Over 150 kW Class CHAdeMO Liquid-Cooled Charging Cable and Connector

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In recent years, there has been a strong demand for shortening battery charging time for EVs because the capacity of batteries installed in EVs is increasing. Consequently, there is a growing need to introduce DC high-power EV chargers to the market. To meet the need, a charging cable and connector for DC high-power EV chargers have to be developed. The optimal solution is to apply liquid cooling technology for forced cooling by circulating a coolant to the charging cable and connector. Therefore, we have developed a liquid-cooled charging cable and connector for over 150 kW class DC high-power EV chargers conforming to the CHAdeMO specification ver. 2.0. This paper mainly describes the applied liquid cooling technology and the evaluation results of cooling performance for the developed charging cable and connector, which has achieved the target cooling performance.

1. Introduction

In recent years, there has been a strong demand for shortening battery charging time for EVs because the capacity of batteries installed in EVs is increasing. As a result, the need to introduce DC high-power EV chargers to the market is growing. We have developed and sold 50 kW class non-forced cooled charging cables and connectors conforming to the CHAdeMO specification ver. 1.1 for the Japanese, Asian and European markets[1)]. Against this background, we have developed a liquid-cooled charging cable and connector for over 150 kW class DC high-power EV chargers conforming to the CHAdeMO specification ver. 2.0. This paper mainly describes the evaluation results of cooling performance of the developed charging cable and connector, which has achieved the target cooling performance.

The development of over 150 kW class charging cable and connector requires size reduction of the cable conductors (power line conductors) and the connector terminals (power line terminals) despite the increase in charging current to reduce the impact on the charging operability. The optimal solution to these technical challenges is to apply a liquid cooling technology for forced cooling by circulating a liquid coolant to the charging cable and connector. Such liquid-cooling technology has already been applied to CCS-compliant DC fast chargers in the European and North American markets. On the other hand, the CHAdeMO-compliant DC fast chargers equipped with a non-forced-cooled charging cable and connector over 100 kW (rated charging current 200 A) [2) 3)] have been introduced to the markets. However, the CHAdeMO chargers at 150 kW or more with a liquid cooling technology have not yet been put to practical use.

The technical challenges in developing the CHAdeMO liquid-cooled charging cable and connector include establishing a liquid cooling technology for a charging system and ensuring quality such as reliability, safety and durability. Specifically, the technical challenges include the design and manufacturing of the liquid-cooled charging cable and connector. Other challenges to be tackled are the design of the cooling system around the mating part between the non-forced-cooled EV inlet and the liquid-cooled charging connector. In addition, the design of the cooling unit for circulating and cooling a coolant and the temperature sensing for charge control by temperature monitoring also require special consideration. This paper mainly describes the applied liquid cooling technology and the evaluation results of cooling performance of the liquid-cooled charging cable and connector, which has achieved the target cooling performance.

2. Development of over 150 kW class CHAdeMO liquid-cooled charging cable and connector

Table 1 shows the typical specifications of the liquid-cooled charging cable and connector developed for over 150 kW class CHAdeMO DC fast chargers, compared to the specifications of the current 50 kW class non-forced-cooled charging cable and connector. Figure 1 shows the overview of the newly developed charging cable and connector. The power line terminals (hereinafter connector

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Panel 1. Abbreviations, Acronyms, and Terms.

EV—Electric Vehicle
A vehicle equipped with an electric motor to drive it and a rechargeable battery to supply power to the motor.

CHAdeMO—CHAdeMO is one of the DC fast charging standards specified by CHAdeMO Association in Japan for EVs and has been adopted all over the world. The standard covers charging and communication methods between a car and a charger.

CCS—Combined Charging System
CCS is one of the DC fast charging standards for EVs in the world and combines both an AC charging method and a DC fast charging method. CCS type 1 is applied in the North American market and CCS type 2 in the European market.

Liquid Cooling—Liquid cooling is to forcibly cool hot parts due to heat generation by circulating a liquid coolant. The coolant is cooled using a heat exchanger. In this paper, a charging cable and connector which become hot due to charging current are cooled by circulating a liquid coolant.

Table 1. Specifications of over 150 kW class CHAdeMO liquid-cooled charging cable and connector.

