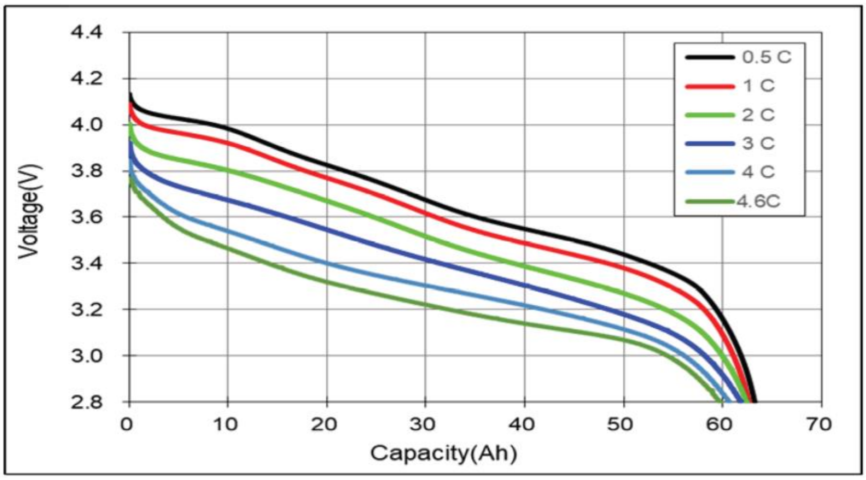


Fig. 1. 2 Discharge capacity profile of a pouch-type unit cell depending on various C-rates

In this study, a lithium-ion battery module was constructed using the unit cells in a 10S1P configuration. Subsequently, different c-rate charge-discharge processes were carried out, and their behavior was measured using a thermal imager and a thermal camera.

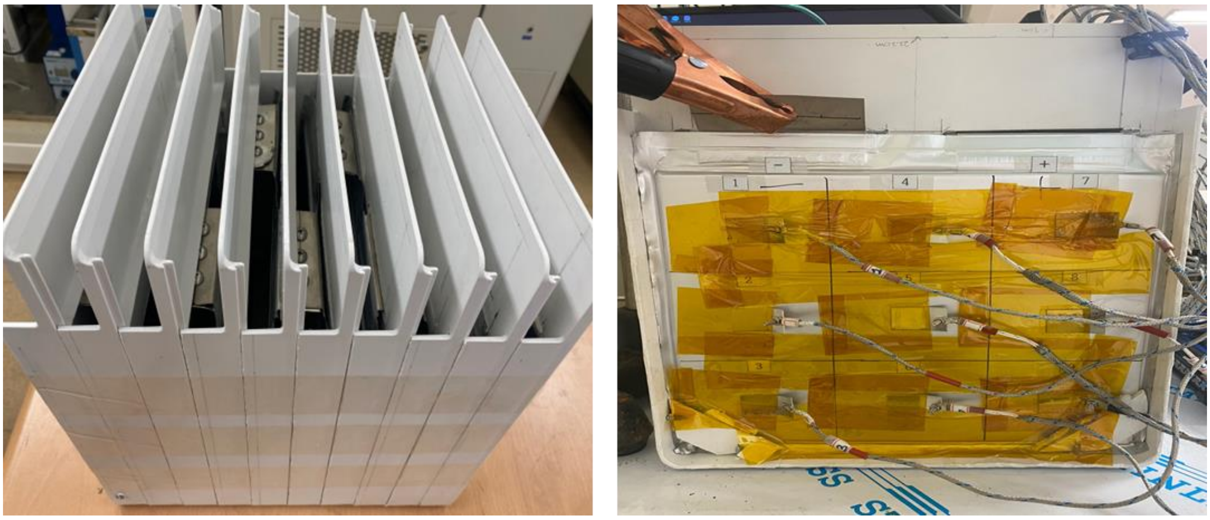


Fig. 2. Configuration of 10S1P module based on 55 Ah unit cells

III. THERMAL ANALYSIS

Thermal analysis of the battery module was numerically studied using the commercial numerical analysis program ANSYS 2023 R2 CFD. Simulations were performed under the same conditions as the test during charge-discharge, and the measured and analytical results were compared. To proceed with the modeling, the shape of the 10S1P module was implemented and the grid size of the module was varied to obtain accurate calculation results. The results are shown in figures 3 and Figure 4, respectively.

