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Cooling Performance of Lubricating Oils for Liquid-Cooled Motor and Battery Thermal Management System in EVs

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ABSTRACT: This study intends to clarify an impact of lubricating oils on the cooling performance for liquid-cooled motor and battery thermal management system applied to EVs. Test methos for evaluating the heat transfer characteristics between heating elements and test oils were originally designed. Lowering kinematic viscosity of lubricating oils improved the cooling performance at forced convection, and this cooling speed could be greatly influenced by base oil molecular structure. Simulation results using particle method revealed the velocity and temperature distribution near the heating elements, which might play a role in affecting the cooling performance.

KEY WORDS: electric vehicles, motor, battery, thermal control, cooling performance, lubricating oils, particle method

1. INTRODUCTION

Numbers of hybrid electric vehicles (HEVs) and electric vehicles (EVs), which provide an excellent fuel economy and reduced carbon dioxides, are increasing [1)]. E-Axle (transaxle for electric vehicles) is an electric drive unit that integrates a motor, an inverter and reduction gears, which is highly versatile and has high fuel efficiency. E-axle is being developed by various manufactures.

For further improvement in motor performance and dedicated utilization for EVs, these units are expected to become a downsized transaxle in future. In addition, for street use with frequent starts and stops, around half of motor power loss is caused by copper loss, which may be affected by coil temperature [2)]. Heat transfer property for between motor and coolant, which is called as motor cooling performance is an important issue for E-axle to improve the efficiency and reliability of driving motors.

There are three types for motor cooling: air, water, and oil. Air-cooled system has an advantage of its simple structure, but also has low cooling ability due to an extremely low heat conductivity of air compared to water or oil. Although water itself has cooling ability, it has no insulating capacity and is used for cooling through a jacket, and therefore water-cooled system result in a combination of low cooling and a complex structure. Excellent cooling can be obtained for oil-cooled system because oil is highly insulating material when the motor is immersed directly into oil. Automatic transmission fluids (ATFs) are used in some cases as a lubricating oil for E-axle [2)].

ATFs have complex compositions designed to provide lubrication and friction control for shift devises and are not always optimal as E-axle fluids. Lubricant additives providing excellent lubricity may generally tend to reduce electric resistance on the condition that the motor is immersed in axle fluid. This lubricant aspect involves the ability of the oil limit corrosion of copper elements, mainly copper wire, and electric sensors [3)].

Lithium-ion batteries are commonly used as energy storage devices in EVs because they have advantages in longer lifetime, low self-discharge rates compared to other batteries [4)]. Heat thermal energy is produced inside the battery while charging or discharging the batteries, which lead to a temperature increment [5)]. This is caused by the internal resistances and electrochemical reactions occurring inside the battery. Temperature rise in the batteries gives an effect on the life cycle, safety, reliability, and efficiency of the battery[6)]. There is an increasing interest in the technical approaches for battery thermal management.

Battery cells usually do not have direct contact between the cell and the cooling fluids. Heat capacity of fluids is known to be more effective than air. Lubricating oil is a cooling fluid which distinguishes it from the other fluids, such as water. Also, oil does not conduct electricity. The battery pack is often submerged in a cooling system designed so that heat is transferred from batteries to oil directly[4)]. Thus, thermal control for the battery system by oil- type coolant may be more attractive.

Heat transfer characteristics between oil fluid and motor/ battery pack seems to be related with viscosity, thermal conductivity, specific heat, and density of fluids. At present, the base properties of required for EVs fluids have not been systematically studied. In this study, we report the results aimed mainly at improving cooling performance for motor and battery system by lubricating oils.