Charging power		Over 150 kW class	50 kW class
Compliant standard		CHAdeMO ver. 2.0	CHAdeMO ver. 1.1
Rated output		DC 400 A / DC 500 V	DC 125 A / DC 500 V
Charging connector	Cooling method of connector terminal (power line terminal)	Forced cooling (Liquid cooling)	Non-forced cooling
	Number of temperature sensor	2	—
	Approximate weight	1.3 kg	1.1 kg
Charging cable	Cooling method of cable conductor (power line conductor)	Forced cooling (Liquid cooling)	Non-forced cooling
	Number of temperature sensor	4	—
	Power line (Nominal size × Number)	17 mm^2 × 4	30 mm^2 × 2
	Signal line (Nominal size × Number)	0.75 mm^2 × 14	0.75 mm^2 × 9
	Number of cooling tube	4	—
	Insulation material	Ethylene propylene rubber	
	Sheath material	Polychloroprene rubber	
	Approximate cable diameter	38 mm	27 mm
	Approximate weight	1.9 kg	1.1 kg
	Compliant standard	JCS4522	JCS4522


(a) Charging connector. (b) Charging cable and connector.

Fig.1. Overview of over 150 kW class CHAdeMO liquid-cooled charging cable and connector.

terminals) and the power line conductors (hereinafter cable conductors) are forcibly cooled by circulating a liquid coolant for the over 150 kW class assembly, whereas they are not forcibly cooled for the 50 kW class assembly. Applying the liquid cooling method enables approximately the same cable conductor size of 34 mm^2 (17 mm^2×2) for the over 150 kW class assembly as that of 30 mm^2 for the 50 kW class assembly even though the rated charging current is increased from 125 A (50 kW class) to 400 A (over 150 kW class). The weight and size of the charging cable and connector (over 150 kW class) can also be designed to reduce the impact on the charging operability.

The liquid-cooled charging cable has four power lines, each containing a cooling tube as a coolant flow path. The four power lines are divided into two pairs, and each pair is assigned to the positive and negative electrodes for DC charging, respectively. For charge control in the charger by temperature monitoring, six temperature sensors are built into the liquid-cooled charging cable and connector. Two temperature sensors in the charging connector are set near the positive and negative connector terminals, respectively, and the remaining four are set on each of the four power lines near the charging cable end on the charger side. The temperature sensors are electrically insulated because a

Table 2. Target cooling performance regarding temperature rise for over 150 kW class CHAdeMO liquid-cooled charging cable and connector.

Parts / items			Target cooling performance	Remarks
Charging connector	Surface temperature	Graspable part	60°C or less	Ambient temperature: 40°C
		Touchable part	85°C or less	
	Connector terminal (Power line)	Temperature rise ΔT	50 K or less	
		Maximum temperature	90°C or less	
Charging cable	Surface temperature	Graspable part	60°C or less	
		Touchable part	85°C or less	
	Cable conductor (Power line)	Maximum temperature	90°C or less	

DC high voltage is applied to the cable conductors and the connector terminals.

An electrically insulating liquid coolant is circulated and cooled using a cooling unit. The reason for using the electrically insulating coolant is mainly to ensure electrical insulation between positive and negative connector terminals and between the high voltage part and the cooling unit. The use of the coolant is also intended to prevent electrical short circuit in the charging cable and connector and an electric shock to the users even if the coolant leaks. The specifications of the coolant and the cooling unit should be set taking into account the conditions required to obtain the target cooling characteristics described below and the chemical compatibility between the coolant and the materials used in the coolant flow path.

The CHAdeMO specification ver. 2.0 has restrictions on temperature rise due to charging current in the charging cable and connector. Table 2 shows the target cooling performance regarding temperature rise for the over 150 kW class liquid-cooled charging cable and connector in consideration of restrictions of the CHAdeMO specification ver. 2.0. This paper mainly describes that the newly developed charging cable and connector have achieved the target cooling performance shown in Table 2 at a maximum rated charging current of 400 A. In particular, this paper focuses on the effect of differences in the coolant characteristics and the cooling capacity of the cooling unit on the cooling performance of the liquid-cooled charging cable and connector. This paper also clarifies the factors that greatly affect the cooling performance and conditions to achieve the target cooling performance. Finally, this paper concludes that the liquid-cooled charging cable and connector can use various coolants and cooling units.

In the cooling characteristic evaluation tests described below, only DC current was applied to the cable conductors and the connector terminals for convenience although both DC voltage and DC current are applied to them for an actual DC fast charger. We have verified that the liquid-cooled charging cable and connector had the required withstand voltage characteristics by the withstand voltage tests, in which only DC voltage was applied to them.

