A Cooling Effect Formulation and Implementation of a Cooling System for Li-ion Battery Modules

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Abstract – This paper discusses the theory and experiments of heating and air cooling of battery modules. Heating mechanism is shown first, and cooling of a single battery is examined. Optimum air flow speed is discussed. Then, similar discussion is made for a battery module of six serial cells.

I. Introduction

Aiming at low carbon and energy-saving society, lithium ion batteries play important roles. The advantage of a lithium ion battery has the outstanding features that repetition charge and discharge can be carried out, that it is a high voltage, that energy density is high, that there is no memory effect, and there is little self-discharge. The large-sized lithium ion storage battery is used for the electric vehicle (EV). Moreover, although using natural power sources is spreading, since many of natural power sources are influenced by the weather etc. Therefore a production of electricity is unstable. Then, by using a lithium ion storage battery, it is used in order to be stabilized and to use electric power. As a use in small size, it is widely adopted as mobile computing devices, such as a mobile phone, a smart phone, and a personal computer.

The lithium ion battery is asked for boost charge. However, when carrying out boost charge, if charging current is only enlarged, heat will occur. The heat is dangerous and leads also to degradation of a lithium ion storage battery. The relation of the current and rise in heat is shown in Fig. 1.

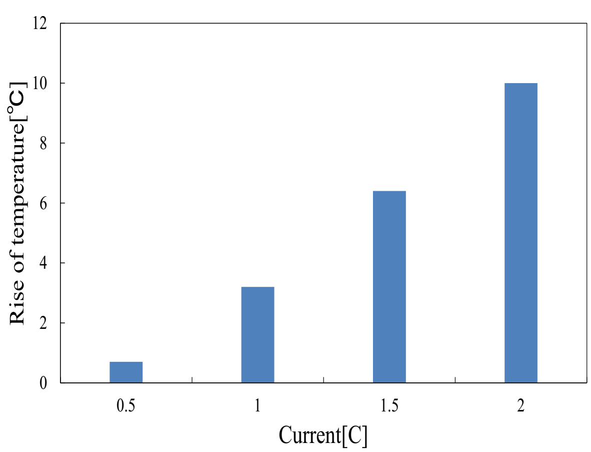

Fig.1. Battery temperature rise by different current.

The current 1C is the current value by which whole capacity is discharged in 1 hour. Thus, it is fully discharged in 0.5 hour by 2C current. It is charged until it reaches maximum voltage. Figure 1 shows that temperature goes up if the current increases. The battery which is used in this experiment is Type 18650. The specification is shown in the following table I.

TABLE I

SPECIFICATION OF THE BATTERY

Nominal Voltage		3.6V
Nominal Capacity		2250mAh
Dimensions	Diameter	Max. 18.6mm
	Height	Max. 65.2mm
Weight		44g

The capacity of a battery decreases. There are two types in the degradation. The one is cycle degradation which takes place by carrying out repetition use. The other is preservation degradation which takes place when saving a battery etc. The cycle degradation is shown in following Fig. 2[1].

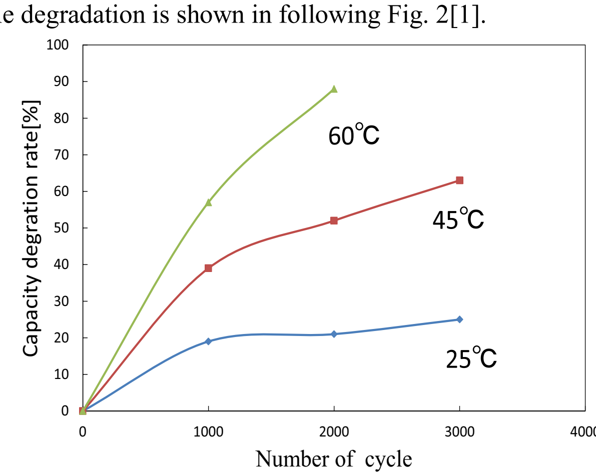

Fig.2. Cycle degradation classified by environmental temperature[1].