2. COOLING PERFORMANCE FOR MOTOR SYSTEM BY LUBRICATING OILS

2.1. Test method

A laboratory test method for the cooling at a forced convection shown as in Figure 1 was originally designed for screening the cooling performance of oil-type coolant. The test oil is supplied by the oil pump from the oil tank and controlled at a constant flow rate of 0.5 kg/min. and at 70 ℃ temperature. Oil bulk temperature in oil pan may be around 70-80℃ in actual use. The test oils are flowed through the rectangular section, the copper plate attached the heater is set up. Heat flux at 160 W was supplied to the copper plate to reach 150℃. It is reported that a three-phase induction motor is operated at the maximum temperature of 150℃ [1]. The change in the copper plate temperature was monitors by thermocouples and then the cooling speed was calculated through the temperature by time.

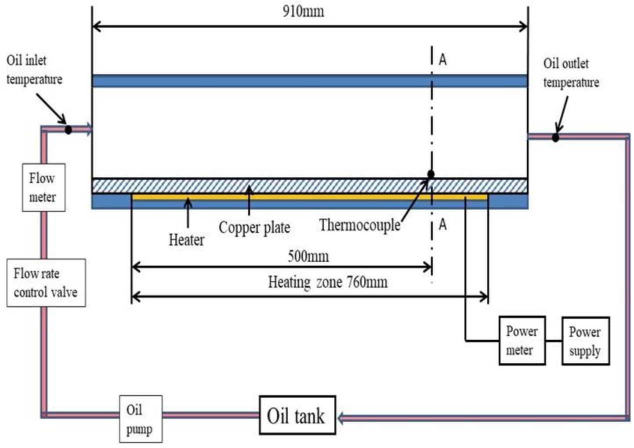

Fig.1 Schematic of test method for cooling performance by fluids at forced convection condition

2.2. Experimental results

Figure 2 shows the effect of viscosity and type of base oil on the cooling speed. Test oils were prepared so that viscosities at 70 ℃ was form 1.3 to 16.4 mm^2/s by using different type base oils. It is obvious that the cooling speed increase with lower viscosity oils comparing between hydrocracked mineral and naphthene mineral base oil similar viscosity 8-9 mm^2/s, hydrocracked base shows a better cooling ability. In addition, synthetic base oil results in an excellent cooling performance. The difference in cooling speed among base oil type may be caused by their molecular structure. Hydrocracked base oil includes more normal chain saturated hydrocarbon rather than naphthene base oil. Thermal vibration energy will come down to the main chain, and such energy transferred through collisions with neighboring molecules propagates to the end of the main chain through intermolecular heat transfer, leading to a higher heat conductivity.

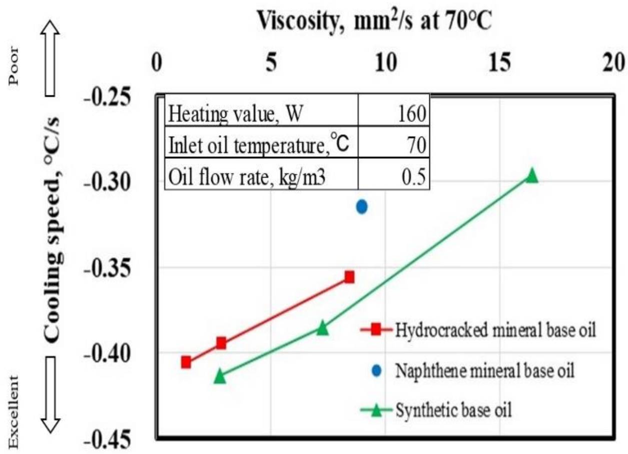

Fig. 2 Experimental result of cooling performance by oils with different viscosity and base oil type

3. COOLING PERFORMANCE FOR BATTERY SYSTEM BY LUBRICATING OILS

3.1. Test method

Kalaf et.al[4] explain that the optimum temperature range in the battery pack is 25℃ to 45℃. Failure in reducing the internal heat generated within the battery during a rapid charging could lead to a temperature increment, which results in electrolyte fires and battery explosions[6]. The mainstream of cooling methods for batteries is air-cooled and water-cooled type. Recently, oil type fluids have been studied as to immersion cooling for batteries because oils do not conduct electricity and have a higher heat capacity compared to air-cooling[7]. In this study, we developed the test method assuming immersion cooling for batteries, as shown in Figure 3. This test is aimed to evaluate the heat transfer characteristics between the heating elements and test oil when heating elements assuming batteries are installed in the test chamber and the test oil is flowed in the chamber.