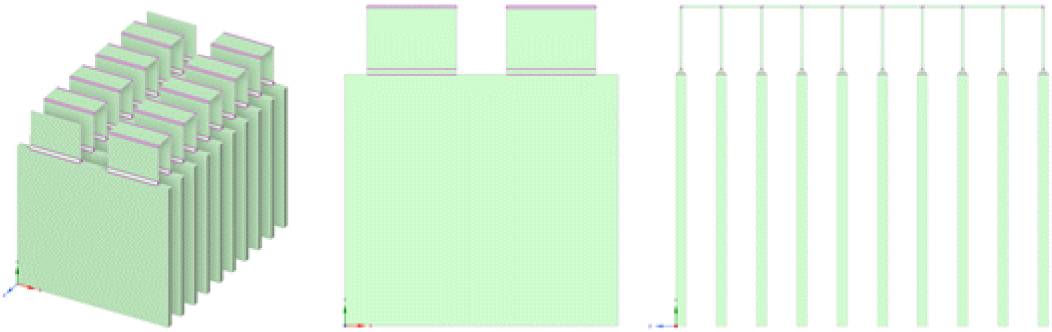


Fig. 3. Shape implementation of a 10S1P module based on a pouch-type unit cell

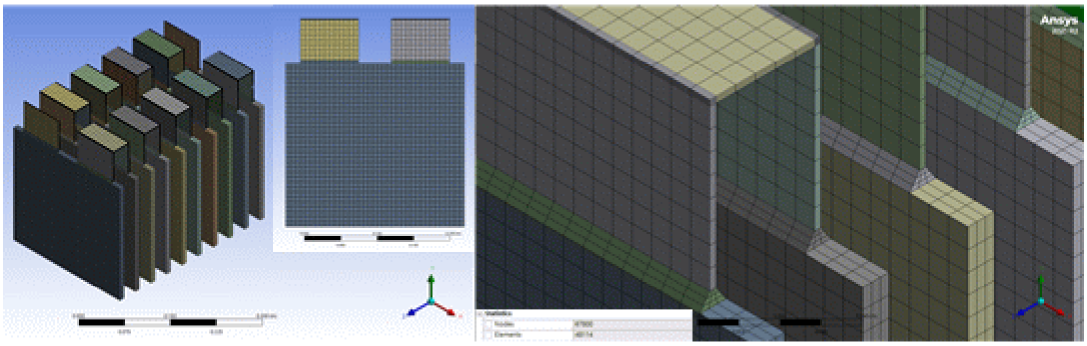


Fig. 4. Lattice implementation of a 10S1P module based on a pouch-type unit cell

Under the standard conditions provided by the manufacturer, the capacity was confirmed to be 60.8 Ah, and although there was a difference in temperature according to the measurement location, the temperature rose during discharge from the initial 23.2℃ to 27.9℃. After performing the thermal analysis based on the NTGK model, the temperature and voltage profiles were implemented, and the heat generation behavior before and after charge-discharge was represented by a contour plot.

The thermal analysis results showed that in the case of 1 C-rate charging and 1 C-rate discharging, as shown in Figure 1, the temperature rose by about 17℃ to 315 K based on the room temperature of 298 K. When comparing it with the actual charge-discharge test, it was found that there was about 6℃ of error in the temperature change of the simulation. This is because, in the actual charge-discharge test, the rest time was applied and the discharge temperature sufficiently dropped before proceeding with the charge-discharge, while in the simulation, continuous charge-discharge and convective heat loss system modeling were not considered.