In Fig. 2, it is shown that the influence of degradation by heat is large. Therefore, suppressing the rise in heat at the time of charge suppresses degradation. In this paper, air cooling is used for the purpose of suppressing the rise in heat at the time of charge.

II. Theory of air cooling

As a factor which the heat of a lithium ion battery generates, there are two. One is Joule heat Q_{p}[J/S] by the internal resistance of a battery. It is shown by the formula (1). In this Joule heat, it generates heat at the time of charge and discharge. i[A] is electric discharge/charging current of a battery, V_{O}[V] is battery voltage, V_{OC}[V] is open circuit voltage, and R_{n}[Ω] is the internal resistance of a battery. Second is entropy heat Q_{s} [J/S] by a chemical reaction. It is shown by the formula (2). T_{in} is battery internal temperature. Entropy heat of this (2) type turns into an endothermic at the time of charge, and it generates heat at the time of electric discharge. A part of heat which arose by two exothermic factors is emitted to the exterior of a battery. When assuming that the temperature inside a battery does not call at a place, but is about 1 law, the amount of heat dissipation from the battery surface is set to Q_{out} [J]. It is shown by the formula (3). $A[m^2]$ is the surface area of the battery, T_s is battery surface temperature, T_a is ambient temperature, and h[J/ $m^2 \cdot$ K] is a coefficient of heat transfer, thermal conductivity of fluid,. h is the thermal conductivity of the air. This value varies by ambient temperature. We formulate these expressions from reference[2].

$$Q_{\mathrm{p}} = i \cdot (V_{\mathrm{o}} - V_{\mathrm{OC}}) = i^2 \cdot R_{\mathrm{n}} \tag{1}$$

$$Q_{\mathrm{s}} = i \cdot T_{\mathrm{in}} \cdot \frac{\partial V_{\mathrm{OC}}}{\partial T_{\mathrm{in}}} \tag{2}$$

$$Q_{\mathrm{out}} = A \cdot h(T_{\mathrm{s}} - T_{\mathrm{a}}) \tag{3}$$

The thermal behavior of a battery is expressed with a thermal circuit as shown in Fig.3. In this figure, Q_{ALL} is total of a heat flow which includes joule heat and entropy heat generated in the battery. C_{in} are calorific capacity of the battery. R_{in} is thermal resistance of the battery. R_a is thermal resistance of air. The rise in heat, in each SOC(State Of Charge) is shown in Fig. 4. The residual quantity of the battery is expressed in SOC. Thereafter, this paper describes State Of Charge with SOC. Capacity is full at the time of SOC=1. Capacity is empty at the time of SOC=0. This experiment is 2C about charging current. SOC carries out CC charge to 0.1. And it waits until temperature settles down. This was repeated until it reached maximum voltage. The quantity of heat in each SOC is shown in Fig. 5. This experiment is the charging current 2C. Moreover, the charge method was CC charge, and it was performed until it reached maximum voltage.

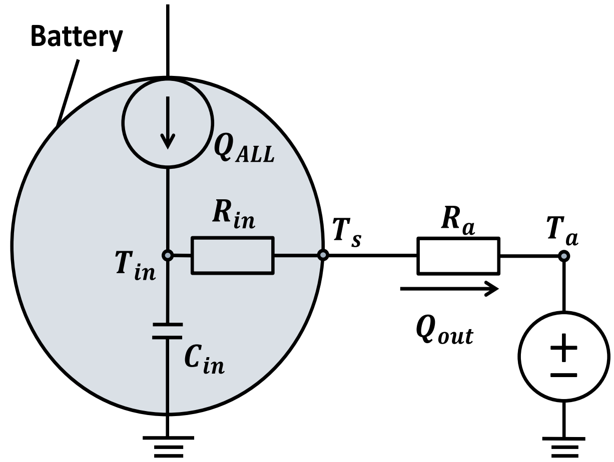

Fig.3. Thermal circuit of a battery.

