IOP Conf. Series: Materials Science and Engineering **278** (2017) 012036 doi:10.1088/1757-899X/278/1/012036

Liquid Hydrogen Recirculation System for Forced Flow Cooling Test of Superconducting Conductors

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Abstract. The knowledge of forced flow heat transfer characteristics of liquid hydrogen (LH_2) is important and necessary for design and cooling analysis of high critical temperature superconducting devices. However, there are few test facilities available for LH_2 forced flow cooling for superconductors. A test system to provide a LH_2 forced flow (~10 m/s) of a short period (less than 100 s) has been developed. The test system was composed of two LH_2 tanks connected by a transfer line with a controllable valve, in which the forced flow rate and its period were limited by the storage capacity of tanks. In this paper, a liquid hydrogen recirculation system, which was designed and fabricated in order to study characteristics of superconducting cables in a stable forced flow of liquid hydrogen for longer period, was described. This LH_2 loop system consists of a centrifugal pump with dynamic gas bearings, a heat exchanger which is immersed in a liquid hydrogen tank, and a buffer tank where a test section (superconducting wires or cables) is set. The buffer tank has LHe cooled superconducting magnet which can produce an external magnetic field (up to 7T) at the test section. A performance test was conducted. The maximum flow rate was 43.7 g/s. The lowest temperature was 22.5 K. It was confirmed that the liquid hydrogen can stably circulate for 7 hours.

1. Introduction

Liquid hydrogen (LH_2) has excellent physical properties, high latent heat and low viscosity of liquid, as a coolant for the high critical temperature superconductors. Moreover, its low boiling point (20.3 K) has advantage for the excellent electro-magnetic properties of the high critical temperature superconductors, such as YBCO and BSCCO. Especially for MgB_2, which is expected to be a superconductor of next generation, has been developing years by years. LH_2 is expected to be the coolant for that superconductor whose critical temperature is 39 K.

It is important for designing a LH_2 cooled superconducting device to understand forced flow heat transfer of LH_2. However, there has been a lack of systematic experimental data of LH_2 in the forced flow. Therefore, basic data necessary are captured for the guideline of LH_2 cooling design of superconducting devices and the evaluation of cooling stability.

For the first step, Tatsumoto et al. [1] developed the thermal-hydraulics experimental system for LH_2 in order to carry out a systematic investigation of the forced flow heat transfer of LH_2. However, the thermal-hydraulics experimental system for LH_2 has only a short-time operation and limited quantity of flow. As the next step of applied superconductors, a liquid hydrogen recirculation system is developed to study characteristics of superconducting wire in stable forced flow of LH_2 for a long time.
In this paper, an experimental set-up, which was designed and fabricated for the above purpose, and basic operation test and forced flow heat transfer test are described.

2. Liquid Hydrogen recirculation system

The liquid hydrogen recirculation system which was designed and fabricated is briefly described as follows.

2.1. System overview

Figure 1 shows an overview of liquid hydrogen recirculation system. Figure 2 is photo view (from above) of the system. This system consists of a centrifugal pump, a heat exchanger and a buffer tank. The test section is set in the buffer tank. Each of devices are connected by hydrogen transfer lines (insulation tube of 65A/25A) with control valves. All the valves as well as the pump are controlled by remote monitoring system and desired experimental conditions, such as temperature, pressure and flow rate are recorded. LH_2 is served from 30,000 L storage tank continuously for long period operation. Two orifice type flow meters (FM##) are set at the outlet of the pump and the inlet of the buffer tank. Temperature sensors (TI##) and pressure sensor (PI##) are equipped along the loop lines as shown in Figure 1.

