Thermal Transport Properties of Multiple Oscillating Heat Pipes under Simultaneous Operation

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Abstract. In this paper, it is shown that the results of experiments on which four oscillating heat pipes (OHP) were simultaneously operated. The OHP is formed into board shape and the four OHPs were put radially. Two FRP disks as dummy winding held the OHPs. Stainless steel sheet heaters were inserted between OHPs and FRP disks, to simulate heat generation in the winding. This equipment was cooled by circulation helium gas. The helium gas flowed in the copper pipe. The copper pipe was soldered to copper plates mounted to cooling edge of the OHPs. Four buffer tanks were connected to each OHP to control the pressure of each OHP individually. The working fluid of the OHPs was Neon. It was demonstrated that all OHPs were simultaneously operated.

1. Introduction

The recent development of technology that creates wire from high-temperature superconductors (HTS), including Bi-2223, Bi-2212, and RE-123, continues. As production technology of long length wires and their performance improve, the expectations for HTS devices that can be used in temperature ranges (20-70 K) higher than the temperature of liquid helium are rising. The reason is that the warmer environment than the liquid helium temperature leads to high stability and high cooling efficiency. For this reason, HTS devices can be applied conduction cooling type without using any cryogen such as liquid helium. In the conduction cooling type, HTS coils are connected to the cryocooler directly with thermal conductive path, for example, copper or aluminum plate. The cooling system is very simple rather than the pool cooling system or forced cooling system with some cryogen.

HTS wires in the coils are cooled by thermal conduction. Therefore, temperature gradients in the coils are easily produced. The inhomogeneous are able to be causes of some degradation originated from mechanical strain. And then coil performance might be limited by the area of the highest temperature in the coil. Besides, the eddy current losses in the thermal path with copper or aluminum, of which resistivity is low, are produced under pulse operations. The losses in the thermally conductive path are not desirable. So new thermal conduction paths with high thermal transport properties are required to improve usability and performance of the conduction cooling HTS coils.
HTS coils with self-oscillating heat pipes, OHP, have been studied in order to improve the heat transfer properties in the coils. In the studies, developments of the OHP with the plate shape have been ongoing. Several papers have reported the superior properties of the OHP experimentally [1-4]. However, these experiments were carried out on one OHP plate. In order to realize the practical HTS coils installed OHP, many OHPs are built-in the coils. In the conceptual design of the HTS coils using multiple OHPs, OHPs are arranged radially in the coils [4].

In order to clarify the properties of multiple OHPs under their simultaneous operation, the experiments have been carried out on sample with four OHPs and two FRP disks. The two FRP disks simulate the HTS windings. In this paper, the detail has described the experiments and the results. The purpose of this paper is to clarify the properties of multiple OHPs. For the purpose, this paper reports that the results of experiments carried out on four OHPs with plate shape put between two FRP disks.

2. Experimental set up and procedures

The purposes of experiments were to clarify the following points. The first one was to check whether multiple OHPs can operate simultaneously under individually controlling pressure in each OHPs or not. The second one was to check whether multiple OHPs can operate simultaneously under the same pressure in each OHPs or not. In this chapter, experimental setups are shown.

2.1. Sample setup

The OHP is formed into board shape, and the four OHPs were put radially in the sample. Two FRP disks as dummy winding held the OHPs. Both edges of each OHP extend outside of the two FRP disks, as shown in Figure 1. Gas helium control is explained in the next section. These both edges were the cooling area where are contacted with copper plates. The copper plates were soldered to copper pipes in which helium gas flow for cooling. Black circles in Figure 1 (b) show temperature measurement points. Thermometers, Cernox, were set on the surfaces of the copper plates. The heaters were mounted on almost center of the OHPs. In this experiment, these heaters are connected in series.

2.2. Cooling system

Figure 2 shows the experimental cooling system and working fluid filling system to OHPs. In the system, two cryo-cooler were used for cooling, and one compressor was used for circulation of helium gas. Helium gas is circulating in the cooling system. The gas is gradually cooled down, as flowing through in the HX1, HX2, HX3, HX4. Moreover, then the gas cools the copper plate attached to each OHPs. The gas flow back to room temperature as flowing through in HX4, HX3, HX2, HX1. HX1 and HX3 are tube-in-tube heat exchanger. The cross-section of the heat exchangers is shown in Figure 2.

For controlling the temperature of the sample, foil heaters were attached to the second stages of the cryo-coolers.
2.3. Working fluid filling system to OHP
In the working fluid filling system, four filling lines exist corresponding to each OHP. The procedure to fill the working fluid in the OHP is as follows: Firstly, all valves, V4-V11, open, then all OHPs are vacuumed. And then all valves close. Next, the power of cryo-coolers turns on, and gas helium circulation also starts. After cooling down have been finished, the valve of the target buffer tank opens. The working gas is filled to the buffer tank. And then the valve of OHP side, V4-V7 open. At the same time, working fluid in the buffer tank flow into the OHP and the fluid is liquified. If pressures of OHPs are individually controlled, V8-V11 are kept closing. If the OHP pressures are identical, V8-V11 open.
Pressure meters, P3-P6, measure pressure in the OHPs. If self-oscillating occurs in the OHP, pressure vibrating might be observed by these pressure meters. In these experiments, we used Ne as working fluid. And filling ratio was 87.5 % at 1 atm.

