Development of a thermal-hydraulics experimental system for high Tc superconductors cooled by liquid hydrogen

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Abstract. A thermal-hydraulics experimental system of liquid hydrogen was developed in order to investigate the forced flow heat transfer characteristics in the various cooling channels for wide ranges of subcoolings, flow velocities, and pressures up to supercritical. A main tank is connected to a sub tank through a hydrogen transfer line with a control valve. A channel heater is located at one end of the transfer line in the main tank. Forced flow through the channel is produced by adjusting the pressure difference between the tanks and the valve opening. The mass flow rate is measured from the weight change of the main tank. For the explosion protection, electrical equipments are covered with a nitrogen gas blanket layer and a remote control system was established. The first cryogenic performance tests confirmed that the experimental system had satisfied with the required performances. The forced convection heat transfer characteristics was successfully measured at the pressure of 0.7 MPa for various flow velocities.

1. Introduction

It is important for the cooling design of high Tc superconducting devices to understand forced convection heat transfer characteristics of liquid hydrogen. Several workers [1-4] have experimentally investigated the steady-state heat transfer in a pool of liquid hydrogen at around atmospheric pressure. Coeling et al. [1] reported that natural convection heat transfer from a flat disk plate to saturated liquid hydrogen and nitrogen can be predicted by conventional correlations. Bewilogua et al. [5] measured the critical heat fluxes on a horizontal flat disc plate in a pool of several cryogenic liquids including hydrogen below its critical pressure. They reported that the best coefficient in Kutateladze’s correlation was determined to be 0.16 based on their experimental data. However, there has been a lack of extensive liquid hydrogen heat transfer data in forced flow conditions.

In this study, a thermal-hydraulics experimental system of liquid hydrogen, which could be remotely operated, was developed in order to investigate the heat transfer characteristics in various cooling channels for wide ranges of subcoolings, flow velocities, and pressures up to supercritical pressure. The cryogenic performance tests were carried out. The forced convection heat transfers of
subcooled liquid hydrogen were measured at the pressure of 0.7 MPa by using the developed experimental system.

2. Thermal-hydraulic experimental system

Figure 1 shows an overview of the thermal-hydraulic experimental system, which mainly consists of a main tank, a sub tank, a hydrogen transfer line with a control valve, a feed hydrogen gas line, a hydrogen vent line, and its remote control system. The experimental system is installed in an explosion-proof laboratory, in which two hydrogen leak detectors are installed on the ceiling. During the experiment, the experimental system is remotely operated at a control room far from the laboratory. The main tank is connected to the sub tank through the transfer line. Test heaters are installed at one end of the transfer line.

Liquid hydrogen in the main tank is pressurized to a desired value by pure hydrogen gas (99.999 %) controlled by a dome-loaded gas regulator, while the sub tank is maintained to be atmospheric pressure by opening the release valve. Forced flow is produced by adjusting the pressure difference between the tanks and the control valve opening. The mass flow rate through the test heaters is estimated by the weight change of the main tank and the flow rate of the feed hydrogen gas.

All the hydrogen is discharged to atmosphere through the hydrogen vent line. A check valve is installed after each release valve to avoid regurgitation. The power cables for heating the test heater are covered with the nitrogen gas blanket layer for explosion protection. A remote control system and interlock system was established. Details of each component are described below.

2.1. Main tank

Figure 2 shows a detail of the main tank, whose design pressure is 2.1 MPa. The main tank made of a stainless steel is insulated by a vacuum layer, in which multilayer insulation with 20 layers is installed.

![Figure 1. Overview of the thermal-hydraulic experimental system.](image-url)
The inner diameter is 406 mm and the height is 1495 mm. The maximum inventory of liquid hydrogen is 50 L, although the total volume of the main tank is 100 L. The overfilled liquid hydrogen is released through discharge pipe located below the lowest convection suppression board. The level of the liquid hydrogen is measured by the weight change of the main tank, which is put on a scale (Mettler Toledo WMHC 300s) that can measure up to 400 kg within 0.002 kg resolution.