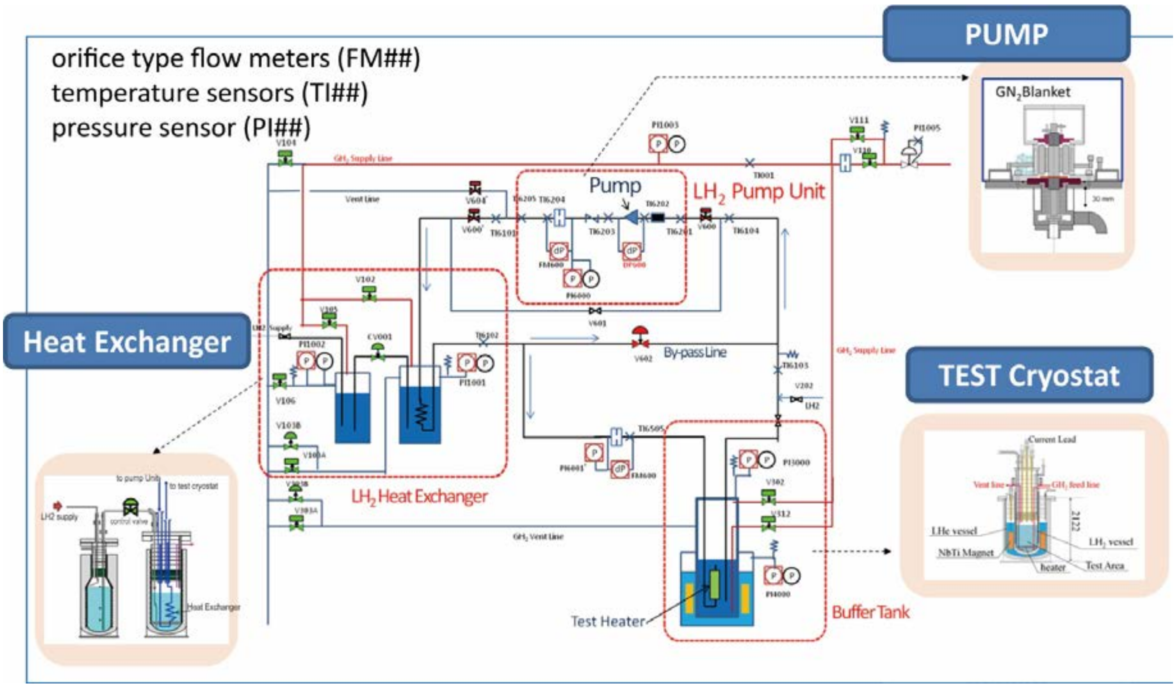

Figure 1. Overview of the liquid hydrogen recirculation system

2.2. Test tank (buffer tank)

Figure 1 lower right shows an overview of the test tank which works as the buffer tank and has gaseous area for LH_2 circulation. This equipment has the large LHe cryostat (175 L) with the NbTi

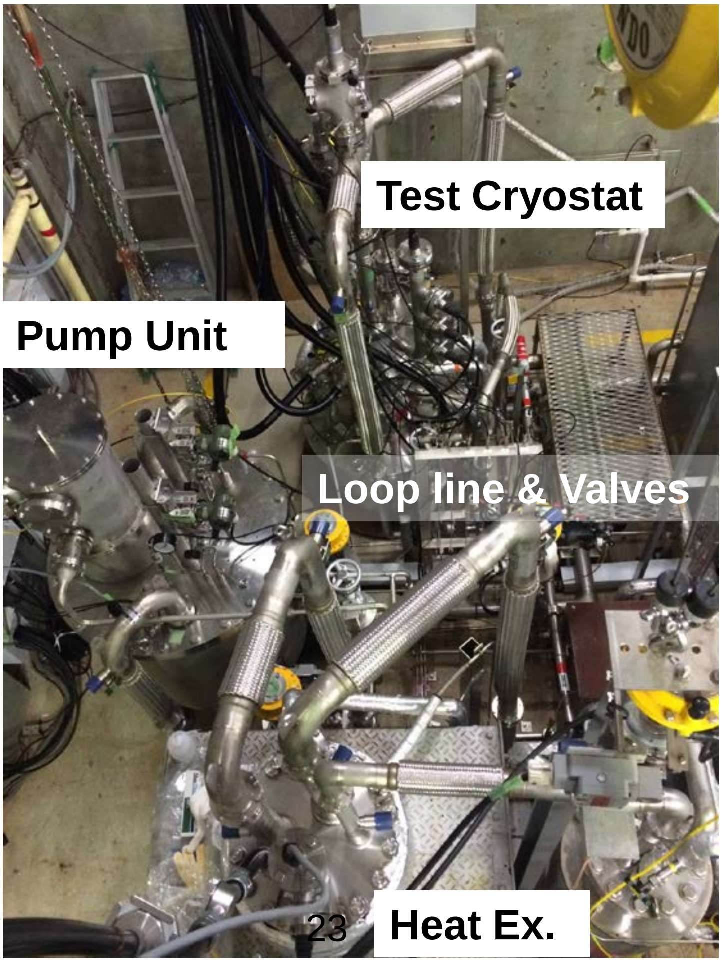

Figure 2. Top view of the LH_2 re-circulation system.