2.4. Experimental procedures to evaluate the thermal properties of OHPs
In order to evaluate thermal properties of the OHPs, temperature differences between high and low temperatures in the OHP were measured when stainless sheet heaters heat to the OHP. The low temperature was the measured temperature at the cooling area of each OHP. The high temperature was the measured temperature at another side of the OHP.
Firstly, temperature differences, $\Delta T$, were measured on four OHPs during heating by stainless steel sheet heater before working fluid filled OHPs. This experiment clarifies the properties of OHP without working fluid. Next, the heating experiments were carried out on OHPs with working fluid. The pressures of each OHPs were controlled individually. Finally, the same experiments were carried out on the four OHPs of which pressures were controlled identically. The first experiment is called Exp-Vacuum. The second and third ones are called Exp-1 and Exp-2, respectively. All heating experiments have been carried out under controlled temperature of 24 - 26 K at the cooling area.

3. Experimental Results
In this chapter, the experimental results are explained. Firstly, figure 3 shows the results on the Exp-Vacuum. The horizontal axis represent heat input every OHP. The vertical axis represents temperature differences, $\Delta T$. Over 12 K of $\Delta T$ were observed. Large temperature differences were produced due to
In order to evaluate the performance of the OHPs, effective thermal conductivities of the OHPs are determined by thermal transport properties. In this case, the properties can be considered to determine by the thermal conductivity of the stainless steel.

Next, figure 4 shows the results of Exp-1. The horizontal and the vertical axes represent the same as figure 3. \( \Delta T \) of OHPs was suppressed below 2 K at 2 W input each OHP by stainless steel sheet heater. \( \Delta T \) is very small compared with 15 K observed on vacuum conditions at 2 W. Figure 5 shows measuring results of pressure in the OHPs. The horizontal axes and the vertical axes represent pressure [MPa] and cooling area. So, the contact thermal resistances are ignored. The measuring results of pressure in the OHPs. The horizontal axes and the vertical axes represent pressure [MPa] and cooling area. So, the contact thermal resistances are ignored. The measuring results of pressure in the OHPs. The horizontal axes and the vertical axes represent pressure [MPa] and cooling area. So, the contact thermal resistances are ignored.

Finally, figure 6 shows the results of Exp-2. \( \Delta T \) of OHPs 1, 2 increased compared with Exp-1, but in cases of OHPs 3, 4, \( \Delta T \) was almost same as Exp-1 below 2 W. Pressure vibrating were observed below 2 W as shown in figure 7. Over 2 W, \( \Delta T \) of OHP 3 increase rapidly. That is considered that the dry out occurred in OHP 3. These results indicate that four OHPs have operated as oscillation heat pipes even if four OHP pressures were identical, although the properties of the OHP under same pressures decreased a little compared with that under individual pressures. The results show that some mechanism to synchronize pressure oscillations in the four OHPs may have worked. That is important points for realizing HTS coils built-in several OHPs. Moreover, it seems that the properties of OHPs divide into two groups, OHP 1, 2 and OHP 3, 4. In the case of OHP 1, 2, \( \Delta T \) under individual pressures are almost twice as that of the same pressures. In contrast, in the case of OHP 3, 4, the differences between \( \Delta T \) under individual pressures and that of the same pressure are small. By investigating the differences between the two groups, it may be possible to gain knowledge for improving the characteristics during the simultaneous operation of several OHPs.

In order to evaluate the performance of the OHPs, effective thermal conductivities of the OHPs are calculated [4]. The thermal conductivity is calculated from temperature difference, OHP dimensions, and length between heating and cooling area. So, the contact thermal resistances are ignored. The

![Figure 5](image)

**Figure 5** Measured pressure in the four OHPs on Exp-1. (a) Heater input is 2W, (b) Heater input is 3.8W. Pressure vibrating can be observed except of OHP3 at 3.8W input.
calculated results at the input power of 2 W are shown in Table 1. Some metals as aluminium have higher values. The most significant reason is the small length between heating and cooling area in these experiments due to arrangements of stainless steel heater. The previously reported results were on experiments in which heating and cooling areas have put both sides of the OHP, respectively. Therefore, the length is different two or three times.
4. Conclusions
In order to clarify the properties of multiple OHPs under their simultaneous operation, the experiments have been carried out on four OHPs. The experiments on individual and identical pressures in OHPs were carried out. The results show that several OHPs can work simultaneously under individual and identical pressures. The results show that some mechanism to synchronize pressure oscillations in the four OHPs may have worked. That is important points for realizing HTS coils built-in several OHPs.

5. References
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