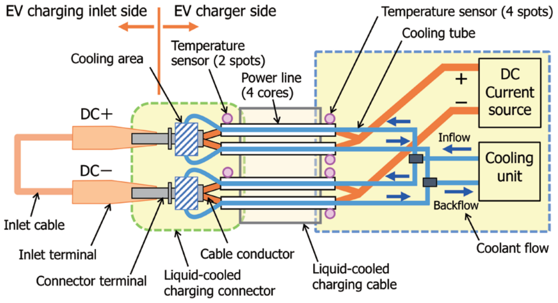

Fig.2. Schematic of cooling evaluation system for the liquid-cooled charging cable and connector.

3. Cooling performance

3.1 Evaluation method and conditions

Figure 2 shows a schematic of cooling evaluation system for the liquid-cooled charging cable and connector. The two pairs of cable conductors connected to each of the positive and negative connector terminals were connected to the positive and negative output terminals of the DC current source, respectively. One end of each cooling tube contained in the two pairs of power lines, each for positive and negative electrodes, was connected to the cooling area of the connector terminal for each polarity, and the other was connected to the coolant outlet and inlet of the cooling unit, respectively. Such a connection of the cooling tubes allows the coolant flow paths to be configured and circulate the coolant for each of the positive and negative connector terminals and power lines (cable conductors).

The charging connector was mated with the testing vehicle inlet to configure the charging current circuit. The positive and negative inlet terminals of the testing vehicle inlet were short-circuited with the inlet cable having a conductor size of 95 mm^2 and a length of 3 m. The effective length of the charging cable conductors in the liquid-cooled charging cable and connector was approximately 6 m.

Four types of electrically insulating liquid coolants A-1 to A-4 with different kinematic viscosities, 6, 20, 100, and 350 mm^2/s in this order, were used to evaluate the effect of coolant fluidity on the cooling performance of the liquid-cooled charging cable and connector. The kinematic viscosities of the coolants A-1 to A-4 depend on the coolant temperature; the kinematic viscosity of the coolant decreases gradually with increasing coolant temperature, and increases sharply with decreasing coolant temperature, based on the kinematic viscosity of the coolant at 25℃. Therefore, the coolant fluidity depends on the coolant temperature as well as on the difference in the kinematic viscosities of the coolants A-1 to A-4. These coolants also have different physical characteristics such as density, specific heat, and thermal conductivity, which are considered relevant to the cooling performance of the liquid-cooled charging cable and connector.

The testing cooling unit prepared for the cooling characteristic evaluation tests basically consists of a pump for coolant circulation, radiator with a fan working as a forced air-cooling-type heat exchanger for cooling the coolant, and coolant storage tank. This cooling unit can adjust the coolant flow rate by changing the coolant pressure at the coolant outlet of the cooling unit. The cooling capacity of the radiator with a fan depends on the ambient temperature and the coolant flow rate. Thus the cooling capacity of the cooling unit can be changed by adjusting the coolant output pressure in a simulated manner. The coolant pressure at the charging cable coolant inlet was adjusted in the range from 0.1 to 0.5 MPa before the start of energization, where 0.5 MPa is the maximum operating coolant pressure for the liquid-cooled charging cable and connector.

Under the above conditions, the temperature at each part of the liquid-cooled charging cable and connector was measured until thermal stabilization was reached while a constant charging current was continuously applied up to the maximum rated charging current of 400 A. In addition to the built-in six temperature sensors shown in Table 1 and Fig.2, the temperature at each part of the charging cable and connector was measured with the thermocouples attached to some major parts. These parts include the connector terminals, charging cable conductors, inlet terminals, inlet cable conductors, and coolant at the coolant inlet and outlet of the charging cable in the cooling evaluation system shown in Fig.2. The flow meter and pressure gauges were also installed in the coolant flow path to measure the coolant flow rate and coolant pressure.

The coolant flow rate was measured as the sum of the coolant flow rates on the positive and negative electrode sides in the liquid-cooled charging cable and connector. The potential difference by the passage of charging current through each region such as the charging cable conductors, the connector terminals, and the inlet terminals was measured to calculate the amount of heat generation per second. Then, the amount of heat generation per second in each of these regions was calculated to be the product of the potential difference and the charging current. After this, unless otherwise noted, the coolant pressure is indicated at the charging cable coolant inlet, the coolant inlet temperature is indicated at the charging cable coolant inlet, and the coolant outlet temperature is indicated at the charging cable coolant outlet.