superconducting magnet (170 A @ 7 T). The LH_2 test cryostat (309.5 mm inner diameter and 2422 mm height) is set in the bore of the NbTi magnet. Magnetic field of 0-7.0 T can be applied at the test space inside the LH_2 cryostat. Pressure in the LH_2 test cryostat can be set to 0.1-2.0 MPa by use of the feed hydrogen gas line. The temperature of the LH_2 in the cryostat can be set 21 ~ 32 K under the appropriate pressure by use of the sheath heater equipped in the bottom part of the cryostat.

Temperature sensors (Cernox) are installed in the LH_2 cryostat to measure the bath temperature. The hall sensor is arranged close to the test sample to measure the magnetic field. The system can be operated by remote control for the sake of safety [2].

2.3. Centrifugal Pump

Figure 1 top-right shows an overview of a centrifugal pump with dynamic gas bearings for LH_2 (made by IHI). The head-pressure versus flow-rate characteristics of the pump is shown in Figure 3. A pump is set in a vacuum insulated container and is removable from a liquid hydrogen recirculation system by bayonet connections. The rotation speed of the pump is controlled within 30,000 ~60,000 rpm by use of the inverter controlled induction motor (water cooled). The pump system including the induction motor is covered with a blanket whose inner area are filled with GN_2 with positive pressure.

The pressure drop of the recirculation test loop (without test sample) and the by-pass loop was estimated as shown in Figure 3 assuming that the each pressure drop of the flow meter, valve, filter and check valve is 5 kPa and that of the heat exchanger is 4 kPa. The operation range of the flow rate is from 20 g/s up to 170 g/s.

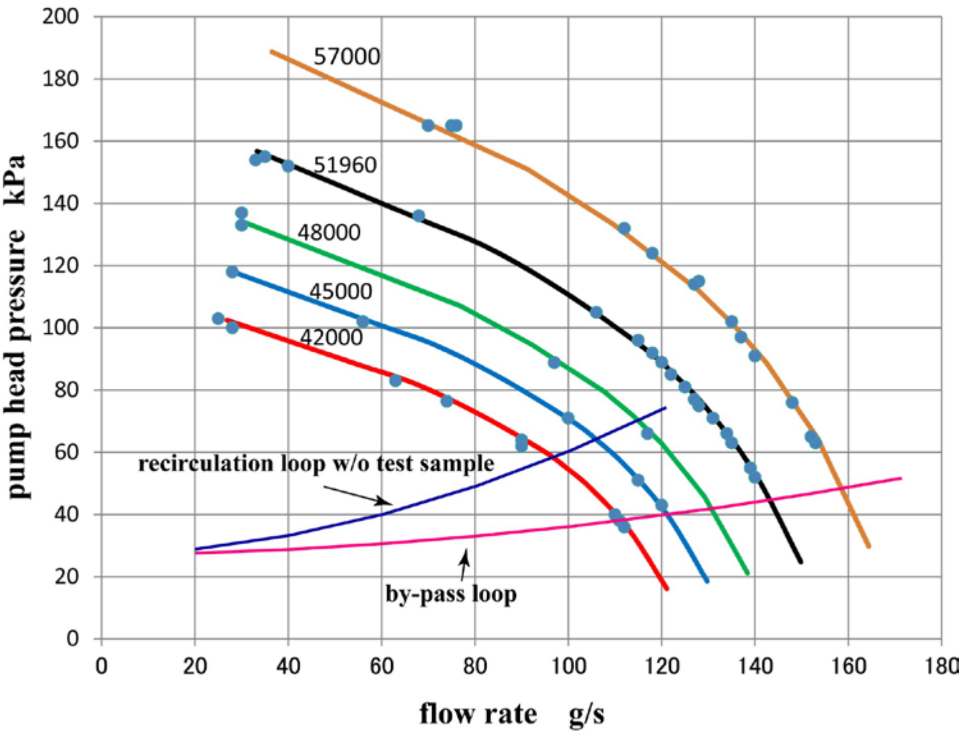

Figure 3. Pump head-pressure versus flow-rate characteristics and the pressure load lines for each loop.

