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Author(s)	Matsumoto, T.; Shirai, Y.; Shiotsu, M.; Fujita, K.; Kainuma, T.; Tatsumoto, H.; Naruo, Y.; Kobayashi, H.; Nonaka, S.; Inatani, Y.
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DNB heat flux in forced convection of liquid hydrogen for a wire set in central axis of vertically mounted flow channel

T Matsumoto¹, Y Shirai¹, M Shiotsu¹, K Fujita¹, T Kainuma¹, H Tatsumoto², Y Naruo³, H Kobayashi³, S Nonaka³ and Y Inatani³

¹Department of Energy Science & Technology, Kyoto University, Kyoto, JP

²Facility for Rare Isotope Beams, Michigan State University, Michigan, USA

³Institute of Space and Astronautical Science, JAXA, Kanagawa, JP

t-matsumoto@pe.energy.kyoto-u.ac.jp

Abstract. Liquid hydrogen has excellent physical properties, high latent heat and low viscosity of liquid, as a coolant for superconductors like MgB₂. The knowledge of Departure from Nucleate Boiling (DNB) heat flux of liquid hydrogen is necessary for designing and cooling analysis of high critical temperature superconducting devices. In this paper, DNB heat fluxes of liquid hydrogen were measured under saturated and subcooled conditions at absolute pressures of 400, 700 and 1100 kPa for various flow velocities. Two wire test heaters made by Pt-Co alloy with the length of 200 mm and the diameter of 0.7 mm were used. And these round heaters were set in central axis of a flow channel made of Fiber Reinforced Plastic (FRP) with inner diameters of 8 mm and 12 mm. These test bodies were vertically mounted and liquid hydrogen flowed upward through the channel. From these experimental values, the correlations of DNB heat flux under saturated and subcooled conditions are presented in this paper.

1. Introduction

The knowledge of characteristics of heat transfer in liquid hydrogen is important for designing superconducting devices. Liquid hydrogen has good physical properties for cooling, like a low boiling point, high latent heat, high specific heat and low viscosity properties.

Tatsumoto et al. [1] have developed a thermal-hydraulics experimental system for liquid hydrogen to investigate the forced convection heat transfer. This system was set in an explosion-proof room and can be remotely operated to carry out experiment safely.

Tatsumoto et al. [2] measured forced convection heat transfers of saturated hydrogen on the inner heated surface in vertically mounted pipe heater. Based on their experimental data they presented DNB heat flux correlation.

Shirai et al. [3] established correlation of DNB heat flux under subcooled condition for vertically mounted pipe heater.

In this paper, DNB heat fluxes in forced convection of liquid hydrogen on the wire were measured. This data is important for cooling design of superconducting wire cooled by liquid hydrogen. From experimental data, we present a correlation of DNB heat flux for wire heater under saturated and subcooled condition.

2. Experimental apparatus and method



2.1. Experiment system

Details on experimental system have been reported in a previous paper [1]. Forced convection experiment system for liquid hydrogen consisted of a main cryostat, a sub cryostat and a transfer line with a control valve connecting two cryostats. The main cryostat was mounted on a digital scale with 0.002 kg resolution for measuring mass flow rate. Test heaters were installed vertically in a main cryostat and connected to the inlet of transfer line.

Liquid hydrogen in the main cryostat was pressurized with pure hydrogen gas (99.999 %) to a desired value with dome-loaded regulator. The temperature of liquid hydrogen was raised by a sheathed heater with maximum power of 500 W that was mounted at the bottom of the main cryostat. The mass flow rate can be changed by the control valve in the transfer line. Heat transfer characteristics for a wide range of subcooled temperature, flow velocities and pressures can be investigated by this system. The mass flow rate was calculated by weight change with a scale and complemented by the feed hydrogen gas weight that was measured by a turbine flow meter.

2.2. Test heater

Figure 1 shows a cross-sectional view of the test heater. A wire of Pt-Co alloy was inserted into a cylindrical hole of the FRP block. Two test heaters were prepared. The specification of each heater is listed in table 1, such as heater diameter (d), heater length (L) and pipe inner diameter (D). These test heaters were vertically mounted in the main tank and liquid hydrogen flowed upward through them.

