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Transparent cryogenic thermosiphon using N_2 and CF_4 mixture as the working fluid

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Abstract-- **A mixed working fluid has a potential to widen the operation temperature range of the thermosiphon. In this study, the thermosiphon using N_2 and CF_4 mixture as the working fluid is fabricated and tested to verify its transient thermo hydraulic characteristic. A transparent pyrex glass tube was used for the thermosiphon itself and the vacuum chamber was also fabricated by glass to visualize the internal state of thermosiphon. Onset of condensation temperature was related to the partial pressure of CF_4. Two solidifications were observed and condensate temperature range of mixed working fluid was from 160 K to 70.7 K with N_2 25% composition.**

1. INTRODUCTION

The thermosiphon, which utilizes a phase change of liquid and vapor is an efficient heat transfer device. Heat is transferred by evaporation and condensation of the working fluid in the thermosiphon. The operating temperature range is typically from the critical to triple points to maintain a two phase state. The thermosiphon shows a small temperature difference between hot and cold ends because a large amount of heat is transferred by phase change. The driving force of thermosiphon is gravity without wick structure that is generally used for conventional heat pipes. Thermosiphons have been used as practical heat transfer devices due to their simple structure and superior heat transfer characteristics [1-2].

A thermosiphon is utilized as a thermal shunt to reduce the cool-down time of a cryogenic system cooled by a two-stage cryocooler. The cooling rate in the case of 2-stage cryocooler, was improved by linking the first stage of cryocooler and the thermal load with a thermosiphon [3]. There is negligible heat transfer between the first stage of the cryocooler and thermal load after solidification of fluid in the thermosiphon. A detachable thermosiphon was devised to eliminate any conduction heat leak for very low temperature, such as 4 K [4]. The cool-down time reduction by the thermosiphon is determined by the type of working fluid which is directly related to the operating temperature of the thermosiphon. Multiple thermosiphons using fluids which have different operating temperature ranges reduce the initial cool down time [5-6]. Single thermosiphon using CF_4 and N_2 mixture as the working fluid has a possibility of reducing the initial cool down time [7]. Operational characteristics of mixed working fluid thermosiphon are difficult to understand such as first condensation, inside thermal condition of thermosiphon when the operation was stopped, and the solidification of the mixed working fluid.

A transparent thermosiphon was fabricated to observe the exact phenomenon of thermosiphon with mixed working fluid in this paper.

2. MATERIALS AND METHOD

N_2 and CF_4 were selected for study and properties of the fluids are listed in Table 1 [8]. The experimental apparatus was composed of a GM cryocooler (Model 350 CS, Austin Scientific), thermosiphon, buffer tank, and vacuum chamber (Figure 1).

TABLE I
PROPERTIES OF CRYOGENIC FLUIDS.

	Critical point (K)	Normal boiling point (K)	Triple point (K)
CF_4	227.5	145.1	89.5
N_2	126.2	77.3	63.2

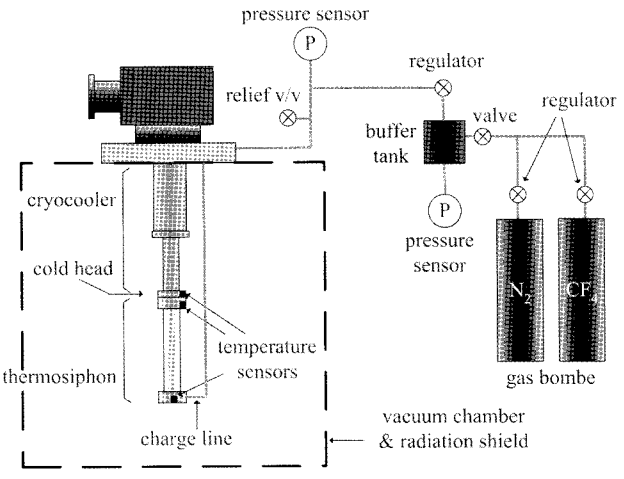

Fig. 1. Schematic diagram of experimental apparatus.

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The condenser and evaporator parts of the thermosiphon were fabricated with copper and the adiabatic region was fabricated with pyrex glass tube. The ends of pyrex glass tube were connected to thin stainless steel tubes. The condenser and evaporator surfaces were protruded as shown in Figure 2.

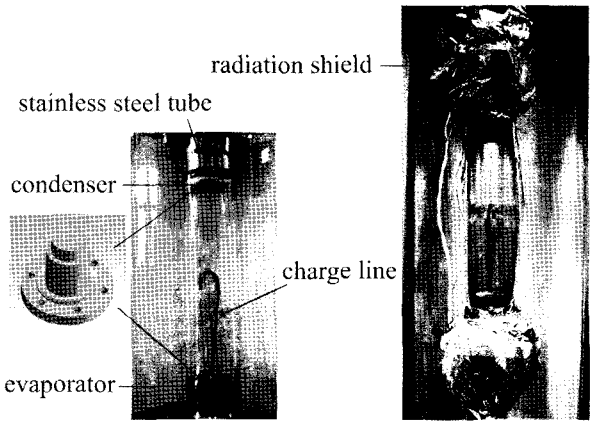

Fig. 2. Configuration of condenser, evaporator, and thermosiphon.