2.4. Heat Exchanger

Figure 1 center-left shows an overview of the heat exchanger. This unit is composed of the main tank and sub-tank connected by the transfer line with a controlled valve. The main tank (heat exchanger cryostat) has the parallel coiled path immersed in LH_2 bath. The circulating LH_2, whose temperature is rising up along the loop line due to the heat load at the pump or the loop tubes, flows through the parallel coiled path and is cooled down by the pool LH_2 of the main tank to be a certain fixed temperature. LH_2 in main tank is supplied continuously from the sub-tank.

The heat exchanger was designed under the following conditions:

1. The pool LH_2 of the main tank is kept 20.5 K, 0.1 MPa (open to the atmospheric pressure).
2. The temperature at the heat exchanger outlet is 21.0 K.
3. The temperature at the heat exchanger inlet depend on the flow rate and the heat input.
4. The heat load of the pump and the loop lines including test section is assumed to be 500 W.
5. LH_2 flow rate is between 20 g/s and 170 g/s.

As a result, the heat exchanging path consists of 10 parallel stainless steel (SUS304) tubes of 8 mm dia. and 2 m long.

2.5. Safety

All devices are put in explosion-proof laboratory, and all operations are conducted by the remote-control from the operation room that is located 70 meters away from the laboratory. The LH_2 test cryostat has three power lead terminals (up to 500 A at steady state, 800 A at transient) for the test sample excitation. Power leads (up to 800A) are covered with blankets pressurized by nitrogen gas kept slightly higher pressure (5 kPa) than the atmospheric pressure for explosion-protection. When some abnormal conditions, for example, some leak of GH_2 or the blanket pressure drop are detected, the interlock system activates to stop the power supply and reset all the valves to the safe position immediately.

3. Performance test

The performance test of liquid hydrogen recirculation system was performed for 7 hours.

3.1. Test condition

Major test parameters are pressure, temperature and flow-rate at the test section. The target points of performance test are shown as follows

- to perform a wide range of flow-rate and a long-term measurement.
- to maintain the fixed conditions (pressure, temperature and flow-rate) constant for the heat transfer tests .

The flow-rate at the test section was varied by changing the rotational speed of the pump and the opening rate of the by-pass valve. The circulating LH_2 temperature was set by changing the temperature of LH_2 in the heat exchanger cryostat using the sheath heater. The pressure of the loop line was set by the GH_2 pressure of the buffer tank, that is, the pressures of 0.2, 1.0, 0.65, 1.4 MPaG.

A forced flow cooling test sample shown in Figure 4 was attached in series of the circulation loop in the test cryostat. The channel with the wire heater is vertically mounted in the buffer tank and liquid hydrogen flows upward through it. The wire heater, which is made of Pt-Co alloy, has a diameter (*d*) of 1.2 mm and a length (*L*) of 200 mm. The wire heater is located on the central axis of a channel with diameter (*D*) of 5.0 mm and a length of 290 mm, which is made of Fiber-Reinforced Plastic (FRP) for thermal and electrical insulation.

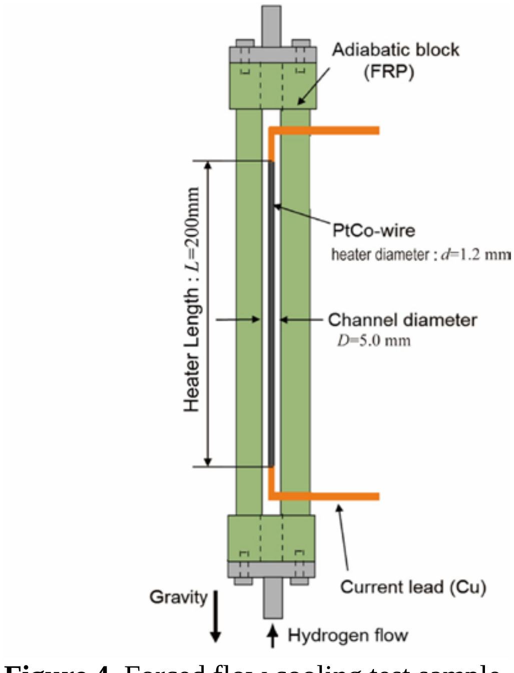

Figure 4. Forced flow cooling test sample.
(PtCo wire of 1.2 mmϕ ,200 mm long: FRP channel path of 5.0 mmϕ, 290 mm long).