The ambient temperature is expected to affect the coolant fluidity and the consequent cooling performance of the liquid-cooled charging cable and connector, considering the temperature dependence of the kinematic viscosity of the coolant. Therefore, the cooling performance evaluation was performed in the ambient temperature range from -10 to +40℃ using a thermostatic chamber, where the basic condition of the ambient temperature was around 25℃.

3.2 Evaluation results of cooling performance

3.2.1 Basic cooling performance

Figure 3 shows the typical temperature rise characteristics at each part of the liquid-cooled charging cable and connector with charging time at a maximum rated charging current of 400 A. First, we consider the temperature distribution in the longitudinal direction of the charging cable conductor with respect to the coolant flow direction in the cooling evaluation system shown in Fig.2. Part of the heat generated by the charging current in the charging cable conductor flows into the coolant through the cooling tube in the radial direction, resulting in cooling the charging cable conductor. Therefore, the coolant temperature increases along the coolant flow direction, resulting in the temperature increase of the charging cable conductor along the coolant flow direction. The temperature of the charging cable conductors was measured at the charging cable center and the end in the longitudinal direction. After this, the temperature at each part of the charging cable conductors as well as that in Fig.3 indicates the maximum value of the four charging cable conductors. In addition, the temperature at each part as well as that in Fig.3 indicates the temperature on the positive electrode side since the temperature at each part was almost the same on both the positive and the negative electrode sides.

As shown in Fig.3, the temperatures of the connector terminal (tip) and the charging cable conductors (cable center and end) increase sharply from the start of energization to about 10 minutes and approximately plateau after 20 minutes. On the other hand, the temperatures of the inlet terminal (tip) and the inlet cable conductor (cable center) gradually increase, compared to the above temperatures of the connector terminal and charging cable conductors and level off approximately in 30 to 40 minutes. In thermal stabilization, the temperatures

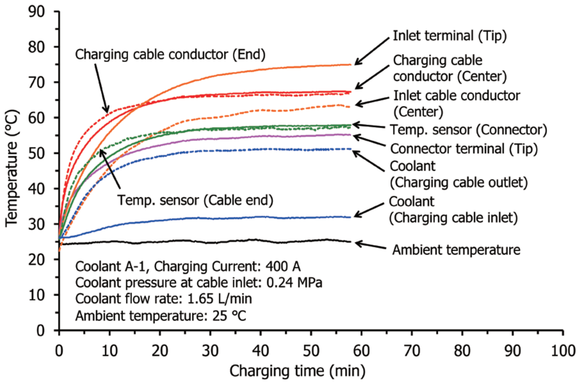

Fig.3. Typical temperature rise characteristics at each part of the liquid-cooled charging cable with connector with charging time.

of the charging cable conductors at the cable center and the end are almost the same, about 65℃, and that of the connector terminal (tip) is about 55℃. After this, unless otherwise noted, the temperature at each part is indicated in thermal stabilization. The temperature rise at each part is defined as the temperature difference between the temperature and ambient temperature except for the temperature rise of the coolant. The temperature rise of the coolant is defined as the temperature difference between the coolant outlet and inlet of the charging cable. As seen in Fig.3, the temperature rise is about 40 K at the charging cable conductors (cable center and end) and about 30 K at the connector terminal (tip) since the ambient temperature is 25℃.

As shown in Fig.3, the temperature measured by the temperature sensors built in the charging connector and the charging cable end changes, following the temperature change of the charging cable conductors (cable center and end) and the connector terminal (tip). The measurement results show that both temperatures measured by the temperature sensors built in the charging connector and the charging cable end are almost the same. The temperature difference in thermal stabilization is about 3℃ between the connector terminal (tip) and these built-in temperature sensors, and about 10℃ between the charging cable conductors (cable center and end) and these built-in temperature sensors. As detailed in Section 3.2.3, the temperature of the connector terminal (tip) and the charging cable conductor can be estimated using the time response and the temperature difference of the built-in temperature sensors as described above.

