NATURAL CIRCULATION LOOP OF SUBCOOLED LIQUID NITROGEN

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ABSTRACT

An experimental study is performed to investigate the thermal and flow characteristics of subcooled liquid nitrogen in a natural circulation loop. A round tube with uniform diameter is fabricated into a circulation loop and vertically located in a cryostat, where a GM cryocooler is heat sink at the top and an electrical heater is heat source nearly at the bottom. Steady flow of subcooled liquid nitrogen in the loop is successfully obtained by setting the heating power at a given level. Temperature is measured at several locations of the loop, and the mass flow rate through the loop is estimated from the local energy balance in terms of the measured temperatures. Experiment is repeated for various values of the heating power and the vertical height between the cryocooler and the heater. The experimental results are in agreement with existing data and correlations to take into account the buoyancy and viscous forces. It is verified that the heat transfer rate of the loop has a maximum at a certain value of loop height.

KEYWORDS: Natural Circulation Loop, Liquid Nitrogen, Heat Transfer

INTRODUCTION

Natural circulation loop is a simple device in which the flow is driven by thermally generated buoyancy force without any pumped power. The circulation loop filled with liquid nitrogen can serve as an effective heat transfer medium between HTS (high temperature superconductor) elements and a cryocooler located at elevated location, as schematically shown in FIGURE 1. Since no circulation pump is required, the natural circulation systems have an obvious advantage in mechanical reliability over the pumped systems. On the other hand, the heat transfer capability of the natural circulation loop may be limited, depending upon the relative magnitude of buoyancy force with respect to flow resistance of liquid nitrogen in the loop. In this paper, a special attention is focused on a single-phase liquid loop
for HTS power devices under current development, such as HTS fault current limiters because subcooled liquid is keen for the purpose of effective electrical insulation and fast recovery at high-voltage applications [1-4]. FIGURE 2 shows the intended subcooled liquid region on the phase diagram of nitrogen for those applications.

A great number of experimental and theoretical studies have been carried out on the single-phase natural circulation loop for decades. The stability in a natural circulation loop is a fundamental thermo-fluid problem and has been extensively investigated by many researchers [5-8]. Greif [9] and Vijayan [10] presented excellent general reviews on the basic theory and experimental data of single-phase circulation loops. The application of the natural circulation loop to cryogenic systems has been proposed or reported lately for HTS devices. A natural circulation of two-phase neon was demonstrated to remove heat from the HTS rotor in a synchronous machine at around 30 K to GM cryocooler [11]. Loop thermosiphon filled with gaseous helium was designed and tested, aiming at a cooling system for HTS transformers [12]. In spite of the wide usage of liquid nitrogen, the natural circulation loop with liquid nitrogen has not been reported as far as the authors are aware.

This study is proposed to investigate experimentally the thermal and flow characteristics of subcooled liquid nitrogen in a natural circulation loop at temperatures between 63 K and 87 K. The work is part of the ongoing efforts towards an efficient and reliable cryogenic cooling system for HTS power devices under the 21C Frontier R&D Program in Korea.

![Schematic representation of pumped and natural circulation loops for cooling HTS elements](image1)

**FIGURE 1.** Schematic representation of pumped and natural circulation loops for cooling HTS elements

![Intended region of subcooled liquid of nitrogen on phase diagram for HTS power applications](image2)

**FIGURE 2.** Intended region of subcooled liquid of nitrogen on phase diagram for HTS power applications
EXPERIMENTAL APPARATUS