3.2. Results

Figure 5 shows the variation of the main parameters with time - rotation of the pump, pump head pressure, pressure of the buffer tank, supply temperature and heat exchanger outlet temperature in the operation test.

The pressure was set 0.2M PaG, 1.0 MPaG, 0.65 MPaG and 1.4 MPaG (supercritical condition) in order. Under each pressure, the flow rate (indicated by circles) was changed by mainly trimming the open ratio of the by-pass valve and subsequently changing the rotational speed of the pump.

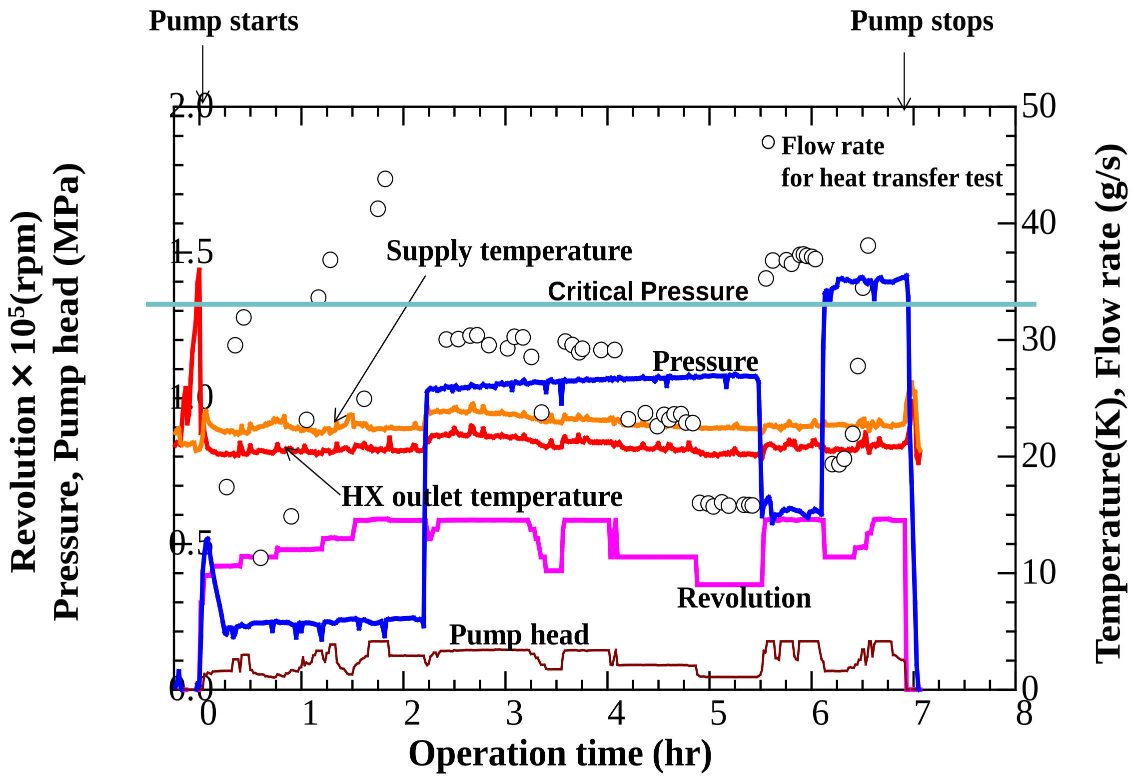

Figure 5. Time course of the parameters in operation test

At each condition, it was confirmed that the flow-rate can be maintained at a desired value. The control range of mass flow-rate was from 3.0 g/s to 43.7 g/s in this test case. The mass flow rate was rather small compared to the designed value, because the test sample with narrow path (5 mm dia. and 290 mm long) was set in series with the loop. The mass flow-rate of 43.7 g/s is equivalent to the flow rate of 28 m/s at the test sample path.

Heat exchanger outlet temperature was kept between 20.4 K and 21.5 K. It was confirmed the performance of the heat exchanger is in accordance with the design. The inlet temperature of the test section (buffer tank) was about 2 K higher than that of the heat exchanger outlet temperature. This was caused by the feeding of warm GH_2 to the buffer tank in order to keep the pressure. Under the low pressure condition, that is less than 0.2 MPa close to the saturated condition, the spindle vibration of the pump increased due to the GH_2 bubbles in the LH_2 flow.

