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Contractible Heat Pipe for Conduction Cooled Superconducting Magnets

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***Abstract*--** **A contractible heat pipe is designed and tested to improve cooling performance of conduction cooled superconducting magnet. When the heat pipe temperature drops below the triple point temperature, heat pipe working fluid freezes to create low pressure. From this moment the heat pipe does not work any more (OFF state) and it just works as a heat leak path when the temperature of the first stage is higher than that of the second stage. Considering small cooling capacity of the second stage around 4.2 K, the conduction loss is not negligible. Therefore, the contractible heat pipe, made of a metal bellows and copper tubes, was considered to eliminate the conduction loss. Nitrogen and argon are as working fluid of heat pipe. The copper block is cooled down with these heat pipe and the cooling performance for each heat pipe is compared. At OFF state, the bellows is contracted due to the low pressure of heat pipe and the evaporator section of the heat pipe is detached about 3 mm from the second stage cold head of the cryocooler. In this way, we can eliminate the conduction loss through the heat pipe wall.**

1. INTRODUCTION

Conduction cooled superconducting magnets use cryocooler for its operation without using any cryogenic fluid such as liquid nitrogen or liquid helium. However, it takes long cool down time to operate the magnet in spite of its conveniences. Especially, using the cooling capacity of the only second stage in the two-stage cryocooler is not so efficient because of its small cooling capacity. Therefore, there have been several researches [1]-[3] on reducing the cool down time by using heat pipes as thermal shunts between the first and second stage of cryocooler. In general, a heat pipe 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 cryocooler.

A heat pipe is a very useful and effective way of heat transfer device due to its simple structure and high heat transfer characteristics. It is also noticeable that the pressure of a heat pipe is reduced to be very low below the triple point temperature by solidification of working fluid and it does not work as a heat pipe. These thermal diode characteristics of a heat pipe can be used to connect the first and second stage of cryocooler to reduce the cool down time of conduction cooled superconducting magnet system.

Although the heat pipe does not work below the triple point temperature, there still exists conduction heat leak through the heat pipe wall when the second stage temperature is lower than the first stage temperature. The conduction heat leak is an order of 0.1 W depending on the heat pipe size and it is not negligible when it is compared to the small cooling capacity of the second stage cryocooler. Therefore, the concept of contractible heat pipe was proposed in this research. Using the pressure decrease at low temperature, the heat pipe with a metal bellows is designed to contract and detach from the second stage of cryocooler or the magnet. Due to this ON/OFF operation of the heat pipe, the conduction heat leak through the heat pipe wall can be completely eliminated.

As a first step of the contractible heat pipe research, a contractible heat pipe was fabricated and tested to cool down a small test copper block. Liquid nitrogen chamber was used instead of an actual two-stage cryocooler and nitrogen and argon were used as a heat pipe working fluid. This paper reports the design concept of the contractible heat pipe and its preliminary test results.

2. EXPERIMENTAL APPARATUS

2.1. Simulated cold head and test magnet

A small liquid nitrogen chamber was used instead of an actual cryocooler. To simulate the actual cryocooler, which will be used for a real conduction cooled superconducting magnet systems at the later stage of this research, the liquid nitrogen boiling surface area was designed to give similar cooling power of a cryocooler.

In the film boiling region, the boiling heat transfer rate is about 2~3 W/cm^2 and the cooling surface area, which was made by copper plate, was designed as 50 cm^2 to give about 100 W cooling capacity. Moreover, the chamber's wall was made by 1 mm thickness stainless steel tube to minimize the heat transfer through it.

The test magnet was replaced by a 1.8 kg cylindrical copper block to test the contractible heat pipe. All copper parts of the experimental apparatus were made of OFHC(Oxygen Free High Conductivity) copper.

2.2. Contractible heat pipe

Using the formed metal bellows (MDC, Part No. 470003), the heat pipe was designed to be contractible according to the pressure variation. As the temperature goes down in the heat pipe, the pressure of the heat pipe becomes lower and lower. Therefore, the contractible heat pipe was designed to detach from the magnet or the second stage of cryocooler below some design pressure. In this manner, the conduction loss through the heat pipe wall can be eliminated.