FIGURE 3 is schematic overview of the natural circulation loop experiment. The test loop is fabricated with a tube whose outer and inner diameter are 6.4 mm (1/4 inch) and 4.4 mm respectively, and placed in a vacuum insulated cryostat. A single-stage GM cryocooler (Cryomech AL60) is mounted on the top plate of the cryostat to serve as a heat sink of the loop. A circular copper plate (20 mm thick and 200 mm in diameter) is horizontally jointed to the bottom of coldhead as an extended cooling surface. The loop horizontally encircles the copper plate one and half turns and is soft-soldered on its circumferential surface. In order to supply uniform heat flux to the lower part of the loop, a copper block (250 mm height and 20 mm in diameter) is manufactured and a pair of cartridge heaters (58 ohms) are mounted in it. The loop passes through the copper block, and is soft soldered. The heating power is controlled by a DC power supply (Kepco Model ATE 36-3DM). In order to control the cooling capacity of the cryocooler, a Thermofoil™ heater (Minco Model HK5562) is attached on the coldhead. The upper section and the lower U-shaped section are connected with two identical tubes to complete the loop. In order to examine the effect of the vertical height between heat source and heat sink, the connecting tubes are prepared in different lengths and the joints are made with Swagelok™ tube fittings.

FIGURE 4 shows a photograph and physical dimensions of the fabricated test loop. Four pairs of the connecting tubes are prepared in length of 250 mm, 350 mm, 450 mm, and 550 mm. The local radius of curvature for the bending parts is 50 mm or 100 mm. As a result, the average height ($H$) in this experiment is 400 mm to 700 mm and the total length of the loop is approximately 2310 mm to 2910 mm. The upper and lower parts of the loop are made with copper tube, and the connecting tubes and fittings are made stainless steel.

FIGURE 3. Schematic overview of experimental apparatus for natural circulation loop with liquid nitrogen
FIGURE 4 Photograph and physical dimensions of fabricated test loop and locations of temperature sensors, denoted by 1, 3, 4, 5, and 6

Pressure of liquid nitrogen in the loop is maintained at 280 kPa with a check valve (Swagelok Model SS-4C-25) so that the boiling temperature of liquid nitrogen is 87 K as shown in FIGURE 2. The main reason for this pressurization is to widen the temperature range of subcooled liquid. To ensure that the loop is filled with liquid, two buffer tanks are connected by tee fittings at the inlet and exit of the cooling section as shown in FIGURE 3. Helium gas is used to pressurize liquid nitrogen at the tanks.

Temperature is measured with platinum sensors (Lakeshore Model Pt-102) at the coldhead of the cryocooler, the surface of the buffer tanks, and four locations on the surface of the loop as shown in FIGURE 4. The calibrated platinum sensors have an accuracy of ±0.05 K. Temperature is recorded every 5.5 seconds in computer through a temperature monitor (Lakeshore Temperature Monitor 218 S).

RESULTS AND DISCUSSION

FIGURE 5 shows the step functions of power input to the heating section and the measured temperature history when the average vertical height between the cooling and heating sections (H as shown in FIGURE 4) is 600 mm. Time is measured from the moment when the heater is turned on after the whole loop is filled with liquid nitrogen and cooled down approximately to 65 K by the cryocooler. Throughout the experiment, liquid pressure is measured at 280 kPa. At the first step, the heating power is 7 W and is increased by 2 W for the following steps. At each step, it takes less than an hour for the loop to reach steady state, but the step duration is 4 to 6 hours to confirm the steady state. The stepwise increase of input power is repeated until the exit temperature of heating section temperature reaches the boiling point (87 K) or the loop circulation is in two-phase region.
The similar procedures are repeated after replacing the connecting tubes with a different length. In this paper, the experimental results are presented for the average loop height ($H$) of 400 mm, 500 mm, 600 mm, and 700 mm. It is noted again that the cooling and heating sections are identical over the whole experiment.

At a steady state, the mass flow rate ($W$) in the loop is estimated from the local energy balance for the heating section in terms of the measured inlet (4) and exit (5) temperatures,

$$W = \frac{\dot{Q}_h}{C_p(T_2 - T_4)}$$  \hspace{1cm} (1)

where $C_p$ is the specific heat of liquid and $\dot{Q}_h$ is the power input to the heaters. Since temperature is measured at the tube surface, liquid temperature must be slightly lower than the measured value. It is believed, however, that equation (1) is still accurate because the error in measuring the liquid temperature occurs both at the inlet and exit of the heating section.