Table 1. Test heater dimension

Test Heater	d (mm)	D (mm)	L (mm)
A	0.7	8	200
B	0.7	12	200

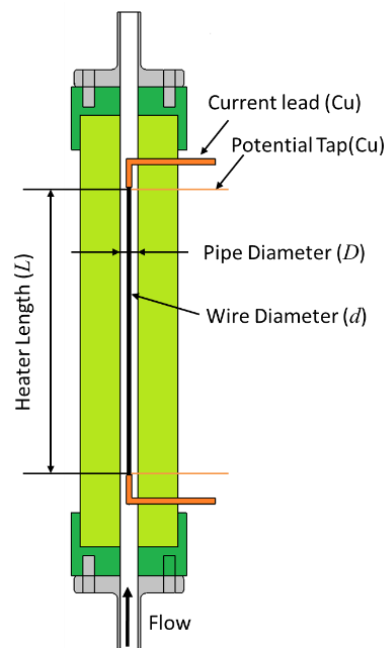


Figure 1. A cross-sectional view of the test heater

2.3. Experimental procedure

Details on experimental procedure have been reported in a previous paper [1, 4]. The wire was heated electrically by a direct current source (rated current and voltage are 800 A and 12 V). The current source was controlled by a digital computer to give a desired heat generation rate. Here, exponential heat generation of Eq. (1) was applied to the wire heater. The heat transfer phenomenon with $\tau = 5.0$ s can be considered as continuous sequence of steady-state by previous experiments.

$$Q = Q_0 e^{t/\tau} \quad (\tau = 5.0 \text{ s}) \quad (1)$$

The heater average temperature was measured by electrical resistivity dependent on its temperature. The resistance of each test heater was calibrated beforehand at various temperatures ranging from 20 K to ambient temperature. The electrical resistance of the test heater was measured by a double bridge circuit including the heater as a branch of the bridge. The bridge circuit was first balanced at the bath temperature. The output voltage of the bridge circuit was affected by variation of the heater resistance and causing a voltage difference between the potential taps of the heater and standard resistance were amplified and sampled. The surface heat flux, q was obtained from the heat generation rate in the heater calculated from measured voltage and the time rate change of energy storage in the heater. The average surface temperature of the heater, T_W was calculated from the average temperature and the surface heat flux by solving a conduction equation in the radial direction of the wire.

Heat transfer characteristics of liquid hydrogen were measured under saturated and subcooled conditions at absolute pressures of 400, 700 and 1100 kPa for various flow velocities in the range of 0.5 m/s to 15 m/s.

3. Results and Discussion

3.1. Forced convection heat transfer characteristics under subcooled condition

Figure 2 shows forced convection heat transfer characteristics for inlet subcooled temperature of 5 K at 400kPa and 700 kPa. The vertical axis is the heat flux, q and the transverse axis is the temperature difference, $\Delta T_L (= T_W - T_{in})$ between the heated wall temperature, T_W and inlet liquid hydrogen temperature, T_{in} . The heat flux gradually increases with an increase in the heat input. In non-boiling regime, the heat transfer coefficients are higher for faster flow velocity. The heat transfer curves agree well with the curves predicted by the Dittus-Boelter equation. The nucleate boiling occurs at the wall temperature higher than the saturation temperature, T_{sat} (26 K at the 400kPa and 29 K at the 700kPa). In nucleate boiling regime, the heat flux steeply increases up to a certain upper limit heat flux, called Departure from Nucleate Boiling (DNB) heat flux. In the following sections, DNB heat flux is discussed.

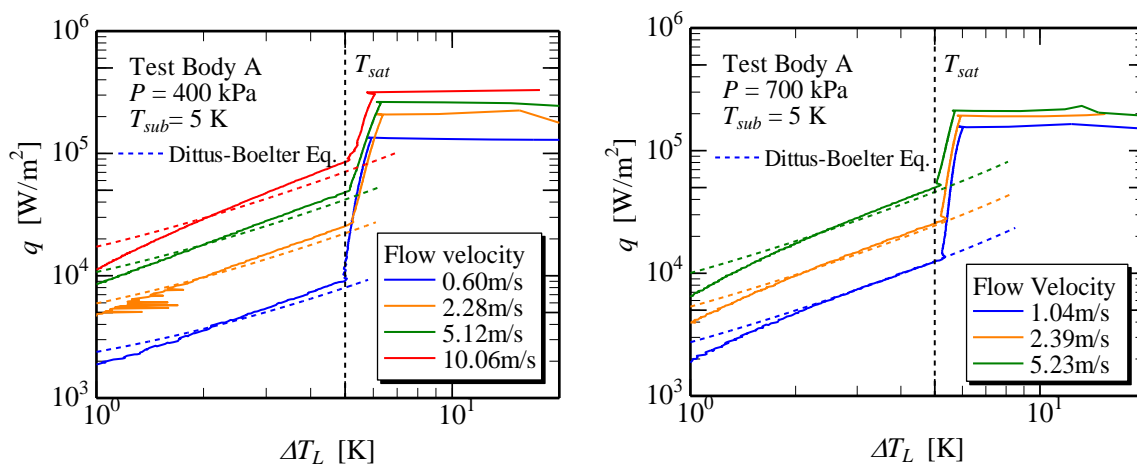


Figure 2. Heat transfer characteristics of liquid hydrogen for subcooled temperature of 5 K