Figure 4 shows the temperature rise at the tip of the connector terminal and the inlet terminal as a function of the total heat generation per second in the connector and inlet terminals at a maximum rated charging current of 400 A. The above total heat generated per second between the rear end of the connector and inlet terminals including the contact part of those terminals was changed using the inlet terminals with different structures and changing the contact conditions between the connector and inlet terminals. The temperature at the tip of the connector terminal and the inlet terminal is indicated near the contact part of those terminals, respectively . As shown in Fig.4, the temperature rise at the tip of the connector terminal can be regarded as almost constant at about 20 K despite a slight temperature rise with the increase in the total heat generation per second. This result indicates that the temperature at the tip of the connector terminal is hardly affected by the mating conditions between the connector and inlet terminals and can be estimated using the built-in temperature sensors as detailed in Section 3.2.3. On the other hand, the temperature rise at the tip of the inlet terminal linearly increases with the increase in the total heat generation, and there is a significant temperature difference of 15 K or more between the connector and inlet terminals. That is why the temperature at the tip of the inlet terminal is significantly affected by their mating conditions and difficult to estimate using the built-in temperature sensors. Therefore, the temperature sensors are required to be built on the inlet terminal side for estimating the temperature at the tip of the inlet terminal.

Figure 5 shows the ambient temperature dependence of the temperature rise at each part of the liquid-cooled charging cable and connector and the coolant flow rate at a maximum rated charging current of 400 A when the coolant A-1 was used in the ambient temperature range from -10 to +40℃. The coolant flow rate increases remarkably with the increase in the ambient temperature, while the temperature rise decreases slightly within about 5 K at the connector terminal, charging cable conductor, and coolant. The above cooling characteristics are considered to be greatly related to the relationship between the ambient temperature and the coolant flow rate due to the temperature dependence of kinematic viscosity of the coolant. The heat inflow rate from the current heating conductor of the connector terminal and the charging cable into the coolant increases with the increase in the coolant flow rate as described in Section 3.2.2. As a result, the connector terminals and the charging cable conductors are effectively cooled. When the ambient temperature decreases, the kinematic viscosity of the coolant increases sharply based on the kinematic viscosity of the coolant at 25℃. This probably reduces the coolant flow rate and increases the temperatures rise of the connector terminal, charging cable conductor, and coolant. At this time, the coolant flow rate increases as the kinematic viscosity of the coolant decreases due to the increase in the coolant temperature, and their temperature rise is limited by their

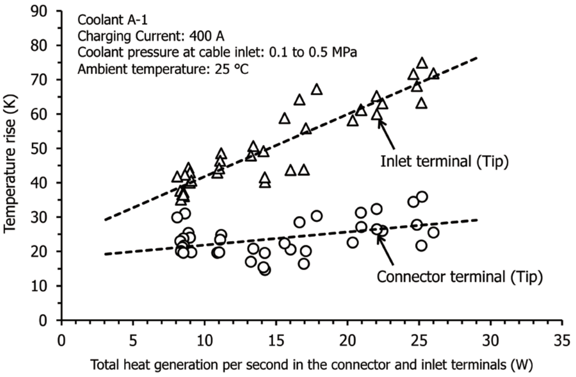

Fig.4. Temperature rise at the tip of the connector terminal and the inlet terminal as a function of the total heat generation per second in the connector and inlet terminals.

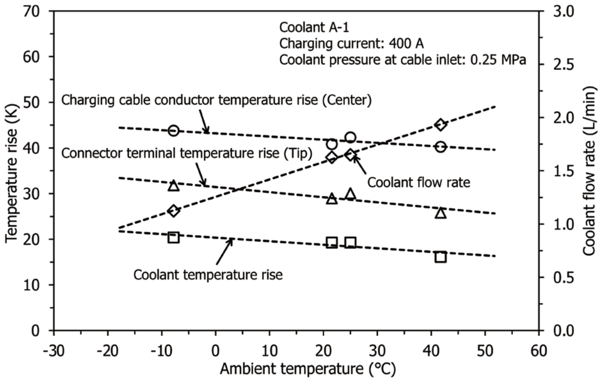

Fig.5. Ambient temperature dependence of the temperature rise at each part of liquid-cooled charging cable and connector and the coolant flow rate.

balance as a result. In contrast, when the ambient temperature increases, the kinematic viscosity of the coolant gradually decreases based on the kinematic viscosity of the coolant at 25℃. This will increase the coolant flow rate and reduce the temperatures rise of the connector terminal, charging cable conductor, and coolant. From the above, sufficient cooling performance can be obtained in the liquid-cooled charging cable and connector even at a high ambient temperature of 40℃. Specifically, the temperature rise is about 26 K at the connector terminal (tip) and about 40 K at the charging cable conductor (cable center) even at a high ambient temperature of 40℃. This has satisfied the target cooling performance such as the temperature rise of 50 K or less and maximum temperature of 90℃ or less as shown in Table 2. On the other hand, at lower ambient temperatures such as around -10℃, the target cooling performance has been also satisfied although the temperature rise is slightly higher at about 32 K at the connector terminal (tip) and about 44 K at the charging cable conductor (cable center).