It was confirmed that long-duration (7 hours) operation can be performed stably at the subcooled and the supercritical conditions.

4. Forced flow heat transfer test

By using the LH_2 recirculation test set up, the heat transfer test was carried out with various flow-rates.

4.1. Basic Operation

Heat transfer from a wire inserted into a vertically-mounted pipe to forced flow of LH_2 were measured over wide ranges of pressure and flow velocity by use of liquid hydrogen recirculation system. The measured critical heat fluxes were compared with those measured using the previous experimental system [1].

4.2. Experimental Method

The wire heater was electrically heated by using a fast response direct current source (24 V, 800 A max.), which was controlled by a digital computer so as to give a desired time function for the heat input. Exponential heat generation of

$$Q = Q_0 e^{t/\tau}, \qquad with\ \tau = 5\ s \tag{1}$$

The average temperature of the heater was estimated by temperature-dependence of the electric resistance of the test wire, which had been previously calibrated in the range of 20 K to ambient temperature. The average surface temperature T_w of the heater, was calculated from the measured average temperature and the surface heat flux by solving a conduction equation in the radial direction of the wire.

4.3. Results and Discussion

Figure 6 shows result of forced flow heat transfer test at pressure of 0.7 MPa and temperature of 23 K (subcooled 6K). Its vertical axis is for heat flux, q, and the horizontal for ΔT_{in}, that indicates the temperature difference between the heated wall temperature T_w and the inlet temperature.

In the non-boiling regime, with increase in the heat input quasi-steadily, the heat flux, q, gradually increases along the curves predicted by the Dittus-Boelter correlation [3]. The nucleate boiling occurs at the wall superheat ΔT_{in} slightly higher than the saturated temperature T_{sat}. The heat flux q steeply increases up to a certain upper limit heat flux, q_{DNB} (heat flux at the departure from nucleate boiling to film boiling). The heat flux q_{DNB} is an important parameter in an industrial field, since the temperature jump occurs with $q > q_{DNB}$. Especially it may cause the degradation of the superconductor. The heat transfer coefficient at the non-boiling regime and q_{DNB} are becoming higher for higher flow velocities.

