Contractible thermosyphon for conduction cooled superconducting magnets

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A thermosyphon, as a thermal switch of a conduction cooled superconducting magnet, was designed, fabricated and tested. When the temperature decreases below the triple point temperature, the working fluid inside the thermosyphon freezes and the thermosyphon does not work as a thermal shunt anymore. Although a usual thermosyphon is at OFF-state below the triple point temperature, there may be heat leak through the thermosyphon wall. The contractible thermosyphon, which has a metal bellows as a contraction component, is proposed to completely eliminate such a heat leak through the wall by mechanical detachment of the thermosyphon at low pressure.

INTRODUCTION

A conduction cooled superconducting magnet uses a cryocooler for its operation without using any cryogenic fluid such as liquid nitrogen or liquid helium. However, it takes a long cool-down time to operate the magnet in spite of its conveniences. Especially, using the cooling capacity of the second stage only in the two-stage cryocooler is not an efficient way of cool-down because of its small cooling capacity. Thermosyphon is a very useful and effective heat transfer device due to its simple structure and high heat transfer characteristics. The thermal diode characteristic of thermosyphon can be used to connect the first and second stages of cryocooler to control heat transfer in superconducting magnet system.

There have been several researches [1]-[3] on reducing the cool down time by using thermosyphons as thermal shunts between the first and second stages of the cryocooler. In general, a thermosyphon installed between the first and second stages of cryocooler can decrease the cool-down time of the magnet by utilizing the large first stage cooling capacity of the first stage. It is also noticeable that the pressure of a thermosyphon is reduced to be very small below the triple point value due to the solidification of the working fluid. The thermosyphon does not work as a heat transfer device in that condition.

Although the thermosyphon does not work at low temperature as an OFF-state, there still exists heat leak through the thermosyphon wall. Therefore, a novel concept of contractible thermosyphon is suggested to eliminate such a heat leak. This paper describes the experimental procedure and the cool-down characteristic during non-isothermal operation of the thermosyphon.

EXPERIMENTAL APPARATUS

Liquid nitrogen container and mock-up magnet

A small liquid nitrogen container was used instead of an actual cryocooler in the experiment. To simulate an actual cryocooler, which will be used for a real conduction cooled superconducting magnet system at the later stage of this research, the liquid nitrogen boiling surface area was designed to give a similar cooling power of cryocooler. Instead of an actual superconducting magnet, a mock-up magnet was made by a 1.8 kg cylindrical copper block to test the cool down performance of the thermosyphon. Fig. 1 shows the system configuration of nitrogen container, the thermosyphon and the mock-up magnet.

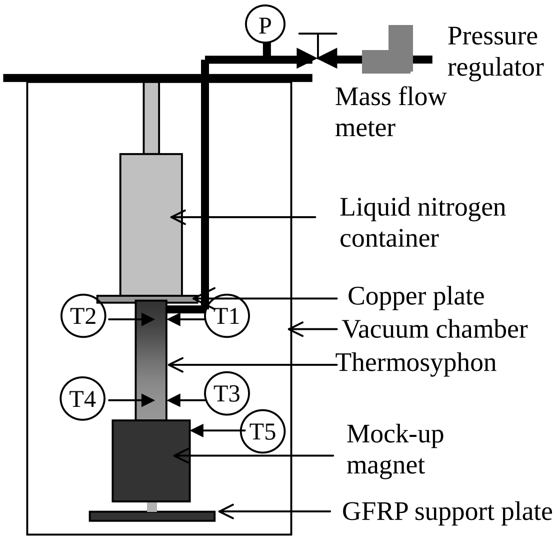

Figure 1 Schematic diagram of experimental apparatus and temperature measurement

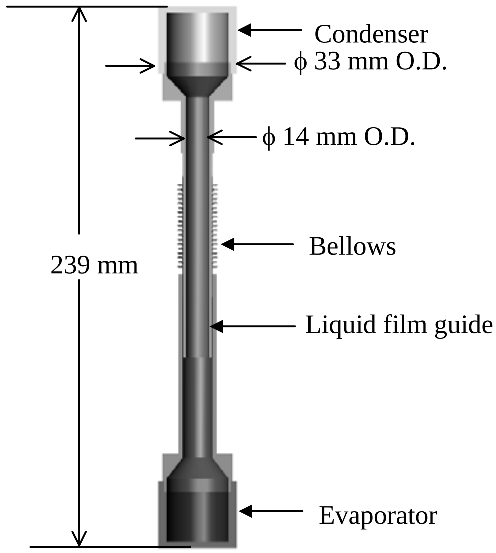

Figure 2 Cross section of the thermosyphon

Thermosyphon

Since a thermosyphon operates at two-phase state, the maximum operating temperature range is limited by the fluid property. In case of nitrogen and argon, which would be used as the working fluid of the thermosyphon, the operating temperature and the pressure lie between the critical and the triple points as listed in Table 1. In addition to the critical temperature and pressure limit, the maximum operating pressure is also limited by the strength of a thermosyphon wall.