The main tank has two release valves and a relief valve whose working pressure is 2.0 MPa. One of the release valves is a control valve of Cv = 0.25, which can adjust to the desired pressure in the main tank. Two test heaters are connected in series at the end of the hydrogen transfer line in the main tank. Liquid hydrogen flows through the test heaters in the upwind direction. The liquid hydrogen temperature is measured by two Cernox temperature sensors calibrated for low temperature service. The hydrogen temperature is controlled by a sheathed heater with the maximum power of 500 W that is wound around the bottom of the main tank. The sheathed configuration is designed to maintain the surface heat flux below $5 \times 10^4$ W/m$^2$, because the critical heat flux in a pool of liquid hydrogen is reported to be in order of $10^5$ W/m$^2$ at atmospheric pressure [1-6].

Four power leads are installed to introduce the heating current up to 400 A to the test heater in order to simultaneously install three test heaters in the main tank. One of them is a common neutral line. For explosion protection, the power cables between the top flange and the power lead terminal are covered with nitrogen gas blanket layer where the nitrogen pressure is always maintained to be 105 kPa slightly higher than atmospheric pressure, in order to avoid contacting with air. The pressure is measured by an absolute manometer in order to avoid the effect of atmospheric pressure fluctuation. Even if hydrogen leak into the blanket layer occurs, hydrogen is automatically released through the check valve with the cracking pressure of 110 kPa and all hydrogen will be released by interlock system.

2.2. Sub tank

Figure 3 shows a detail of the sub tank that is made of a stainless steel and is also insulated by a vacuum layer with 20 layers of multilayer insulation. The inner diameter is 310 mm and the height is 1375 mm. The level of the liquid hydrogen is measured by three thermocouples (type T) located in the vertical direction, which correspond to (a) 60 L, (b) 20 L, and (c) 9 L, respectively. The sub tank has a release valve and a safety valve with the working pressure of 2.0 MPa. The main tank and the sub tank
are connected to the hydrogen transfer line with a control valve of $C_v = 1.1$ by a bayonet joint.

2.3. Feed hydrogen gas line and hydrogen vent line
The feed hydrogen gas line consists of a turbine flowmeter, a dome-loaded gas regulator, a release valve, and a relief valve. The dome-loaded gas regulator plays roles in reducing the high pressure hydrogen gas from the hydrogen gas clustered cylinders and maintaining the pressure in the main tank to a desired value. The flow rate of the feed hydrogen gas into the main tank is measured by the turbine flowmeter in order to compensate the mass flow rate through the test heater.

All hydrogen is released from a stack to atmosphere through the hydrogen vent line with the length of 80 m. A check valve is installed at the exit of it in order to avoid entering air into the vent line.

2.4. Control system
The control system is developed using programmable logic controller (PLC), which performs conversion from analogue signals to engineering values, remote operations for control valves, ON/OFF valves, and heater, and interlocks for failure. Labview running on a Windows operation system is used as the human machine interface. Figure 4 shows the developed control monitoring screen, on which we can monitor real time data, control the valve operation, and analyze historic data at the control room far from the explosion-proof laboratory. In order to maintain the safety of the experimental system when off-normal event occurs, the control system has interlocks; (1) power shutdown for electrical current supplying to the heater, (2) releasing hydrogen down to atmosphere pressure, and (3) shutoff of liquid hydrogen transfer.

2.5. Test heater channel
In this study, two stainless pipe heaters are mounted vertically as shown in Figure 5, although three test heaters can be installed into the main tank simultaneously. The tube heaters are (a) 6.0 mm and (b) 3.0 mm in inner diameter, $D_i$, 100 mm in length, $L$, and 0.2 mm in thickness, $t$. Outside of the tube...
The heaters were thermally insulated by FRP blocks. Both ends of the heater tubes are also electrically insulated from the hydrogen transfer line by the FRP channel, whose diameter is equal to \( D_i \). The test heater has the non-heated straight tubes with the length of 200 mm. Six small Ruthenium-oxide temperature sensors are set at 20 mm intervals along the center axis of the test heater. The copper current leads and the voltage taps are soldered at both ends of the heaters. The heat leakage to the liquid hydrogen through the FRP block is estimated to be less than 2%.

3. Experimental procedure

The experimental system is purged by using helium gas and was evacuated by a vacuum pump in order to minimize the existence of oxygen before providing liquid hydrogen. This process is repeated more than three times. Firstly, liquid hydrogen is transferred from the liquid hydrogen container to the sub tank, until it is filled up 60 L of liquid hydrogen. Then, the evaporating gas is partially used as precooling of the main tank. After that, the liquid hydrogen is provided to the main tank via the sub tank. The level of the liquid hydrogen in the main tank is measured by the weight change of the scale. Liquid hydrogen of 3.54 kg, which corresponds to the volume of 50 L at 0.1 MPa and 20.4 K, is stored in the main tank.