3.2.2 Important factors contributing to the cooling performance

Figure 6 shows the heat inflow rate from the current heating conductor into the coolant as a function of the coolant flow rate. The current heating conductor refers to the whole of the charging cable conductors and the connector terminals which generate heat by the passage of charging current. The heat inflow rate γ from the current heating conductor into the coolant is defined in the following equation.

$$\gamma = q_2 / q_1 \cdots\cdots\cdots\cdots\cdots\cdots(1)$$

where q_1 [W] is the total heat generation per second in the current heating conductor, and q_2 [W] is the total heat per second transferred from the current heating conductor to the coolant calculated by the following equation.

$$q_2 = \rho \cdot c \cdot U' \cdot \Delta T_{cl} \cdots\cdots\cdots(2)$$

where ρ[kg/m^3] is the density of the coolant, c [J/(kg・K)] is the specific heat of the coolant, U' [m^3/s] is the coolant flow rate, and ΔT_{cl} [K] is the temperature rise of the coolant.

It is worth noting that the heat inflow rate γ from the current heating conductor into the coolant (hereinafter the heat inflow rate into the coolant) is roughly expressed as a function of the coolant flow rate for all cooling conditions. These conditions include the coolant types A-1 to A-4, charging current (200 A to 400 A), and ambient temperature (-10 to +40℃), as shown in Fig.6. In other words, the relationship between the heat inflow rate into the coolant and the coolant flow rate tends to be independent of the cooling conditions such as the coolant types, charging current, and ambient temperature. It should be noted that the effect of the coolant types appears in the range of the coolant flow rate by the difference in the kinematic viscosity of the coolant and its temperature dependence. Specifically, the coolant flow rate increases for the coolant with low kinematic viscosity while the coolant flow rate decreases for the coolant with high kinematic viscosity in the coolant pressure range up to a maximum operating coolant pressure of 0.5 MPa. Considering the coolant flow rate of about 0.5 L/min as the boundary, the heat inflow rate into the coolant gradually increases in the range of 0.5 to 0.7 with the increase in the coolant flow rate while it decreases sharply with the decrease in the coolant flow rate. The total heat generated per second in the current heating conductor is basically transferred separately to the outside and inside (coolant side) of the conductor in the radial direction. Therefore, the heat inflow rate into the coolant can be considered as an important factor, which directly determines the temperature rise and the maximum temperature of the current heating conductor.

Figure 7 shows the temperature rise of the connector terminal as a function of the coolant flow rate for each charging current from 200 A to 400 A. Figures 6 and 7 are the graphs plotted from different viewpoints for the same evaluation results. The temperature rise of the connector terminal is roughly expressed as a function of the coolant flow rate for each charging current, that is, the total heat generation per second in the current heating conductor under all cooling conditions such as the coolant types A-1 to A-4 and ambient temperature. In other words, the relationship between the temperature rise of the connector terminal and the coolant flow rate also tends to be independent of the cooling conditions such as the coolant

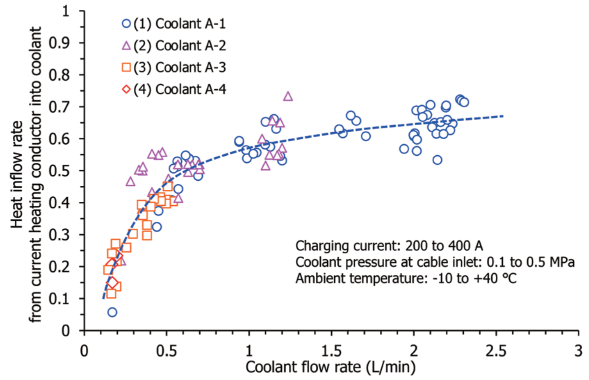

Fig.6. Heat inflow rate from the current heating conductor into the coolant as a function of the coolant flow rate.