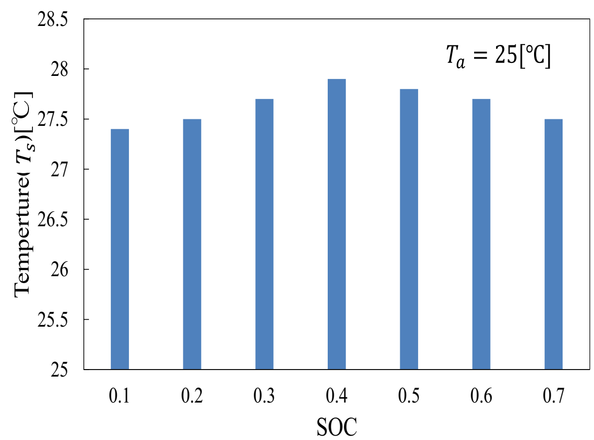

Fig.4. Battery surface temperature in each SOC.

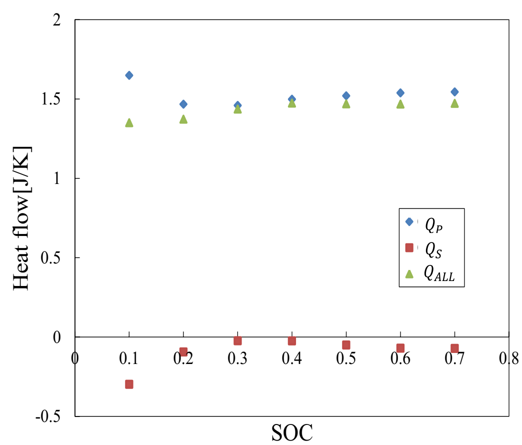

Fig.5. Quantity of heat in each SOC at the time of charge.

Air cooling [3-5] is executed by controlling the value of R_a [K/W]. It is shown by the formula (4). Then, the h[J/m^2·K] is shown by the formula (5). Nu is Nusslet number, λ[W/(m·K)] is the thermal conductivity of fluid, and d [m] is characteristic length.

$$R_a = \frac{1}{Ah} \quad (4)$$

$$h = \frac{Nu\lambda}{d} \quad (5)$$

In the case of a natural convection, Nu is shown by the following formula (6). α is a numerical value determined with the form of a battery. In a cylinder type case, it is 0.53. Pr is Prandtl number. It is shown by the formula (6). Gr is Grashof number. It is shown by formula (7). g [m/s^2] is acceleration due to gravity. β[[1/K] is a volume expansion coefficient of fluid. In the case of air, β will be set to $1/T$ if temperature is set to T [K]. ν[m^2/s] is dynamic viscosity. ν, α, and λ are physical-properties values.

$$Nu = \alpha(Gr \cdot Pr)^{0.25} \quad (6)$$

$$Gr = \frac{g\beta(T_s - T_a)d^3}{\nu^2} \quad (7)$$

$$Pr = \frac{\nu}{a} \quad (8)$$

In the case of a forced convection, Nu is shown by the formula (9). Re is Reynolds number. C and n depend on it. Re is shown by the formula (10). U[m/s] is wind velocity. Formula (11) is derived for by (4-5) and (9-11). By increasing the wind velocity U, the value of R_a becomes smaller. Consequently, the battery temperature can be reduced. Here, K is a compensation parameter to need condition.

$$Nu = C(Re^n \cdot P_r^{\frac{1}{3}}) \quad (9)$$

$$Re = \frac{U \cdot d}{\nu} \quad (10)$$

$$R_a = \frac{K \cdot d}{A \cdot C\left(\frac{Ud^n}{\nu} \cdot P_r^{\frac{1}{3}}\right)\lambda} \quad (11)$$