TABLE I
SPECIFICATION OF THE BELLOWS IN THE HEAT PIPE

Inner diameter	12.7 mm
Bellows thickness	0.15 mm
Material	Stainless 321
Yield strength	200 MPa
Effective diameter	19.05 mm
Max. internal pressure	2.5 MPa
Spring constant	1500 N/m
Estimated elongation	0.84 mm/atm

TABLE II
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

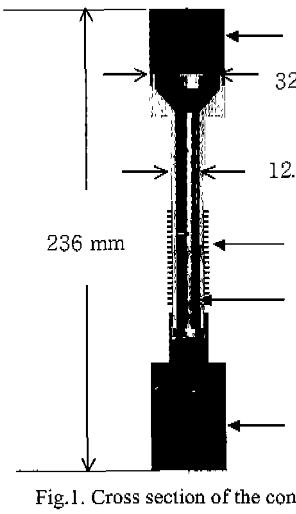

Fig.1. Cross section of the contractible heat pipe

Due to the thin-walled bellows the internal pressure of heat pipe was limited by its yield strength as shown in Table I. The elongation by internal pressure is 0.84 mm per 1 atm.

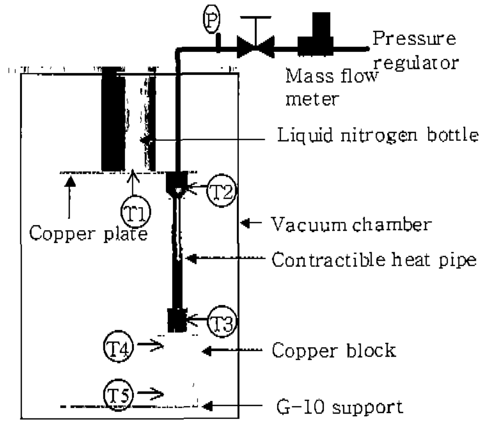

Fig.2. Schematics of experimental apparatus and its measurements

Since a heat pipe operates as two phase state, the temperature range of operation is limited between the critical temperature and triple point temperature. In case of nitrogen and argon, which would be used as working fluid of heat pipe, the operating temperature and pressure range is listed in Table II.

To use the full operating range of working fluid, the heat pipe should be designed to withstand the high pressure more than 3 or 4 MPa. However, the maximum pressure of thin-walled bellows is only 2.5 MPa and the operating temperature is limited by this pressure. The minimum operation temperature is also determined by considering the pressure for the detachment. In this experiment the detachment distance was adjusted as 3 mm from the copper block and it was about 360 kPa of the heat pipe pressure.

The contractible heat pipe was fabricated with copper except bellows part to increase conduction heat transfer. A liquid film guide was also installed to induce smooth liquid flow and prevent the buckling fracture by high operation pressure as shown in Fig. 1.

2.3. Experimental setup

As shown in Fig. 2, the contractible heat pipe and the copper block were installed in a vacuum chamber. For the attachment and detachment during the cool down process the distance between the heat pipe and test magnet was precisely adjusted. The G-10 support was connected to the copper plate to prevent the heat leak from the bottom of the vacuum chamber. Since the evaporator of the heat pipe and the test magnet were not fastened tightly with some bolts or other methods, cryogenic thermal grease was used to reduce the thermal contact resistance.

To measure the cool down process, the surface temperatures of each component were measured by E-type thermocouples, which are installed at the locations of T1 to T5 in Fig. 2. The heat pipe pressure and mass flow rate were also measured.

Since the maximum pressure was limited by the thin-walled bellows, the nitrogen and argon gas were continuously charged from the high pressure gas cylinder with constant pressure of 14 atm until the heat pipe's filling ratio reached designed level. In this experiment the filling ratio was designed as 25 % at 1 atm. For the precise control of filling ratio, the mass flow rate was measured and integrated by software until the filling ratio reached 25 %.