The adiabatic region was 150 mm of length and 38 mm of outer diameter. The surface of cryocooler and adiabatic region of thermosiphon except a small area of observation were covered by radiation shields to reduce radiative heat loss. The thermosiphon was fixed at the end of 2nd-stage of the cryocooler. The buffer tank (3.4 L), a reservoir of the working fluid, was placed outside of the vacuum chamber. Initial buffer tank pressure was calculated to make enough condensate in the evaporator to observe the solidification process. About 30% of thermosiphon volume was filled with liquid when the initial pressure of buffer tank was 896 kPa. A regulator was used between the buffer tank and thermosiphon to maintain the inside pressure of the thermosiphon below 310 kPa due to danger of fracture. A relief valve, installed between the regulator and thermosiphon, was set to release at 310 kPa. The vacuum chamber was also fabricated with glass for transparency.

The temperature of the cold head, condenser, and evaporator during the cool down process were measured by silicon diode sensors. Temperature sensors were attached on the outer surface of each part, and the accuracy of sensors were ± 0.25 K. The inside pressure of the thermosiphon was measured by a pressure transducer which was installed between the regulator and thermosiphon. The accuracy of the pressure transducer was ± 0.5 kPa. The pressure of the vacuum chamber was maintained under 10^{-3} torr during the experiment.

The experimental procedure was as follows. The regulator, which was located between the pressure transducer and thermosiphon (Figure 1) was closed, and N_2 was charged to the buffer tank. The initial pressure of N_2 was controlled from 237 kPa to 462 kPa to change the mixing composition. CF_4 was charged until the total pressure of the buffer tank reached 896 kPa. Six experiments were conducted for different mixing compositions (Table 2). The regulator was opened to charge the thermosiphon up to 310 kPa, after charging of the buffer tank was completed. The cool down was started by the cryocooler. Temperature and pressure were measured and internal state of mixed working fluid thermosiphon was observed until the working fluid was frozen.

TABLE II
EXPERIMENTAL CONDITIONS.

Case	Mass ratio of N_2	Pressure of N_2	Pressure of CF_4
1	0%	896 kPa	0 kPa
2	10%	237 kPa	659 kPa
3	15%	324 kPa	572 kPa
4	20%	399 kPa	497 kPa
5	25%	462 kPa	434 kPa
6	100%	0 kPa	896 kPa

3. RESULTS

The first condensation temperature of pure N_2 and CF_4 was in a good agreement with T_{sat} (saturation temperature) of the thermosiphon pressure. The first condensation temperature of the mixed working fluid was determined by the partial pressure of CF_4 in the thermosiphon (Table 3). The maximum error between the theoretical T_{sat} and measured condenser temperature was 2.13%.

TABLE III
ONSET OF CONDENSATION TEMPERATURE OF MIXED WORKING FLUID.

Case	Partial pressure of CF_4	Theoretical T_{sat}	Condenser temperature
2	220 kPa	157.1 K	155.8 K
3	191 kPa	154.8 K	151.5 K
4	163.5 kPa	152.3 K	151.3 K
5	143.5 kPa	150.3 K	149.6 K

The overall temperature transition behavior of each case was analogous, and the cool down history of N_2 15% (case 3) is shown in Figure 3. Liquid was started to form on the surface of the condenser and dropped down to the evaporator. This condensation process continued after the onset of condensation, but the amount of liquid droplet was increasing and decreasing from 110 to 135 minutes (Figure 3-a). A white color haze was formed around the condenser surface at 132 minutes and fell down to the evaporator. The haze was not observed in a single working fluid thermosiphon. The amount of haze increased and finally all the volume of thermosiphon was filled with the haze. The haze disappeared at 235 minutes. There was liquid at the bottom of the evaporator and T_C (condenser temperature)

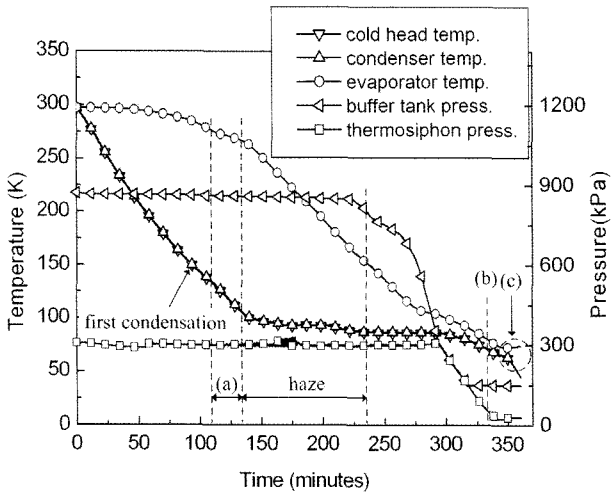

Fig. 3. Cool down history of N_2 15% (case 3).