III. The Charge Method of a Lithium ion Battery

Charging method for the lithium ion battery has been mainly used Constant-Current and Constant-Voltage charge. Thereafter, this paper describes Constant-Current and Constant-Voltage charge with CC-CV charging. This charging method executes a charging time of constant voltage after charging of the constant current. Constant current charging at 1C current value would remain active material within the electrode is not completely reaction. For example, if you charge at a current value of a very small 0.1C, the active material of the majority is able to react at the stage where the terminal voltage has reached the upper limit charging voltage. Therefore, Constant voltage charging is not necessary, but it will be take 10 hours on a single charge in this current value. As a result it takes much time. The CC-CV charging is Continued charging switch to constant voltage charging when the terminal voltage reaches the charging limit voltage. Quantity of heat becomes large by giving big current from a formula (1) and (2). Therefore, a rise in heat becomes large.
By CC-CV charge, at the time of CC charge, since the rise in heat was large, it considered suppressing the rise in heat at the time of CC charge.

IV. Experiments of Air Cooling

A. Air Cooling Experiment for a Single Cell

To verify the formula, we set up the experimental environment as shown in Fig.6. Charging current is set 2C. Wind velocity is set 0 [m/s], 4.2 [m/s], 5.7 [m/s], 7.1[m/s], and 8.6 [m/s]. Result of the temperature rise is shown in Fig.7. When wind velocity is 5.7 m/s, it expresses with the dashed line.

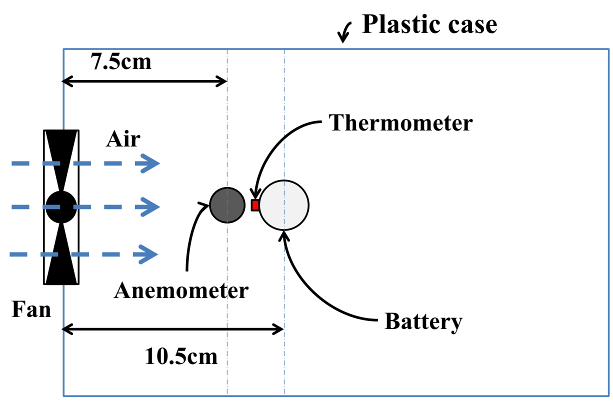

Fig.6. Cooling experimentation for a single cell.

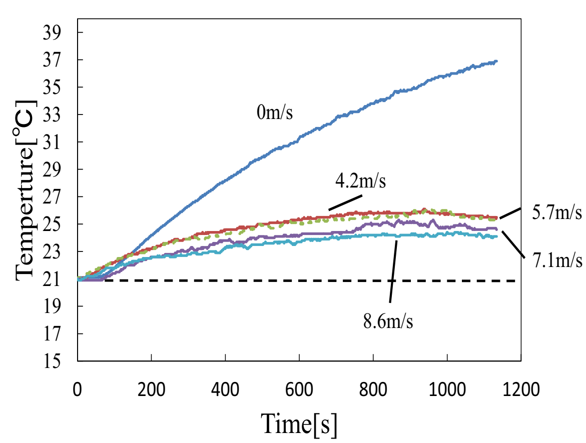

Fig.7. Temperature rise vs air flow. (Charge current = 2C)

The value given by equation (5), and the value given by the experiment are verified and it is confirmed that they are very close. (See Fig. 8.) K is 0.39. Also, the power consumption by the fan is measured. Moreover, a measurement value, the theoretical correction value, and an error are shown in Table Ⅱ. The summary of the cooling effect is shown in Table Ⅲ. By wind velocity 4.2 [m/s], the cooling is executed most effectively.