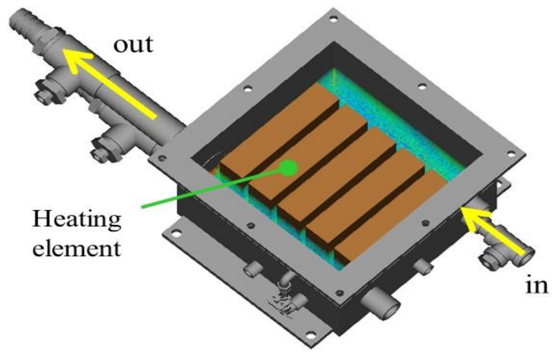

Fig.3 Overview of the test method for cooling performance assuming immersion cooling for batteries

3.2. Experimental results

Figure 4 shows the results of evaluating the effect of oil kinematic viscosity on the heater surface temperature. The test oil circulated by the oil pump flows in from the lower part of the test chamber and flows out of the test chamber from the upper part of the heating elements with a flow rate of 7.5 L/min. Heat flux at 500 W was supplied to the heating elements. The temperature change in the element was monitors by thermocouples.

The surface temperature stabilized after 15 minutes elapsed. Comparing at 30 minutes after starting tests, lower viscosity oil shows lower surface temperature than that of higher viscosity oil. As shown in Fig.2 and Fig.4, the lower viscosity oil could improve the cooling performance.

Oil Temp., °C	30
Flow rate, L/min	7.5
Total Calorific value (Heater), W	500

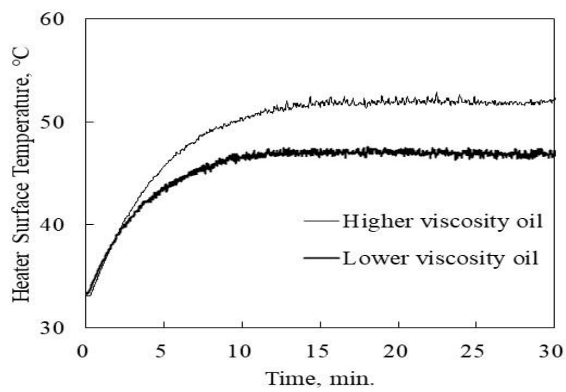

Fig.4 Effect of oil viscosity on the heater surface temperature

The effect of oil flow rate and heater surface temperature was evaluated ranging flow rate from 0.5 to 7.5 L/min., as shown in Fig.5. In case of the flow rate 0.5 L/min., the heater temperature shows the highest value, and the time reaching stable temperature is slower than that of the larger flow rate. Heating element temperature shows a lower value with higher flow rate, indicating that flow control as well as oil properties would be important for cooling performance.

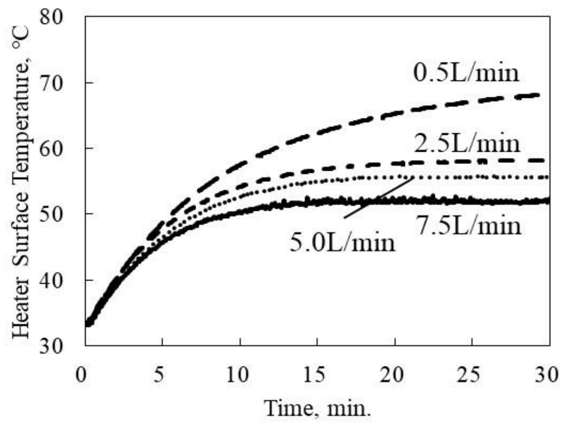

Fig. 5 Effect of oil flow rate on the heater surface temperature

3.3. Simulation study

It is necessary to understand oil flow behaviors near the heating elements. Particle method[8)] is used for fluid simulation, which represents a fluid as a collection of particles, so local flow distribution can be analyzed.

