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Experimental investigation on the detachable thermosiphon for conduction-cooled superconducting magnets

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Abstract

A detachable thermosiphon, as a transient thermal switch for conduction-cooled superconducting magnet, is designed, fabricated and tested. A thermosiphon between the first and second stages of a cryocooler can reduce the cool-down time of a conduction-cooled superconducting magnet by using the large cooling capacity of the first stage. The thermosiphon is a very efficient heat transfer device until all the working fluid in it freezes (off-state). After the working fluid freezes and the second stage temperature becomes lower than that of the first stage, however, the thermosiphon then becomes a conduction heat leak path between two stages of the cryocooler. Considering a very small cooling capacity of the second stage of the cryocooler around 4.2 K, the conduction heat loss is not negligible. Therefore, a detachable thermosiphon, made of a metal bellows, is considered to be able to eliminate such a conduction heat leak. The mock-up magnet is cooled down with the thermosiphon and the thermodynamic states of the thermosiphon and the mock-up magnet are precisely examined during the whole cool-down process. At off-state, the thermosiphon is detached mechanically from the magnet. In this way, the conduction heat leak path through the thermosiphon wall is completely eliminated. This paper describes the detailed transient operation of the detachable thermosiphon using nitrogen as the working fluid.

Keywords: Thermosiphon; Detachable; Conduction-cooled; Superconducting magnet; Cryocooler; Thermal switch

1. Introduction

Thermosiphon is an efficient heat transfer device utilizing phase change phenomenon of fluid in a closed volume. Since the boiling and the condensation of pure fluid occur at fixed temperature, the heat transfer between two ends of the thermosiphon (i.e. the evaporator and the condenser) is possible with negligible temperature difference. This superior heat transfer characteristic of thermosiphon to plain thermal conduction has been readily recognized in many applications. Either wickless heat pipe which is a thermosiphon or regular heat pipe with porous wick have been developed for various temperature range as a better thermal conductor than copper or aluminum one with the same cross-sectional area. One of the drawbacks of thermosiphon or heat pipe is that the operation temperature range is limited by the working fluid. Especially at cryogenic temperature, selection of the working fluid is narrower than that at room temperature. Nevertheless, several cryogenic thermosiphons were successfully utilized in diverse fields such as cryopump [1], cold neutron source [2], high temperature superconducting motor [3], and CMS (Compact Muon Solenoid) superconducting magnet [4].

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Conduction-cooled superconducting magnets use cryocoolers for their operation without using any cryogenic fluid such as liquid nitrogen or liquid helium. However, it takes long time to cool down a large superconducting magnet in spite of its convenience. Especially, using only the cooling capacity of the second stage in a two-stage cryocooler is not so an efficient cool-down way because of its small cooling capacity. Therefore, there have been several researches [5,6] on reducing the cool-down time by using a thermosiphon as a thermal shunt between the first and second stages of the cryocooler. A thermosiphon installed between the first and the second stages of cryocooler can decrease the cool-down time of the magnet by utilizing the large cooling capacity of the first stage. It is also noticeable that the pressure inside the thermosiphon is reduced to be a very small value below the triple point temperature when the working fluid is solidified. After that moment, the thermosiphon does not work as a heat transfer device any more. Although the thermosiphon does not operate below the triple point of the working fluid, there still exists some conduction heat leak through the thermosiphon wall when the second stage temperature is lower than that of the first stage. This heat leak is approximately a few tenth watts and it is not negligible when it is compared to the cryocooler's small cooling capacity at the second stage around 4.2 K. If the thermosiphon is detached from the second stage, this conduction heat leak is completely eliminated. This paper describes the design and the experimental results of a detachable thermosiphon for conduction-cooled superconducting magnets. The thermosiphon, which is made of metal bellows is mechanically detached from the second stage of cryocooler at low pressure when its normal operation period is finished. The detailed transient process of the detachable thermosiphon is monitored with temperature and pressure sensors.

2. Experimental apparatus

2.1. Cryocooler and mock-up magnet

A two-stage GM cryocooler (Sumitomo, Model RDK-415D) is used for the experiment. Its nominal cooling capacity is 45 W at 50 K in the first stage and 1.5 W at 4.2 K in the second stage. A 5 kg cylindrical copper block is used as a mock-up superconducting magnet. All copper parts of the experimental apparatus are made of OFHC (oxygen free high conductivity) copper.

2.2. Thermosiphon and heater

Fig. 1 shows the detailed configuration of the thermosiphon. The evaporator and the condenser are made of copper and the adiabatic part between them is composed of stainless steel bellows. Two stainless steel tubes as guides around the bellows keep the thermosiphon straight. Nitrogen is used as the working fluid. Since the thermosiphon operates between the critical temperature and the triple point temperature of nitrogen, the initial charging pressure at room temperature must be higher than its critical pressure. Considering the burst pressure of the bellows, the maximum system pressure is always maintained below 50 atm.

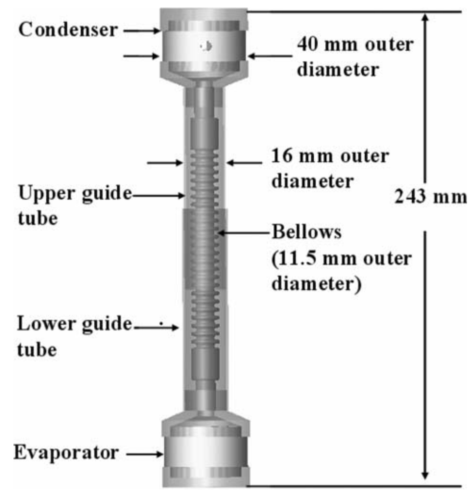

Fig. 1. Schematic diagram of the thermosiphon.

A heater is used to increase the operation time of the thermosiphon by preventing the working fluid from freezing in the condenser. Nichrome wire is wound on the condenser surface as a heater and the supplied power is adjusted by a temperature controller (Lakeshore model 331). The total resistance of the wound nichrome wire heater is 45 Ω at 77 K. The temperature controller supplies appropriate electric power to try to maintain the predetermined setting temperature of the condenser surface.

2.3. Experimental setup and measurements

As shown in Fig. 2, the cryocooler cold head and the mock-up magnet are enclosed in a vacuum chamber. Two flanges are fastened tightly on each stage of the cryocooler to install the thermosiphon and the mock-up magnet. Thin indium plate is used to reduce thermal contact resistance between the flanges and the cryocooler. Indium wire is used between the bottom part of the evaporator and the second stage flange for the same purpose. Each flange is supported by GFRP (glass fiber reinforced plastic) rods attached on the top flange to prevent excessive bending stress on the cryocooler cold heads. The buffer tank, as the reservoir of the working fluid, is installed outside of the vacuum chamber. Kevlar wire is attached on the evaporator's topside and connected to the room temperature lifter through the top flange. The bottom surface of the evaporator is separated from the second stage flange when the thermosiphon is lifted by the Kevlar wire. During the cool-down experiment of the mock-up magnet, the temperatures are measured with various temperature sensors and the operating pressure of the thermosiphon is also measured. The detailed information of the temperature sensors are listed