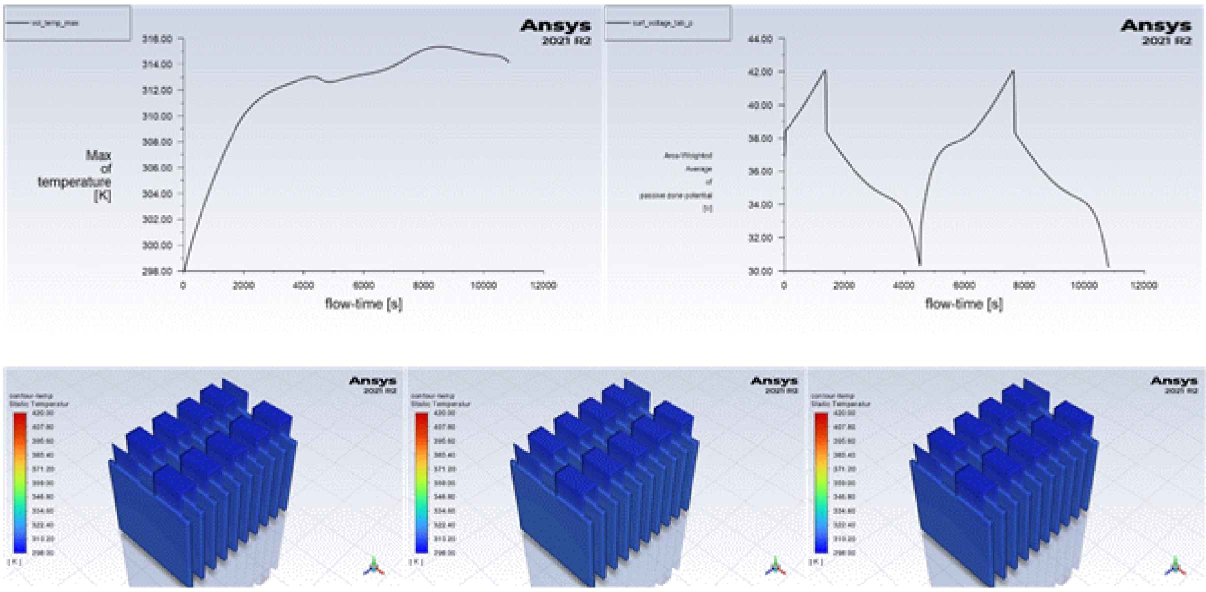


Fig. 5. 1 C-rate discharge temperature, voltage profile, and contour plot before charge, after charge, and after discharge

In the case of 2 C-rate discharge, the temperature rose by about 47℃ to 345 K based on the room temperature of 298 K, and in the case of 4 C-rate discharge, it was found to rise by about 112℃. The results are shown in Figures 6 and 7, respectively.

As the discharge C-rate increases, the difference between the actual charge-discharge temperature becomes larger, and as mentioned earlier, it is judged that the granting of rest time in the actual charge-discharge is the intensification of the difference. Through the above results, although there is some difference between the experimental results and the modeling results, it can be confirmed that they follow the trend and are valid to some extent.

The heating of the battery not only affects the battery's performance but also has a significant impact on the user's safety. There are several modeling methods to interpret and estimate the battery's heat generation. The electrochemical model interprets the battery's heat generation through the electrochemical reactions that occur inside the battery. Although the calculation amount of this model is large due to the combination of lithium ion concentration, current density, and temperature distribution, the electrical-thermal model simplifies the electrochemical-thermal model by minimizing chemical parameters and treating them as constants for each state of charge (SOC). Therefore, it is possible to predict the heat generation of the lithium-ion cell using simple equations and parameters. The thermal runaway model is used to check the thermal distribution of the battery cells under extreme conditions, such as overcharging and over-discharging. This is used to determine the thermal runaway threshold and failure factors of the battery cells.

Therefore, research on battery management system and battery thermal management system is necessary to solve the battery heating problem. For the design of these battery thermal management systems, Lee et al. studied the operating principle of lithium-ion and lithium-polymer batteries, verified the explosion mechanism through reproduction experiments, and established research on fire detection techniques and safety measures through this[11]. Yoon et al. configured an electrochemical-thermal model as one program, modeled it and developed a thermal model of the battery. This thermal model of the battery was experimented and compared by changing the environmental conditions with batteries of various capacities[12-13]. Kim et al. developed a simulation program to predict the dynamic behavior of a lithium-ion battery by using two-dimensional computer simulation[14]. Jung et al. developed a temperature estimation model using a thermal network method to estimate the temperature during the operation of the battery system used in xEV[15]. Gu et al. analyzed the power loss due to the internal resistance of the lithium-ion battery, which varies depending on the battery temperature. They confirmed that as the temperature increases, the internal resistance increases and the power loss also increases proportionally[16-17].