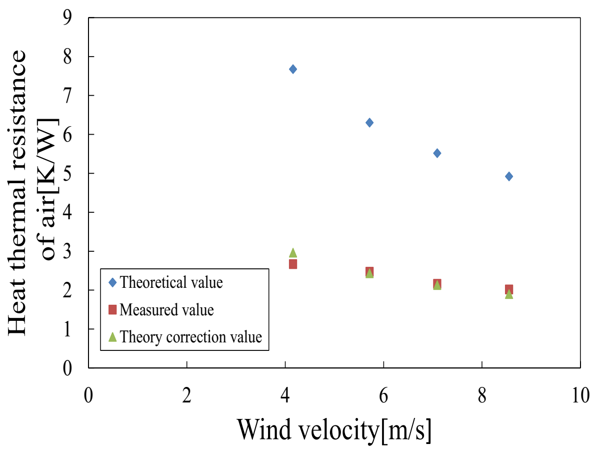

Fig.8. Air thermal resistance, *Ra* vs wind velocity, *U*

TABLE II

MEASURED VALUE AND THEORETICAL CORRECTION VALUE

Wind velocity [m/s]	4.20	5.70	7.10	8.60
Measured value[K/W]	2.67	2.47	2.16	2.01
theoretical correction value[K/W]	2.96	2.43	2.12	1.89
Error[%]	9.76	1.65	1.89	6.35

TABLE III

COOLING EFFECTS

Wind velocity [m/s]	4.20	5.70	7.10	8.60
C: Temperature reduction [℃]	11.4	11.6	12.3	12.8
P: Power for cooling[W]	1.00	2.90	4.70	7.20
C/P: Cooling effect [℃/ W]	11.4	4.03	2.62	1.78

B. Air Cooling Experiment for Stacked Cells

To verify the variability by battery location, we set up the experimental environment for stacked cells as shown in Fig.9 and Fig.10. Each battery is identified by number of 1-6. It is separated from the neighbor cell by 2 cm. Wind velocity and temperature sensors are provided as shown in the figure.

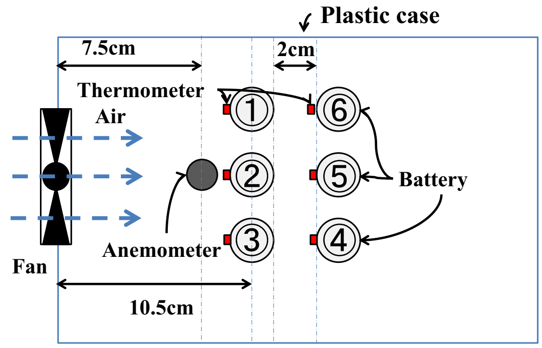

Fig.9. Cooling experimentation for stacked cells

Results of temperature rises of cell 2 and 6 are shown in Fig.11 and Fig.12, respectively. The result of the cell 2 is similar to the Fig.7. However, that of the cell 6 is much higher than that because of the difference of air flow and surrounding temperature. From this observation, it can be compensated by giving lower wind velocity and higher ambient temperature. Simple compensation coefficients are formulated by the difference of the wind velocities of two sensors and the separation distance of cells.

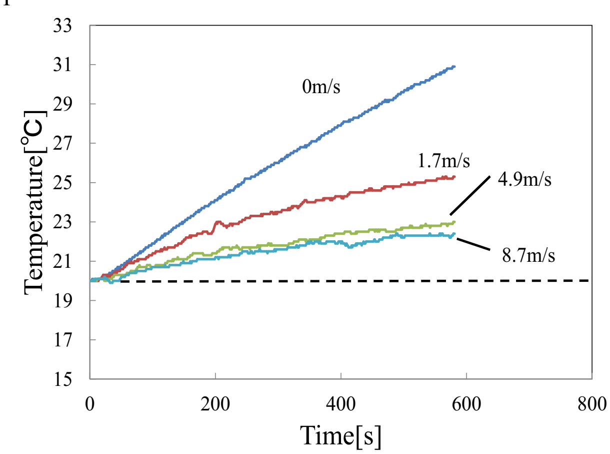

Fig.11. Temperature rise vs air flow for cell 2.
(Charge current = 2C)

