Experimental investigation of the thermal performance of the thermosyphon cooling system with rotating

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Abstract. Rotating machine applications with superconductors attract much interest in the industry. For maintaining the operating temperature of high-temperature superconductor (HTS) field poles, a sophisticated cooling system is required. A thermosyphon (TS) is one of the ways for this purpose. The cryo-mechanical system composition is relatively simple, lightweight, and based on natural convection therefore not using any mechanical pump. It can supply the refrigerant from the static condenser part to the rotating evaporator part by using a successful rotary joint. The operating temperature of the TS cooling system depends on the refrigerant. Considering the current HTS materials, the suitable refrigerant is neon, hydrogen. Nitrogen which provides a higher operating temperature than neon and hydrogen is employed for future development. In this work, we focused on and investigated the heat transfer capacity of TS using nitrogen as the refrigerant. The heat transfer performance with rotating was also studied. As a result of the experiment, the TS cooling system could maintain the evaporator temperature by rotating. Moreover, it could transfer the 90 W heat load with rotating.

1. Introduction

For realizing high-temperature superconductor (HTS) rotating applications such as electric ships and aircraft, we have to develop the cooling system. A series of 1 to 36.5 MW HTS rotating machines have been developed with sophisticated cooling systems [1-5]. Currently, the HTS rotating machines required light and compact, this indicates the cooling system is required to be light and compact. A thermosyphon (TS) cooling system based on the natural convection retain the potential to be light and compact because it is not necessary to use the circulator. Moreover, the composition of the TS cooling system is simple. It is composed of a cryocooler, condenser, and adiabatic tube, and the evaporator. The operating temperature of the TS cooling system depends on the saturation temperature of the refrigerant. Considering the current HTS materials development, the nitrogen with a 77 K saturation temperature under atmospheric pressure has the potential to use HTS rotating applications.

We have studied the TS cooling systems with enough cooling power for HTS machines since 2006 [6-12]. For ship propulsion, the cooling system operate at the sea state. We made a model of the TS cooling system for HTS rotating machine and operated the TS cooling system under the actual operating situation. The performance of TS cooling systems at sea has been studied [10-11]. In the TS cooling system, the liquid and gaseous refrigerant are coexisting and the liquefied refrigerant quantity depends on saturation temperature. We investigated the relationship between the saturation pressure and liquefied quantity in the TS cooling system using neon as a refrigerant [12]. Considering ship and electrical aircraft applications, the TS cooling system can operate in the inclined condition, we investigate the
thermal performance TS cooling system under the inclined conditions [13-14]. We also developed cryogenic rotary-joint for high-speed rotating applications such as electrical aircraft and we achieved 1000 rpm [15-17].

The thermosyphon has a limitation of heat transfer capacities such as a counter flow, boiling form change, and dry-out. For the design of the cooling system of the HTS motor/generator, the thermal performance of the TS cooling system should investigate to evaluate the limitations of the heat transfer. In this paper, we conducted the heat load test using a TS cooling system with 90 rpm rotating. From the results, we calculated the thermal resistance and heat flux with rotating.

2. Experimental setup

Figure 1 shows the experimental equipment in this work. The TS cooling system was composed of the condenser, adiabatic tube, and evaporator. The condenser is connected to GM cryocooler which has a 164 W at 78 K. In the condenser, there is an optimal fin array for promoting the heat exchange. To maintain and measure the condenser temperature, we equipped the heat exchange plate which has a silicon diode sensor (DT-670-CU, Lakeshore) and a cartridge heater (EA72, Watlow). The condenser temperature was maintained by the temperature controller (Model 331 S, Lakeshore). To provide the refrigerant from the condenser to the evaporator through the shaft, the adiabatic tube is divided into a horizontal tube and a vertical tube. The vertical tube and the horizontal tube length are 451 mm and 517 mm, respectively. The adiabatic tube outer diameter and inner diameter are 12.7 mm and 10.7 mm, respectively. For promoting the convection of the refrigerant, the horizontal tube and vertical tube was connected with 91 degrees inclination.

The evaporator is placed in the rotor which can rotate by the pony motor. To separate the rotate part and static part, we equipped the cryogenic rotary-joint as shown in Figure1. On the evaporator, we attached two cartridge heaters for applying the heat load and a silicon diode sensor for measuring the evaporator temperature. The inside evaporator diameter and width are 120 mm and 26 mm, respectively. The total volume of the inside evaporator is 0.31 L.