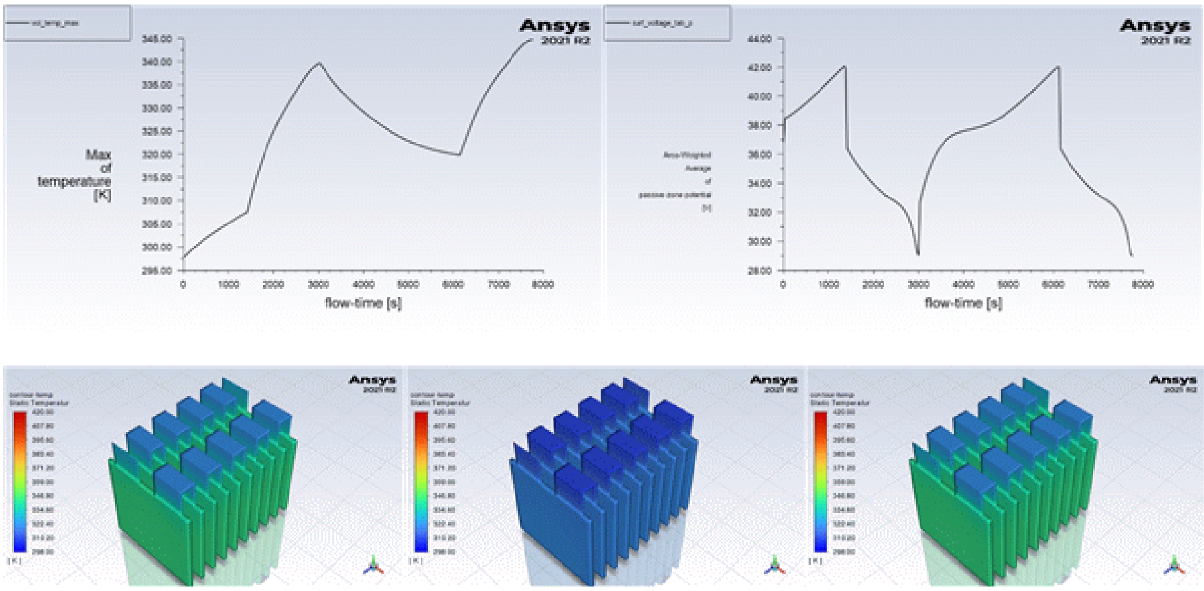


Fig. 6. 2 C-rate discharge temperature, voltage profile, and contour plot before charge, after charge, and after discharge

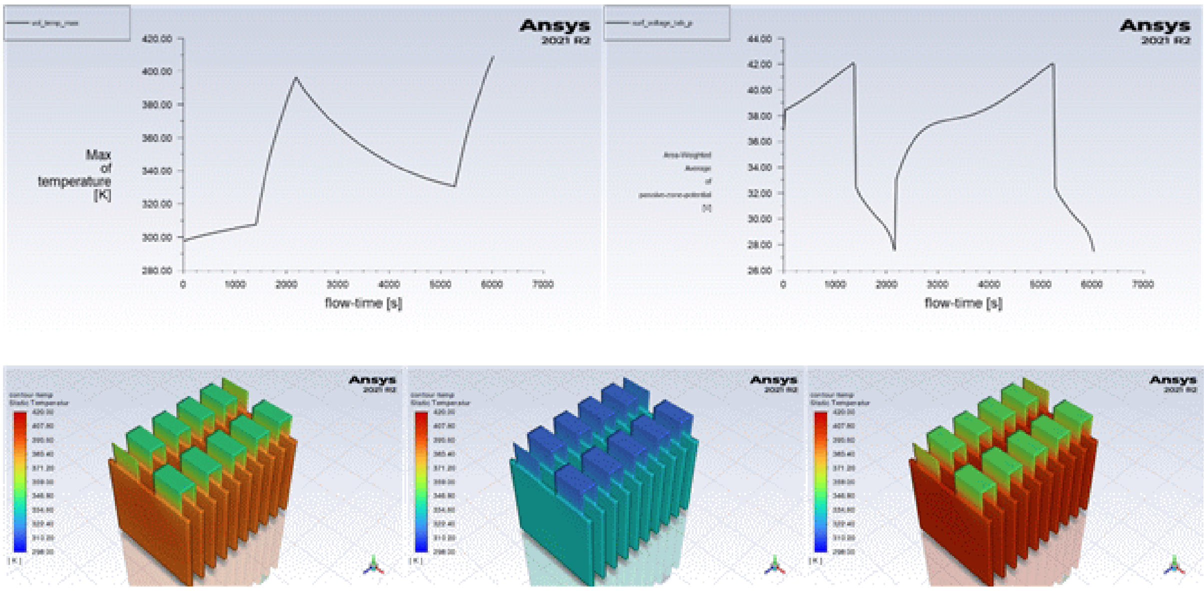


Fig. 7. 4 C-rate discharge temperature, voltage profile, and contour plot before charge, after charge, and after discharge

IV. CONCLUSION

In this study, we conducted a simulation of a 10S1P lithium-ion battery module using the NTGK model to verify its validity. The main issues of lithium-ion batteries, such as durability, safety, energy and power density improvements, are closely related to the thermal characteristics of the battery and battery pack. Therefore, a systematic understanding and consideration of the thermal behavior of lithium-ion batteries is recognized as a core challenge in battery research.

As the demand for lithium-ion batteries in fields such as Personal Air Vehicles increases significantly, the need for thermal behavior prediction considering safety and life is becoming increasingly high. Among various causes of battery degradation, battery thermal analysis considering SEI resistance increase, electrolyte depletion due to continuous side reactions, and collapse of the cathode particles is considered essential.

In the future, by systematically accumulating data on battery performance in various discharge conditions, it is expected that the temperature distribution inside the battery pack can be obtained with a higher reliability. This method can be commonly applied to various battery operating conditions and is expected to be effectively used in the basic design and development process to improve the thermal performance and durability of the battery.

ACKNOWLEDGEMENTS

This work was supported by the Technology Innovation Program (20011283) funded by the Ministry of Trade, Industry & Energy of Republic of Korea.

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