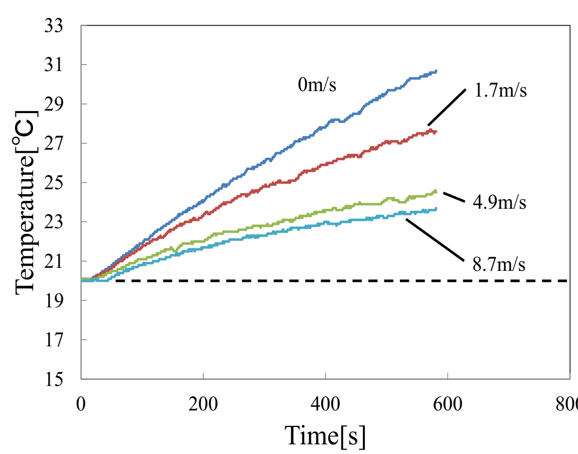

Fig.12. Temperature rise vs air flow for cell 6.
(Charge current = 2C)

In the case of stacked cells, the correction factor of each place is changed because the flow of wind and the heat from the neighbor batteries are different. The correction factors are shown in Table IV.

Measured values, theoretical correction (estimation) values, and estimation error of cells 2 and 6 are ploted in Fig. 13 and shown in Table V. The correction coefficient is smaller for the batteries in the front row.

TABLE IV

A CORRECTION FACTOR AT EACH PLACE

Battery cell	1	2	3	4	5	6
Compensation parameter	0.366	0.269	0.315	0.580	0.484	0.404

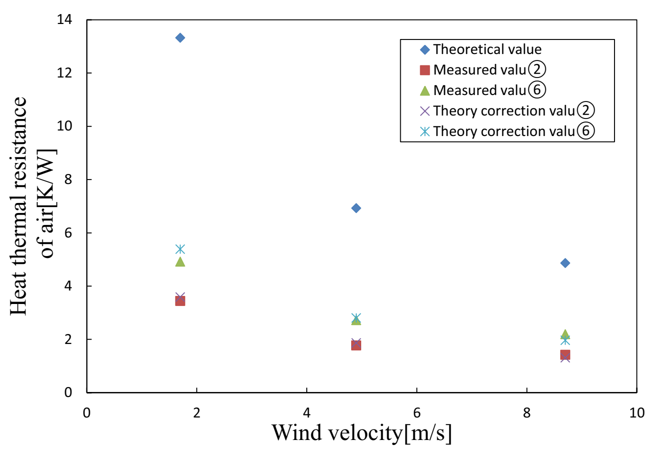

Fig.13. Air thermal resistance, Ra vs wind velocity, U of cell 2 and cell 6

TABLE V

MEASURED VALUE AND THEORETICAL CORRECTION VALUE OF CELL2 AND CELL6

Wind velocity [m/s]	1.70	4.90	8.70
Measured value of cell 2[K/W]	3.44	1.77	1.42
Measured value of cell 6[K/W]	4.91	2.71	2.19
Theoretical correction value of cell 2[K/W]	3.58	1.86	1.30
Theoretical correction value of cell 6[K/W]	5.38	2.80	1.96
Error of cell 2[%]	3.93	4.90	8.84
Error of cell 6[%]	8.68	2.97	11.6

V. Cooling System for Assembled Battery

Since the performance of stacked battery is bottlenecked by the worst battery. Thus, the cooling process must aim temperature balancing and minimizing the maximum temperature.

The cooling system is constructed with the aluminum pipes between battery rows. Cooling is executed by sending a wind to selected pipes. The assembled battery used for an experiment is structured 4 serial and 3 parallel. The picture of the equipment is shown in Fig. 14. Each battery is identified by number of 1-12. (See Fig. 15). Temperature sensors are provided as shown in the figure. Charging current is set 1C. The wind velocity is about 8.5 [m/s].

Fig.14. Cooling system for assembled battery

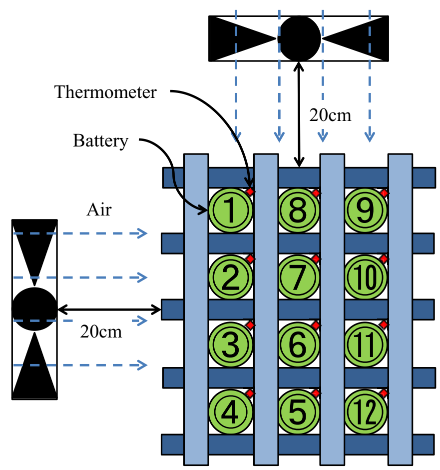

Fig.15. Experimentation environment of assembled battery

Cooling for assembled battery in Fig. 14 is examined in two different ways. First, air is flowed to both of the aluminum pipes and batteries. Fig. 16 shows the result of the temperature rise of each battery cell. Temperature range is 2 [℃].