3. EXPERIMENTAL RESULTS

Experiments were performed for nitrogen and argon gas as working fluid. Fig. 3 (a) and (b) show the cool down process for nitrogen and argon. Temperatures of each component, pressure and mass flow rate were recorded by digital scope during the experiment. From the experimental results, the cool down process could be divided into 4 periods according to the state of the heat pipe.

3.1. Conduction period; A

The temperatures of copper plate were decreased by pooling boiling of liquid nitrogen and the condenser was cooled by thermal conduction to the copper plate. Since the temperature of condenser was higher than the critical temperature, there was no liquid phase at all during this period. The dominant heat transfer mechanisms in the heat pipe were gas convection and wall conduction. Therefore, the temperature decrease in the evaporator and the copper block was very small. The condenser temperature decreased continuously to the saturation temperatures at 14 atm.

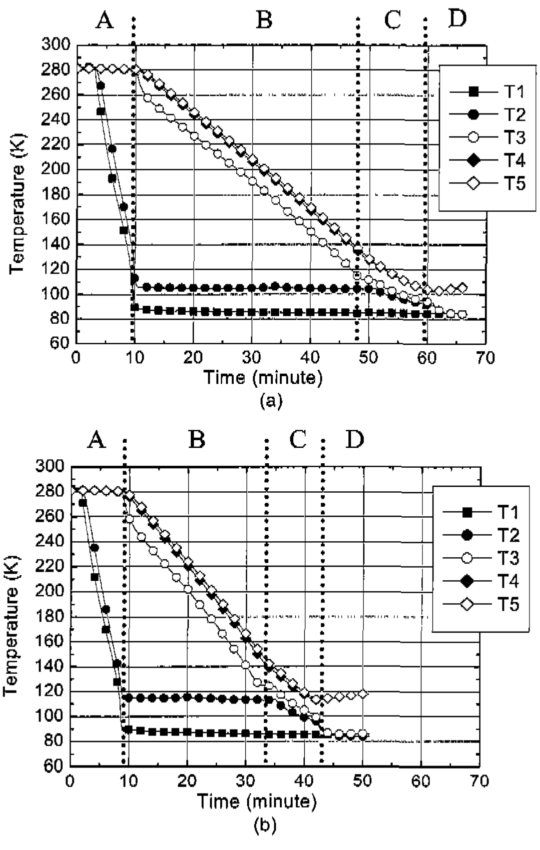

Fig. 3. Cool down history of test apparatus (a) with nitrogen heat pipe and (b) with argon heat pipe

3.2. Partial heat pipe period; B

Although the condenser temperature reached saturation state and condensation started at the condenser surface, the evaporator temperature was still higher than the saturation state. Therefore, the condensed liquid did not accumulated at evaporator and there was no liquid in the evaporator.

The condensed liquid film may immediately evaporate by the hot liquid film guide or evaporator and the liquid could not accumulate in the evaporator. This period can be called as partial operation of heat pipe. A little increase of gas inlet flow due to the starting of condensation was observed at the beginning of this period as shown around 10 minutes in Fig. 4.

Especially, rapid increase of the pressure was observed around 30 minutes, although there was no more gas flow into the heat pipe as shown in Fig. 4.

This seemed that the condensed liquid film stated to drop to the bottom of the evaporator and the liquid drop, which immediately evaporated by the hot surface of evaporator, induced the increase of the pressure. The large temperature difference between the condenser and evaporator was due to the thin- walled bellows that prevented the conduction heat flow.

Although the operation of the heat pipe was not complete, the evaporator was cooled by the liquid drop and the copper block was also cooled by the evaporator. This period continued until the evaporator also reached saturation temperature.

3.3. Full heat pipe period; C

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

During the large gas flow, the evaporator temperature was kept almost constant due to continuous condensation at the condenser. However, the evaporator and condenser temperature started to decrease simultaneously after the end of charging.

The pressure of the heat pipe also decreased rapidly according the temperature decrease. This is a complete operation period as a heat pipe. It means that there is enough liquid phase at evaporator and the condensation and evaporation are occurring continuously.