Fig.6 shows the simulation results by the particle method. Physical properties of the test oils, inlet flow rate, and heat capacity of the heating element were the same as in the experimental test. The particle size of the fluid was 0.3 mm, and the analysis was performed for 900 seconds, no external force was applied to the fluid in the chamber. From the velocity distribution in the left side of Fig.6, the inlet speed in the lower right is higher, and the inflow fluid is vigorously injected in the oil. The temperature distribution in the right side of Fig.6 shows the fluids take away heat when it passes between the heating elements, resulting in a temperature increase of the fluid.

Fig.7 shows the velocity distribution near the heating element comparing higher viscosity and lower viscosity oil. It is shown that the flow velocity with lower viscosity oil is relatively higher than that of higher viscosity oil. Even if the inlet flow rate is the same value, the flow velocity near the heating element would be different depending on fluid viscosity. This is one of the factors for the difference in cooling performance by facilitating heat transfer in the interfaces, resulting in the heater surface temperature from higher and lower viscosity fluids as shown in Fig.4.

The above results indicate that simulation work using the particle method is useful for understanding the velocity and temperature distribution of the fluid in the chamber. Further phenomenon analysis can be conducted by varying flow rate and physical properties

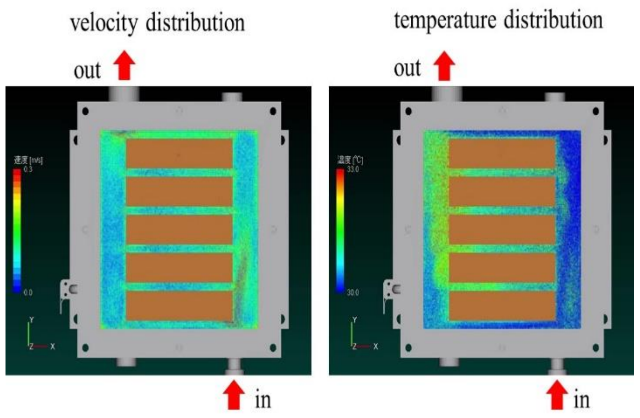

Fig. 6 Simulation results in the test chamber

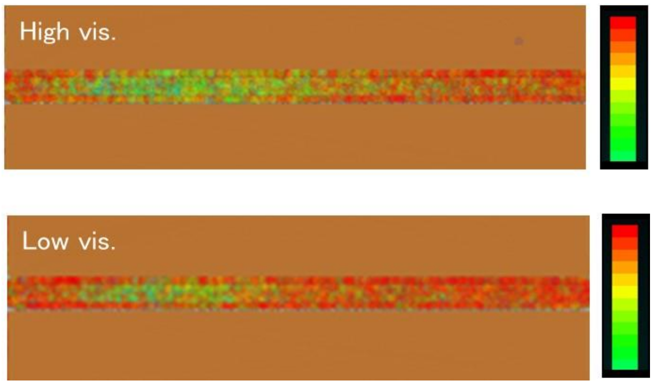

Fig.7 Velocity distribution near the heating element

4. CONCLUSION

We investigated lubricant oil impact on the cooling performance for motor and battery thermal management system applied to EVs. Test method for the cooling ability assuming usage condition in a motor system was designed.

As a result, lowering kinematic viscosity of lubricating oils improved cooling performance at forced convection, and this cooling speed could be greatly influenced by base oil molecular structure. Furthermore, the test method assuming immersion cooling for batteries was developed. the lower viscosity oil could improve the cooling performance. Heating element temperature shows a lower value with higher flow rate, indicating that flow control as well as oil properties would be important for cooling performance.

Simulation study using particle method for was carried out for understanding phenomenon of the fluid flow near the heating elements in the chamber. Results revealed the velocity and temperature distribution near the heating elements in the chamber, which might play a role in affecting the cooling performance.

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