Next, the air is flowed only in the aluminum pipes. Fig. 17 shows the result of the temperature rise of each battery cell. Temperature range is 1 [℃].

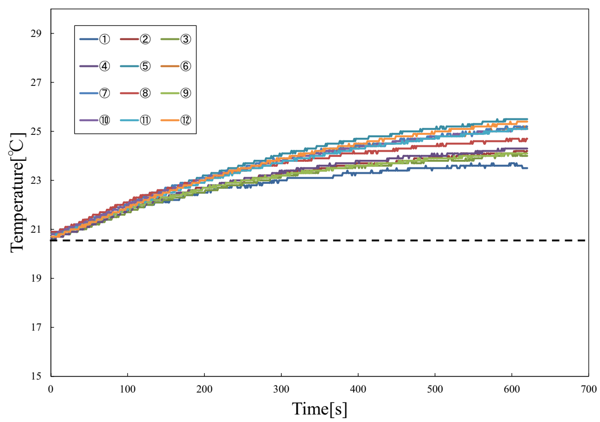

Fig.16. Temperature difference in the environment of Fig. 15

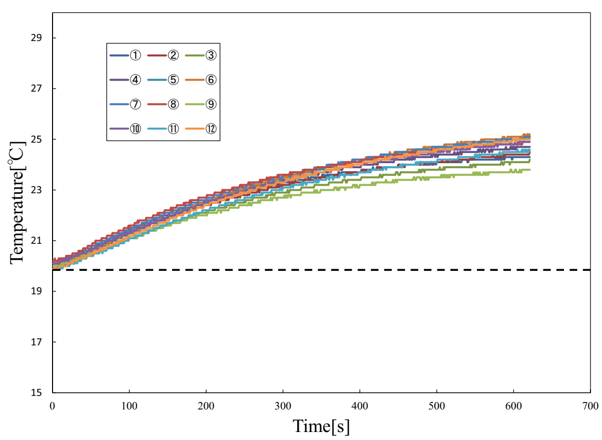

Fig.17. Temperature difference of wind flow in the pipe

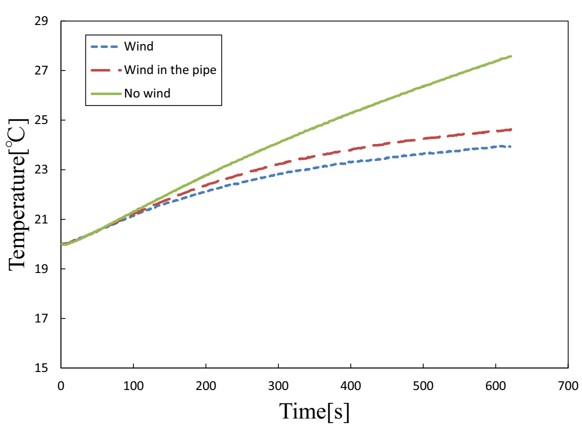

Fig.18. Comparison which were averaged temperatures

VI. Conclusions

By forced convection, from 11.4 [℃] to 12.8 [℃] temperature reduction is observed. Also, tradeoff between temperature reduction and power to cool was discussed. Theory and verification by experimentation of heating and air cooling of battery modules were presented. It was verified that the air cooling is formulated by using air resistance surrounding a battery cell, and it is dependent of surrounding temperature and surrounding wind velocity. The experimental results show it is very accurate. Variation of temperature rise is observed and an efficient compensation coefficient is applied. An efficient cooling is shows by reducing the temperature range. Actually, temperature difference is reduced from 2 [℃] to 1 [℃]. In addition, temperature redaction is made more.

Acknowledgment

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