3.4. Detach period; D

Finally, the decreased pressure induced the contraction of the heat pipe and it detached from the copper block. From this moment, the copper block was thermally isolated from the heat pipe and conduction loss path was eliminated.

Since the cooling load was removed, the temperature of the heat pipe was rapidly decreased to the copper plate temperature. However, the temperature of the copper block stated to slowly increase by parasitic heat loss such as radiation from the surroundings and heat conduction from the supporting plate.

4. Discussion

From the experimental results, the average cooling capacity $\bar{Q}$ during the period B and C was calculated by equation (1).

$$\bar{Q} = \frac{\rho \bar{C}_p \Delta T}{\Delta t} \tag{1}$$

where, ρ is density, $\bar{C}_p$ is a temperature averaged heat capacity of copper and ΔT is temperature variation during the heat pipe operation time Δt.

The calculated cooling capacity during the period B and C was 36.4 W and 52.7 W for nitrogen and argon respectively. The argon heat pipe showed larger cooling capacity than the nitrogen. This is because the critical temperature of argon is larger than that of nitrogen and it has wide operation temperature range for this simulated cold head.

There the copper block was more effectively cooled by argon heat pipe. In addition, it took 52 min by nitrogen and 39 min by argon to cool down the copper block to 120 K. In general, a gas of higher critical temperature is better for high temperature range and that of the lower critical temperature is better for low temperature range. Although the heat pipe operated as fully two phase only in the period C, enough heat was also transferred to the liquid nitrogen in the period B by the partial operation of the heat pipe.

At the end of cool down process the heat pipe was successfully detached from the copper block and eliminated the conduction loss path by the contraction of the heat pipe. This means that the contractible heat pipe can be perfectly OFF state when the second stage temperature is lower than the first stage for actual application to conduction cooled superconducting magnet systems.

Although the cryogenic thermal grease was used to reduce the thermal resistance between the heat pipe and the copper block, the temperature difference was over than 10 K. This can be reduced by improving the thermal contact of the heat pipe and the copper block. Increasing the contact rea or plating the contact surface with soft metal such as indium can be an effective way to reduce the thermal resistance.

Since the heat pipe operation is limited by its critical temperature and triple point temperature, the entire cooling range cannot be covered by one heat pipe. Therefore, heat pipes of various working fluids such as nitrogen, argon, oxygen and ethane should be used together to cover the wide range of temperature. Moreover, the optimized design is necessary for more effective operation of heat pipe considering the transient response [4], [5].

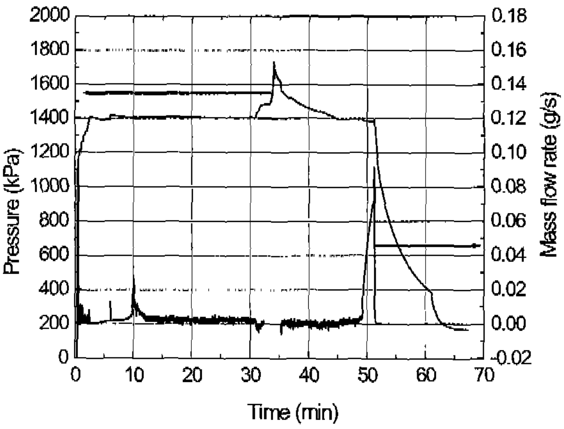

Fig. 4. Pressure and mass flow rate for the nitrogen heat pipe

Summary

Two types of contractible heat pipes, which use nitrogen and argon as working fluid, were tested to cool down copper block. Over than 30 W was transferred through the contractible heat pipes during the partial and full heat pipe period and the copper block was cooled down to 120 K within 52 min by the nitrogen heat pipe and 39 min by the argon heat pipe. After cooled down to the desired temperature and pressure, the heat pipe was contracted and successfully detached from the copper block to eliminate the conduction heat leak path through the heat pipe wall.

Acknowledgment

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