The liquid hydrogen in the main tank is pressurized by the pure hydrogen gas. The liquid temperature is controlled by the sheathed heater. Forced flow of the liquid hydrogen is produced by adjusting the control valve opening. The mass flow rate is calculated by the weight change of the main tank measured by the scale with 0.002 kg resolution. The flow rate is calibrated by the mass of the feed hydrogen gas measured by the turbine gas flowmeter. Flow measurement error is estimated to be within 0.1 g/s, if the flow rate is assumed to be constant during the test period of 40 s, for example.

The heating current to the test heater was supplied by a power amplifier, which can supply a direct current of up to 400 A at a power level of 4.8 kW. The input signal of the power amplifier was controlled so that the heat generation rate in the test heater agreed with a desired value. In this study, exponential heat generation of \( Q = Q_0 e^{t/\tau} \) and \( \tau = 10.0 \) s was applied to the tube heater. It was confirmed experimentally that the heat transfer phenomenon by this heat generation rate could be regarded as a continuous sequence of steady-state. The electric resistance of the heater was measured.
using a double-bridge circuit including the test heater as a branch of the bridge. The double bridge circuit was first balanced at the bath temperature. The output voltages of the bridge circuit due to the deviation of the heater resistance during the current heating were amplified by a couple of amplifiers with high and low gain for each signal because of the wide dynamic range of the current change throughout the test. These signals were simultaneously sampled at the interval of 30 ms and stored in 16 bit digital memory. The average heater temperature was estimated using the relationship between the resistance and the average temperature of the heater, which had been previously calibrated ranging from 20 K to ambient temperature. The calibration for the temperature from 20 K to 32 K was performed in saturated liquid hydrogen and at 77 K in liquid nitrogen. The heat generation in the heater was calculated from the measured voltage drop across the heater and the standard resistance. The surface heat flux was given as the difference between the heat generation rate and the time rate of change of energy storage in the heater. The average inner surface temperature, \( T_{ws} \), of the heater is calculated by solving the conduction equation in a radial direction of the heater using the measured average heater temperature and the heat generation.

The double bridge circuit to measure the heater resistance has the accuracy of 1 x 10^{-4}. The gradient of the resistance-temperature relation is lowest at the boiling point, where the gradient is about 10 \( \mu \Omega/K \) at the resistance of 12.96 m\( \Omega \). As a result, the temperature deviation of about 0.1 K can be measured by the bridge. Inlet temperature of liquid is measured by Cernox sensor with the accuracy of 10 mK. Only the temperature increment of the test heater from the inlet liquid temperature is necessary for the test. As a result, experimental error is estimated to be within the heater surface temperature of 0.2 K and the heat flux of 2 %.

The forced convection heat transfers of subcooled liquid hydrogen through the tube heater were measured at the inlet temperature of 21 K and the pressures of 0.7 MPa by the quasi-steadily increasing heat inputs.

4. Results and Discussion

4.1. Performance test results of the experimental system

Figure 6 shows the first cool down process of the experimental system. First, liquid hydrogen was provided to the sub tank from the liquid hydrogen container with the volume of 2460 L, which was pressurized to 0.3 MPa. The sub tank was filled up with 60 L within 10 minutes. Although the evaporating gas was mainly discharged through the release valve of the sub tank, some of it was also used as precooling of the main tank. After that, the release valve of the sub tank was closed, and liquid hydrogen was transferred to the main tank via the sub tank. The pressure of the sub tank increased up to 0.3 MPa close to that of the container and the temperature (TI1001) at the bottom of the main tank.

Figure 6. Cool down process of the experimental system.
decreased down to 20 K within 4 minutes. The weight of it increased up to 3.3 kg, which corresponded to 47.5 L. The cool down process was finished within 23 minutes and liquid hydrogen of 200 L was consumed. After the end of the cool down, the transfer line between the container and the sub tank was purged by helium gas.