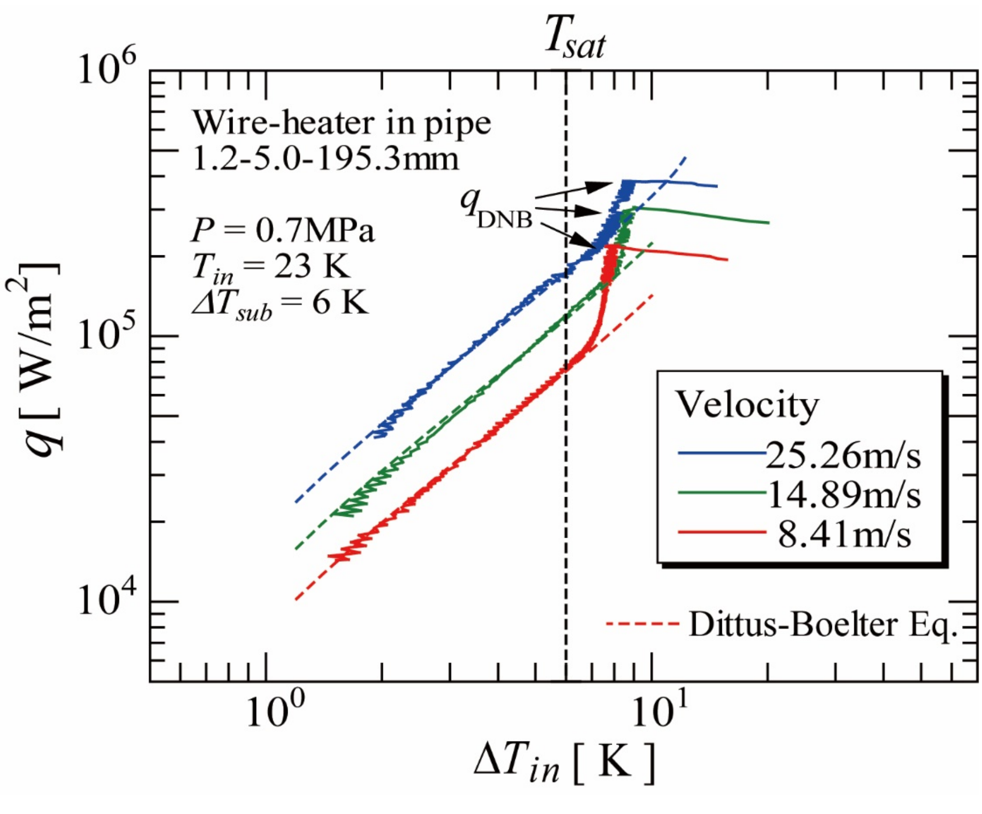

Figure 6. Forced flow heat transfer curves

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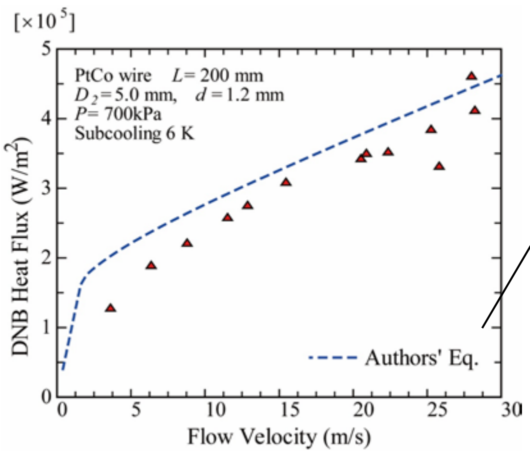
Figure 7 shows q_{DNB} of the test sample versus LH_2 flow velocity up to 30 m/s. The authors also have been discussing q_{DNB} under forced flow condition and have derived the correlation (Author's Eq.) [4]. The correlation was derived with the experimental data of flow velocity less than 10 m/s obtained using the previous test set-up[4]. The broken line in Figure 7 indicates the Author's Eq. extended up to 30 m/s. The experimental data obtained by the recirculation system (indicated by triangles) are compared with the correlation in Figure 7. Calibration of the orifice flow meter was necessary, even so, it was confirmed that the correlation can be applied in higher velocity region.



Saturated condition :

$$q_{DNB,sat} = Gh_{fg}\left(\frac{\rho_v}{\rho_l}\right)^{0.43}\left(\frac{L}{D_H}\right)^{-0.35}F_b,$$

$$where,\ F_b = 0.29We^{-0.45} + 0.001 \quad for\ We \geq We_b,$$

$$F_b = 0.026\left(\frac{L}{D_H}\right)^{-0.43} \quad for\ We < We_b,$$

$$We = \frac{G^2 D_W}{\rho_l \sigma}, \qquad {We_b}^{-0.45} = 0.077\left(\frac{L}{D_H}\right)^{-0.18}$$

Subcooled condition

$$q_{DNB,sib} = q_{DNB,sat}(1 + ASc_{out}),$$

$$where,\ A = 1.4\left(\frac{\rho_v}{\rho_l}\right)^{-0.43}\left(\frac{L}{D_H}\right)^{0.25}E^{-0.1}, \quad E = \frac{D_W}{\sqrt{\sigma/g(\rho_l-\rho_v)}}$$

$$Sc_{out} = \frac{c_{pl}\Delta T_{sub,out}}{h_{fg}}$$

G: mass flux , h_{fg}: latent heat
L: path length , σ: surface tension ,
D_H: heated equivqlent diameter $= (D^2 - d^2)/d$,
D_W: hydraulic equivalent diameter $= (D - d)$
ρ_v: vapour density , ρ_l: liquid density
c_{pl}: averaged specific heat , $\Delta T_{sub,out}$: subcooling at outlet

Figure 7. Critical heat flux versus flow velocities.

5. Conclusion

A liquid hydrogen recirculation system was designed and developed to study characteristics of superconducting materials and devices cooled by a stable forced flow of liquid hydrogen for a long period.

The performance test of liquid hydrogen recirculation system was performed over 7 hours, while changing conditions, such as, pressure, temperature and flow-rate. The test targets were established to perform a wide range flow-rate and a long-term measurement and to keep desired conditions (pressure, temperature and flow-rate) at stable values.

Furthermore, forced flow heat transfer from the PtCo wire in the vertically-mounted pipe was also measured with the quasi-steady increase of the heat generation rate for wide ranges of pressure and flow rate. It was confirmed that the experimental data obtained agree with those obtained using the previous experimental system.

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