To compare these experimental results with the previous data and correlations, the Reynolds number ($Re$) and modified Grashof number ($Gr_m$) \[10\] are calculated respectively as

$$Re = \frac{4W}{\pi D \mu}$$  \hspace{1cm} (2)

$$Gr_m = \frac{D^4 \rho^2 g \beta \Delta T_e}{\mu^2} \left( \Delta T_e = \frac{4\dot{Q}_h H}{\pi D^2 \mu C_p} \right)$$  \hspace{1cm} (3)

where $D$ is the inner diameter of the loop tube, and $H$ is the average height between the cooling and heating sections. The fluid properties including $\rho$ (density), $\beta$ (thermal expansion coefficient), and $\mu$ (viscosity) are evaluated at average liquid temperature.

FIGURE 6 indicates the experimental data on the existing Re-$Gr_m$D/L plot for uniform diameter closed loops \[10\]. The two curves for laminar and turbulent flows are obtained from the one-dimensional momentum equation.
\[ \rho g \beta \int Tdz = \frac{W^2}{2\rho} \sum_{i=1}^{\infty} \left( f_i \frac{L}{D_i} + K_i \right) \frac{1}{A_i} \]  

(4)

where the left-handed side is the buoyancy force over a cycle based upon the Boussinesq approximation and the right-handed side is the viscous force in the loop in terms of the friction factor \((f)\) over the loop length and the pressure loss coefficients \((K)\) for curved parts and fittings.

The experimental data are generally in a good agreement with the existing data and correlations in the laminar regime. There maybe two reasons for the small discrepancies observed in FIGURE 6. First, the heating section in the experiment is a vertical tube above the bottom of the loop, while most of the existing data are obtained for the system where the heating section is horizontal at the bottom. Secondly, there is some effect of heat leak to the loop in the experiment, mainly due to thermal radiation. The heat leak to the vertical tube may augment the ascending flow, but causes an additional resistance to the descending flow. To clarify these points, for example, a circulation cycle of step 3 is drawn on T-z (temperature-vertical distance from the bottom) diagram in FIGURE 7. It is noted that the shape of cycle differs significantly from a rectangle that represents a simple circulation loop with \(H = 600\) mm. The rectangle represents a cycle in which the cooling and heating sections are horizontal and all other parts are adiabatic.

The effect of loop height on the heat transfer rate and mass flow rate is demonstrated in FIGURE 8. Clearly, the heat transfer rate through circulating liquid has a maximum approximately at 15 W, when the average height \((H)\) is 600 mm. When the loop height is shorter than this, heat transfer is smaller because of less buoyancy force to drive the flow. On the other hand, when the loop height is longer, heat transfer is also smaller because of heavier frictional loss. These behaviors are also consistent with the observation that the estimated mass flow rate does not increase over a certain limit (about 1.3 g/s) as the loop height increases.
SUMMARY AND CONCLUSIONS

A natural circulation loop was fabricated and tested to verify its heat transfer capability driven by buoyancy force of subcooled liquid nitrogen. The intended circulating flow through the loop was successfully obtained, with a GM cryocooler at the top and electrical heaters at the bottom. It was demonstrated that as the level of heating power increases, the temperature span between the heating and cooling sections becomes larger and the estimated flow rate of liquid nitrogen increases. These phenomena are in agreement with the existing correlations and the theoretical results estimated with one-dimensional analysis for the buoyancy and viscous forces.

It was also observed that the vertical height between the heating and cooling sections significantly affected the thermal and fluid characteristics. When the loop height was shorter, the flow rate was smaller because the buoyancy force to drive the flow was less. As the loop
height was increased, the flow rate also increased only to a limit due to the increased flow resistance. In this test loop made with 4.4 mm ID tube, the optimal loop height was about 600 mm and the corresponding flow rate of liquid nitrogen was estimated as 1.3 g/s to remove approximately 15 W from the heating section. In the design of natural circulation loop with subcooled liquid nitrogen, it is important to determine the optimal vertical height in consideration of the driving buoyancy force and the flow resistance of the loop passage.

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REFERENCES