The steady heat load of the main tank was measured by the evaporate boil-off rate of liquid hydrogen. The weight of 0.556 kg was reduced for 6 hours. Accordingly, the total heat load was estimated to be 11.5 W, which was in good agreement with the design value of 11.03 W.

Figure 7 shows an example of the weight change for the valve opening of 35 %. The initial temperature in the main tank was 21.2 K. The weight change was almost maintained constant and then the hydrogen pressure was also maintained to be 0.7 MPa by the dome-loaded gas regulator. The main tank weight of 0.48 kg was reduced for 31 s. The feed gas flow rate, which was measured by the turbine flow meter, was almost 0.422 g/s. Accordingly, the average mass flow rate through the heater was estimated to be 15.91 g/s, which corresponded to flow velocity, v, of 7.93 m/s in the heater with the diameter of 6 mm. It was confirmed that the mass flow measurement was adequate. The pressure drop temporary appeared in the main tank, after closing the control valve and the supply valve. This is because the provided hydrogen gas, which was around ambient temperature, would be condensed in the main tank.

During the first cryogenic test, it has been confirmed that the nitrogen blanket including electrical current leads can maintain the pressure of around 105 kPa, which is slightly higher than atmospheric pressure, without problems.

4.2. Steady-state forced flow heat transfer of liquid hydrogen

Steady-state heat transfer characteristics in forced flow of subcooled liquid hydrogen with the tube heater for various flow velocities are shown in Figure 8. The inlet temperature, $T_{in}$, and the pressure are set to be 21.2 K and 0.7 MPa, respectively. The subcooling, $\Delta T_{sub}$, corresponds to 8.1 K, because the saturated temperature, $T_{sat}$, is 29.3 K. Longitudinal axis is the heat flux and transverse is the excess heater surface temperature, $T_w$, beyond inlet temperature, $\Delta T_w = T_w - T_{in}$. With an increase in the heat input quasi-steadily, the heat flux gradually increases. In nucleate boiling regime, the heat flux rapidly increases up to a departure from nucleate boiling (DNB) heat flux, $q_{DNB}$, with relatively little increase in wall superheat. After $q_{DNB}$, the heat transfer characteristic continuously changes to film boiling regime. With an increase in the flow velocity, the heat transfer coefficient in the non-boiling region, the inception heat flux of nucleate boiling, and the DNB heat flux increase. The values predicted by
Figure 8. Forced convection heat transfer characteristics at the pressure of 0.7 MPa and the inlet temperature of 21.2 K.

The Dittus-Boelter correlation [7] are also described in the figure for comparison. It seems that the heat transfer characteristics in non boiling region agree with the Dittus-Boelter correlation.

5. Conclusion
A thermal-hydraulics experimental system of liquid hydrogen was developed in order to investigate the heat transfer characteristics in various cooling channels for wide ranges of subcoolings, flow velocities, and pressures up to supercritical. Forced convection heat transfers from a vertical channel heater to subcooled liquid hydrogen were measured at a pressure of 0.7 MPa and a temperature of 21.2 K. Experimental results led to the following conclusions.

The experimental system was installed in an explosion-proof laboratory. The main tank was connected to the sub tank through the transfer line with a control valve. Liquid hydrogen in the main tank was pressurized by pure hydrogen gas, and forced flow was produced in the test heater, which was installed at one end of the transfer line, by adjusting the control valve opening. For hydrogen safety measures, electrical equipments were covered with a nitrogen gas blanket layer. A remote control system was established using a programmable logic controller.

Liquid hydrogen of 50 liters was provided to the main tank within 20 minutes in the first cryogenic test. The total heat load of the main tank was measured to be 11.5 W, which agreed with the design value, by the evaporate boil-off rate. It was confirmed that the experimental system successfully produced a stable forced flow and measured the mass flow rate by the weight change.

Forced convection heat transfers from a vertical channel to subcooled liquid hydrogen were measured at a pressure of 0.7 MPa and a temperature of 21.2 K by using the experimental system. The heat transfer characteristics in non boiling region agreed with the Dittus-Boelter correlation. With increase in flow velocity, the heat transfer coefficient in the non-boiling region, the inception heat flux of nucleate boiling, and the DNB heat flux increased.

The remote control system, which included the control valves, the heating control and measurement, was operated without problems. The first cryogenic tests were successfully carried out and confirmed that the experimental system met the required performance.

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