Although a thermosyphon cannot operate below the triple point temperature, there might be some conduction heat leak through the wall of thermosyphon. Therefore, the thermosyphon was designed to be contractible and detachable from the mock-up magnet at reduced pressure and temperature. This novel feature eliminates conduction heat leak at the OFF-state. For the contraction capability, the adiabatic region of the thermosyphon was composed of a copper tube and the formed metal bellows (MDC, Part No. 470003) as shown in Fig. 2. In principle, the thermosyphon should be designed to withstand the high pressure more than 3 or 4 MPa considering critical temperature to use the full operating range of the working fluid. This means that much higher charging pressure is required at room temperature. However, since the allowable maximum pressure of the thin-walled bellows was only 2.5 MPa, the operating temperature of the thermosyphon was practically limited by this pressure. In the experiment, the thermosyphon was pressurized at 1.6 MPa and a continuous charging method was applied.

Experimental set up

As shown in Fig. 1, the thermosyphon and the mock-up magnet were installed in a vacuum chamber. Soft metal such as indium wire was used to reduce the thermal contact resistance between the evaporator and the mock-up magnet. During the cool-down process, the surface temperatures (T1, T3), the inside fluid temperatures (T2, T4) and the magnet temperature (T5) were measured by E-type thermocouples as shown in Fig. 1. The thermosyphon pressure and the mass flow rate were also measured continuously.

Nitrogen or argon gas was continuously charged from a high pressure gas cylinder at constant pressure of 1.6 MPa until the thermosyphon's filling ratio reached 25 % to avoid the dry out limit. For precise control of the filling ratio, the charged mass flow rate of the working fluid was instantaneously measured and integrated.

Table 1 Critical States and Triple Points of Nitrogen and Argon

	Nitrogen	Argon
Critical state	126.1 K,3.39 MPa	150.7 K,4.89 MPa
Triple point	63.2 K,12.85 kPa	83.8K, 68.8 kPa

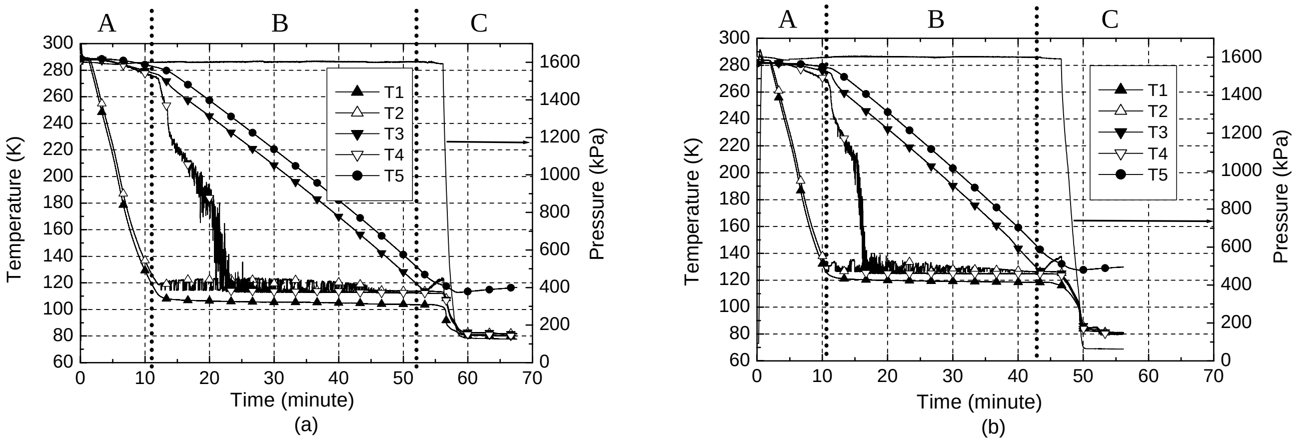

Figure 3 Cool down history of thermosyphon (a) with nitrogen and (b) with argon, at charging pressure of 1.6 MPa

EXPERIMENTAL RESULTS

The cool-down process of the thermosyphon is divided into 3 periods according to heat transfer mode of the thermosyphon (Fig. 3).

Conduction period; A

When the liquid nitrogen container was filled with liquid nitrogen, the temperature of the condenser started to be cooled by thermal conduction to the bottom copper plate of the liquid nitrogen container. Since the temperature of the condenser was higher than the critical temperature, there was no liquid phase at all during this period. The dominant heat transfer mechanisms in the thermosyphon were natural convection and wall conduction. Therefore, the temperature decrease of the evaporator and the copper block was very small and most of the cooling capacity was used to cool down the copper plate and the condenser.