was 87.3 K at this time. 87.3 K of T_C was continued until the pressure of thermosiphon fall below 300 kPa. The condensate accumulation coincided with the pressure drop of buffer tank. T_E was 162 K when the buffer tank pressure started to decrease. The pressure of thermosiphon was 62 kPa, T_C was 72.5 K, T_E (evaporator temperature) was 81.7 K, and the large amount of liquid existed at the evaporator section at 332 minutes (Figure 3-b). T_{sat} of N_2 at 62 kPa is 73.4 K and triple point of CF_4 is 89.5 K. The temperature of the mixed liquid at the bottom of thermosiphon was lower than the triple point of CF_4 and higher than T_{sat} of N_2. Two solidifications were observed. A portion of accumulated transparent liquid at the evaporator section changed to an opaque solid, and the other one existed in liquid state during the solidification process. The thermosiphon operation was stopped after the lowest T_E was achieved, and it was shown as the temperature separation of T_C and T_E (Figure 3-c). The remaining liquid continuously evaporated and solidified on the condenser surface. (Figure 4) The first T_S (solidification temperature) and the lowest T_E were different according to mixture composition. (Table 4) First T_S is the temperature of evaporator at the start of solidification and T_E decreased a little more during the solidification process. T_C was constant by 63.5 K independent of mixture compositions when the solidification was occurred at the evaporator.

TABLE IV
SOLIDIFICATION TEMPERATURE AND LOWEST T_E.

Compositions	N_2 10%	N_2 15%	N_2 20%	N_2 25%
First T_S	77 K	74.2 K	73	70.7
Lowest T_E	76.5 K	73 K	71 K	67.7 K

4. DISCUSSION AND CONCLUSION

It was assumed that two gases were mixed homogeneously in the buffer tank, and the gases entered the

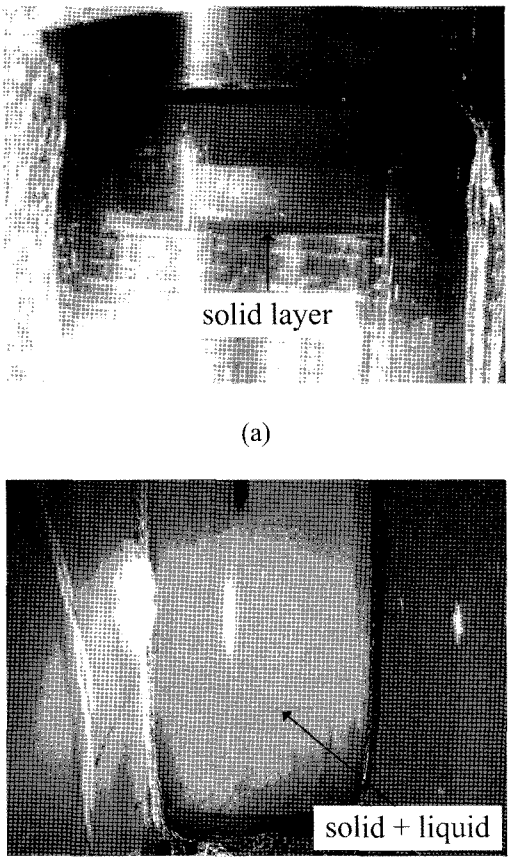

Fig. 4. Formation of solid; (a) condenser and (b) evaporator.

thermosiphon with constant mixture composition. It seems that the haze was CF_4 because it was formed with onset of condensation and disappeared when the condensate accumulated at the evaporator. T_E was 162 ± 1 K independent of composition when the condensate started to accumulate at the bottom of evaporator. This temperature is saturation temperature of CF_4 at the pressure of thermosiphon. The liquid at the evaporator is CF_4 because liquid and vapor pressures are same. T_C was constant as 87.3 K, when the condensate was accumulating at the bottom of thermosiphon, in all cases. 87.3 K is T_{sat} of N_2 at the pressure of thermosiphon. It is concluded that CF_4 and N_2 are mixed homogeneously in the thermosiphon and CF_4 starts to condense and then CF_4 starts to accumulate at the evaporator. The condensation temperature is determined by saturation temperature at partial pressure of CF_4 in the thermosiphon, and the accumulation temperature is determined by saturation temperature of CF_4 at the thermosiphon pressure. N_2 starts to condense. The upper part of thermosiphon is filled with N_2 gas, and the bottom of thermosiphon is filled with CF_4 and N_2 mixture liquid. Liquid properties such as evaporation and solidification temperatures are changed in a mixture. In other words, CF_4 exists as liquid under the triple point, and N_2 exists as liquid at the superheated state. CF_4 solidifies first and then N_2 solidifies.

The first condensation temperature is determined by the partial pressure of low volatile gas in the mixed working fluid. Two solidifications occur. One is at the evaporator and the other is at the condenser. The operation of thermosiphon stops when the two solidifications are completed. The mixing effect, extending the operating temperature range of thermosiphon, is observable when the two fluids coexist as liquid state at the evaporator section.

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