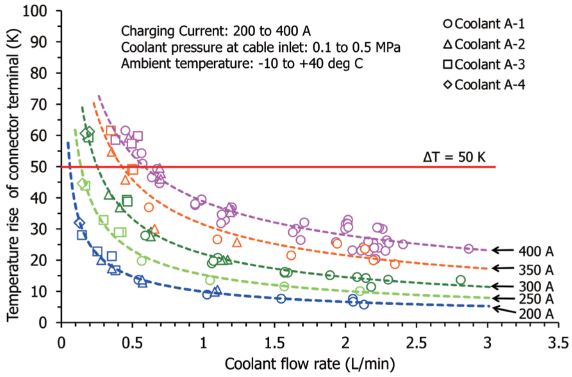

Fig.7. Temperature rise of the connector terminal as a function of the coolant flow rate for each charging current from 200 A to 400 A.

types and ambient temperature. Such tendencies and features are the same in the relationship between the temperature rise of the charging cable conductor and the coolant flow rate. As mentioned above, it should be noted that the effect of the coolant types appears in the range of the coolant flow rate by the difference in the kinematic viscosity of the coolant and its temperature dependence. Considering the coolant flow rate of about 0.5 L/min as the boundary, the temperature rise of the connector terminal gradually increases with the increase in the coolant flow rate while it decreases sharply with the decrease in the coolant flow rate. As can be seen from Fig.7, there is a lower limit of the coolant flow rate to satisfy the temperature rise of connector terminal of 50 K or less at an ambient temperature of 40℃ as shown in Table 2. The above lower limit of the coolant flow rate can be obtained as the coolant flow rate at which the temperature rise reaches the upper limit of 50 K for each charging current in Fig.7.

Figure 8 shows the lower limit of the coolant flow rate as a function of charging current obtained from each temperature rise upper limit (50 K) of the connector terminal and the charging cable conductor at an ambient temperature of 40℃ by the method described above. The lower limit of the coolant flow rate limited by the temperature rise upper limit of the charging cable conductor is larger than that limited by the temperature rise upper limit of the connector terminal, where both increase with increasing charging current. Therefore, the lower limit of the coolant flow rate is determined by the temperature rise upper limit of the charging cable conductor for the whole liquid-cooled charging cable and connector. For example, the coolant flow rate of the coolant A-1 is about 1.7 L/min at an ambient temperature of 40℃ without charging current when the operating coolant pressure is set at 0.25 MPa considering a maximum operating coolant pressure of 0.5 MPa. The above coolant flow rate of 1.7 L/min has a sufficient margin for the lower limit of the coolant flow rate of about 1.0 L/min at a maximum rated charging current of 400 A as shown in Fig.8. Moreover, the coolant flow rate becomes larger than 1.7 L/min with charging current since the kinematic viscosity of the coolant decreases with increasing coolant temperature. Therefore, it is considered that there is a sufficient margin for the lower limit of the coolant flow rate at a maximum rated charging current of 400 A in the cooling performance of the liquid-cooled charging cable and connector. From the above results, the coolant flow rate is considered to be the most important factor for obtaining the target cooling performance of the liquid-cooled charging cable and connector. The coolant flow rate determines the heat inflow rate into the coolant and, as a result, the temperature rise and the maximum temperature of the connector terminals and the charging cable conductors. It is necessary to select a coolant type and cooling unit ensuring a coolant flow rate above its lower limit within the ranges of the coolant operating pressure and ambient temperature for the liquid-cooled charging cable and connector. Although measuring the coolant flow rate for an actual charger may be difficult, the coolant flow rate can be controlled by measuring and controlling the coolant pressure. This will become possible, for example, by using the relationship between the coolant pressure, the coolant flow rate and the ambient temperature obtained without charging current.

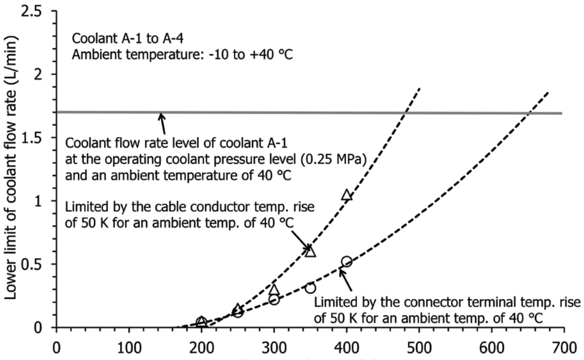

Fig.8. The lower limit of the coolant flow rate as a function of charging current obtained from each temperature rise upper limit (50 K) of the connector terminal and the charging cable conductor at an ambient temperature of 40 ℃.