Non-isothermal period; B

When the condenser temperature reached the saturation state, the condensation of the working fluid started at the condenser surface and the incoming mass flow to the thermosyphon was increased slightly around 10 minute as shown in Fig. 4. Nevertheless, the evaporator temperature was still higher than the saturation temperature of the operating pressure and the condensed liquid did not accumulate at the evaporator. Therefore, there was little liquid in the evaporator. The condensed liquid film might immediately evaporate by hot liquid film guide or the evaporator when it came down. This period can be called as the non-isothermal operation of the thermosyphon. Although the operation of the thermosyphon was non-isothermal, most of the cool-down time occupied this period. This period continued until the evaporator was cooled down to the saturation temperature.

Isothermal period and detachment; C

The evaporator temperature also decreased to the saturation state and the liquid started to accumulate from the bottom of the evaporator. During this period, the gas flow rate increased very rapidly as shown in Fig. 4 to compensate for the increase of liquid phase and to keep the constant pressure. The valve of gas flow into the thermosyphon was closed when the total mass of the working fluid reached 25 % of the filling ratio.

During the large gas flow, the evaporator surface temperature was not decreased due to continuous condensation at the condenser. Moreover, the gas temperature at the condenser was a little bit increased by the large inflow of the working fluid. After the end of the gas charging process, the evaporator and the condenser temperatures started to decrease simultaneously. The pressure of the thermosyphon also decreased rapidly as the temperature decreased. From this moment, the thermosyphon was at isothermal state. It means that there is enough liquid phase at the evaporator and the condenser.

When the pressure decreased below 0.26 MPa, the bellows was contracted and the evaporator was detached from the mock-up magnet. As a result, the temperature of mock-up magnet was slowly increased by a parasitic heat leak from environment.

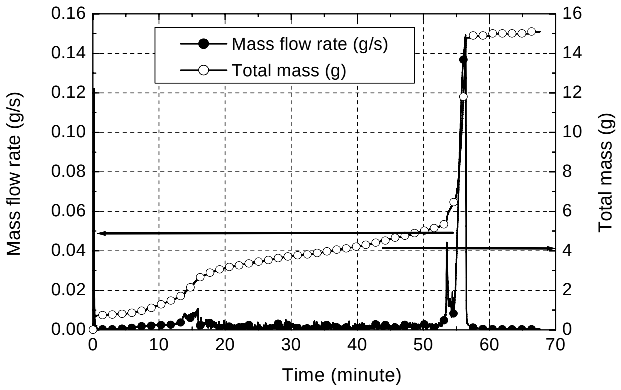

Figure 4 Mass flow rate and total mass into the thermosyphon in 1.6 MPa nitrogen thermosyphon

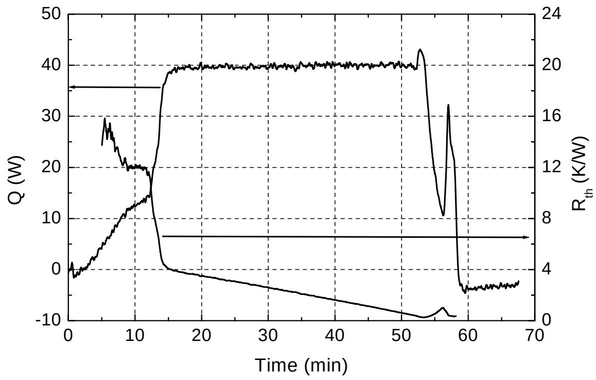

Figure 5 Heat transfer rate and thermal resistance through thermosyphon calculated from Fig. 3 (a)

Heat transfer rate and thermal resistance

The heat transfer rate through the thermosyphon can be calculated by equation (1).

$$\dot{Q} = mC\frac{dT}{dt} \tag{1}$$

where *m* and C is the mass and the heat capacity of the mock-up magnet. *dT/dt* is its temperature rate. Fig. 5 shows the calculated heat transfer rate through the thermosyphon and the overall thermal resistance between the condenser and the evaporator. In the beginning of the non-isothermal period, heat transfer rate was rapidly increased to 40 W and kept constant during this period, which was limited by the stable film boiling at the copper plate of liquid nitrogen container. The thermal resistance was rapidly decreased around 12 minute by the transition to the non-isothermal period. It was also slowly decreased during the non-isothermal period and it reached 0.28 K/W at isothermal thermosyphon.

CONCLUSION

Two types of contractible thermosyphons, which used nitrogen and argon as working fluid, were tested to cool-down a mock-up superconducting magnet. About 40 W was the cooling rate through the thermosyphon during the non-isothermal period. After the end of the cool down proccess, the thermosyphon was successfully detached from the mock-up magnet. Although more effective cooling can be achieved by high working pressure, the entire cooling range is not covered by a single fluid thermosyphon due to limitation of the critical temperature and the triple point temperature. Therefore, thermosyphons of various working fluids such as nitrogen, argon, oxygen and ethane should be used together to cover wide operating temperature range of a cryocooler. Moreover, the optimized design is necessary for effective operation of thermosyphon in consideration of its transient response.

ACKNOWLEDGEMENTS

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