![Figure 1. (A)Schematic view of a rotor-scale model of TS cooling system for HTS rotating machine. The TS part is composed of a condenser, an L-shape adiabatic tube, and the evaporator. GM cryocooler attached to the condenser via the heat exchange plate. (B)Schematic view of the evaporator. A pair of cartridge heaters and a silicon diode sensor are attached to the outside surface of the evaporator.](image-url)
We conducted the initial cooling test and the heat load test in this paper. The initial cooling test was conducted by supplying gaseous nitrogen at 0.1 MPaG until it is filled to 58.9 NL (NL= Normal Liter: 1 liter of gaseous nitrogen at 1 atm and 273 K).

In the heat load test, we applied heat load to the evaporator using a cartridge heater from 0 W to 105 W with 15 W increments. Each heat load was applied for 30 minutes. During the heat load, the evaporator rotated with 90 rpm and the condenser temperature was controlled at 78.0 K.

3. Results and Discussion

3.1. Initial cooling test

Figure 2 shows the results of the initial cooling test. Firstly, the condenser starts to cool down. When the cool down of condenser until 78.0 K, the evaporator starts to cool down because the condensation is started. Full of TS cooling system is cool down to 78.0 K with 102 minutes. The condenser heater which maintains the condenser temperature is unstable during the cooling down. This indicates the counter flow has occurred in the adiabatic tube. After the initial cooling test, the evaporator temperature stabilized at 78.2 K and the condenser heater stabilized at 154 W. Considering the cooling power of GM cryocooler, there is 10 W heat invasion in this system.

![Figure 2. The behavior of the condenser temperature, the evaporator temperature, and condenser heater upon the initial cooling test of the TS cooling system.](image)

3.2. Heat load test

Figure 3 shows the stabilized evaporator temperature and the internal pressure of the TS cooling system with 90 rpm. We applied heat load until 105 W with 15 W heat load increment. Until 90 W heat load, the evaporator temperature and internal pressure of the TS cooling system stabilized. However, when we applied the 105 W heat load, the evaporator temperature could not stabilize and the condenser temperature started to decrease. This indicates the boiling form of liquid nitrogen in the evaporator changed from nucleate boiling to film boiling. When the film boiling was started, the heat transfer rate decreased and it has made to rise the evaporator temperature.
3.3. Thermal resistance

Thermal resistance is one of the thermal performance of the TS cooling system. From the results of the heat load tests, we calculated the thermal resistance using the following equation;

$$R_{th} = \frac{(T_{evp} - T_{cond})}{Q}$$

Where $R_{th}$, $T_{evp}$, $T_{cond}$, and $Q$ are the thermal resistance, the stabilized evaporator temperature, the stabilized condenser temperature and heat load, respectively. This calculation result is shown in figure 4. According to the increase of the heat load, the thermal resistance decrease. This indicates the thermal performance is increasing with the increase the heat load. However, after the applied 60 W heat load, the thermal resistance did not change and started to increase. This indicates the boiling form of liquid nitrogen started to change and the heat transfer limit is close even 60 W heat load.

![Image](image1.png)

**Figure 3.** The temperature of the evaporator and the internal pressure as a function of applied heat load

![Image](image2.png)

**Figure 4.** The calculation results of the thermal resistance as a function of applied heat load
3.4. Heat flux
The boiling state is important for the TS cooling system. The heat flux is one index to know the boiling state. The heat flux is also calculated using the following equation;

\[ q = \frac{Q}{A} \]  \hspace{1cm} (2)

Where \( Q \), \( A \) are heat load and thermal transfer area, respectively. This calculation result is shown in Figure 5. The temperature difference has defined the difference of temperature between the evaporator and saturation temperature calculated by internal pressure. Until 60 W heat load applied, the heat flux increased proportionally, however, over the 60 W heat load, the heat flux is jumped. This indicates the boiling form change is started from 60 W heat load.

![Figure 5. The calculation results of the heat flux as a function of temperature difference](image)

4. Conclusion
For realizing the HTS rotating application, the cooling system is required which can maintain the operating temperature with rotating. Considering the current HTS motor/generator, light and compact are also necessary for the cooling system. TS cooling system has the potential to fill the light and compact. We investigated the thermal performance of the TS cooling system using nitrogen as a refrigerant with rotating. From the results of the tests, we succeeded to maintain operating temperature with 90 W heat load. However, over the 90 W heat load, the boiling form change has occurred. From the calculation, the thermal resistance and heat flux curve shows start to boiling form change over the 60 W heat load.

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