From the above evaluation results of cooling performance, we macroscopically conclude as follows. The coolant flow rate is the most important factor determining the cooling performance of the liquid-cooled charging cable and connector. The relationship between the temperature rise at each part and the coolant flow rate does not depend on the coolant types, the cooling capacity of the cooling unit, or the ambient temperature at least under the evaluated conditions. On the other hand, considering the cooling mechanism microscopically from a hydrodynamic and heat transfer perspective, it is considered that complex physical phenomena are occurring in the liquid-cooled charging cable and connector. The cooling performance of the liquid-cooled charging cable and connector is mainly determined by the heat transfer between the inner wall surface of the coolant flow path and the coolant. The above heat transfer characteristics are considered to be strongly dependent on the flow velocity distribution of the coolant in the coolant flow path although they depend on the physical properties of the coolant and the related components. In particular, the flow velocity of the coolant near the inner wall surface of the coolant flow path is considered to determine the heat transfer from the wall surface to the coolant. The flow velocity of the coolant near the inner wall of the path is considered to macroscopically be determined by the coolant flow rate in the range of physical properties of the coolants A-1 to A-4 used for the cooling characteristic evaluation, although the difference in the kinematic viscosity of the coolant affects the flow velocity distribution of the coolant.

3.2.3 Temperature estimation by built-in temperature sensors

From the above, it is found that the liquid-cooled charging cable and connector we developed has the sufficient target cooling performance as shown in Table 2. Finally, we consider whether the temperature of the connector terminals and the charging cable conductors can be estimated using the built-in temperature sensors.

Figure 9 shows the relationship between the temperature of the connector terminal (tip) and the charging cable conductor (cable center and end) and the temperature measured by the temperature sensors built in the charging connector when thermal stabilization is reached for all the cooling characteristic evaluation results. Figure 9 shows a good proportional relationship between the temperature of the connector terminal (tip) and the charging cable conductor (cable center and end) and the temperature measured by the built-in temperature sensors in the charging connector. The temperature of the connector terminal and the charging cable conductor can be estimated from the temperature measured by the built-in temperature sensors using their proportional relationship. Their temperature can also be estimated using the built-in temperature sensors in the charging cable end in the same way. As already explained in Fig.3, their transient temperature during charging can also be estimated using the good time response of the built-in temperature sensors in the liquid-cooled charging cable and connector.

Consequently, an actual charger can estimate the temperature of the connector terminal and the charging cable conductor in real time using the built-in temperature sensors and control charging based on the estimated temperature for the liquid-cooled charging cable and connector.

4. Conclusion

This paper has proved that the over 150 kW class liquid-cooled charging cable and connector have the sufficient target cooling performance in various cooling conditions such as the coolant types, the cooling capacity of the cooling unit, and the ambient temperature. In particular, we have clarified that the most important factor for obtaining the target cooling performance is the coolant flow rate. We have also found that the coolant flow rate determines the heat inflow rate from the current heating conductor into the coolant and, as a result, the cooling performance of the liquid-cooled charging cable and connector. Other factors affecting the cooling performance include the physical properties of the coolant, cooling capacity of the cooling unit, charging current, and ambient temperature. We have also verified that the charging operation can be managed on the charger side by setting and controlling the operating coolant pressure. This allows the coolant flow rate to be kept above the lower limit of the coolant flow rate to obtain the target cooling performance since the coolant flow rate can be controlled by adjusting the coolant pressure for the coolant type used.

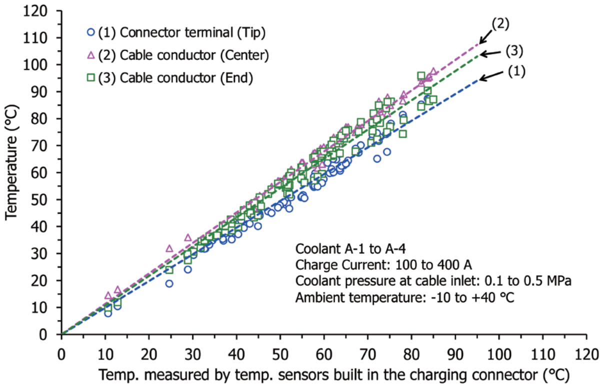

Fig.9. Relationship between the temperature of the connector terminal and the charging cable conductor and the temperature measured by the temperature sensors built in the charging connector.

In addition, we have also shown that an actual charger can estimate the temperature of the connector terminal and the charging cable conductor in real time using the built-in temperature sensors in the liquid-cooled charging cable and connector and perform the charging control based on their estimated temperature.

From the above results, we conclude that the over 150 kW class liquid-cooled charging cable and connector can be used with various coolants and cooling units. In the near future, we will incorporate the liquid-cooled charging cable and connector into an actual charger and carry out a verification test on the whole system.

References

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