3.2. DNB heat flux

In this section, the various factors affecting DNB heat flux are discussed. Figure 3 shows the effect of pressure with subcooled temperature as a parameter. Within the range of pressures measured in the experiment, it appears that DNB heat flux for the same subcooled temperature is lower for higher pressure. The main reason for this is the dependence of the latent heat on pressure. Shirai et al. [5] reported pressure dependence of critical heat flux for pool boiling of saturated liquid hydrogen. From the experimental data, the critical heat flux increases with the increase of pressure from the atmospheric pressure, takes the maximum value at around 300 kPa and decreases with further increase of pressure. In case of forced convection, pressure dependence on DNB heat flux is almost same as pool boiling. Also, it can be said that DNB heat flux increases as both subcooled temperature and flow velocity increases.

Figure 4 shows the effect of channel diameter on DNB heat flux at 700 kPa and subcooled temperature of 8 K, 5 K and saturated condition. First, we focus on the data of DNB heat flux for saturated condition. It appears that DNB heat flux of test body B is higher. However, for both test bodies A and B at subcooled conditions, results shows that the DNB heat fluxes are similar.

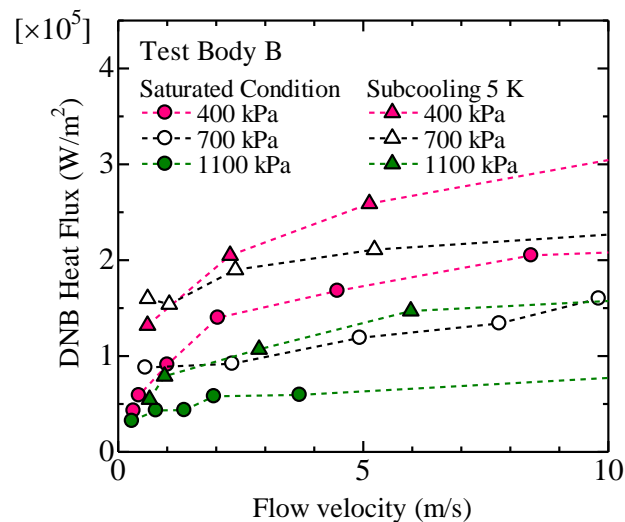


Figure 3. Effect of pressure at subcooled temperature of 5 K and saturated condition.

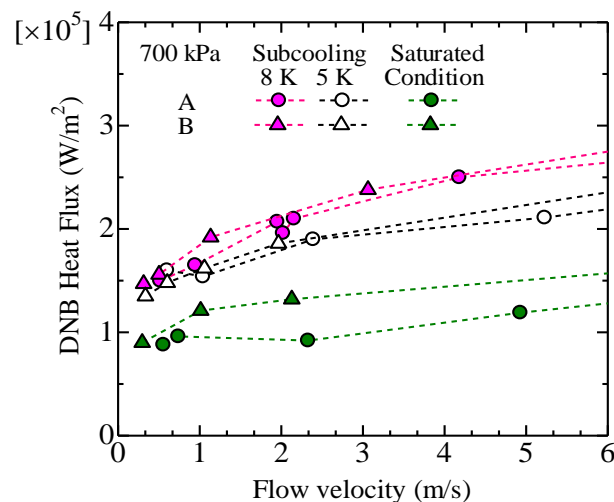


Figure 4. Effect of flow channel diameter

3.3. Correlation for DNB Heat Flux

Tatsumoto et al. [2] presented DNB heat flux correlation in forced convection of saturated liquid hydrogen for a vertically-mounted pipe heater. They assumed that a factor causing the departure from nucleate boiling was the transportation limit of the vapour. In addition, Tatsumoto et al. [4] applied that correlation to vertically-mounted wire heater set in central axis. Then, heated diameter, D_H for L/d was applied instead of hydraulic diameter, D_W .

We have measured heat transfer characteristics for various test heaters and modified the correlation to fit better for the experimental data.

$$q_{DNB,sat} = Gh_{fg} \left(\frac{\rho_v}{\rho_l} \right)^{0.43} \left(\frac{L}{D_H} \right)^{-0.35} F_b \quad (2)$$

$$F_b = 0.29We^{-0.45} + 0.001 \quad \text{for } We \geq We_b \quad (3)$$

$$F_b = 0.025 \left(\frac{L}{D_H} \right)^{-0.3} \quad \text{for } We < We_b \quad (4)$$

$$We_b^{-0.45} = 0.086 \left(\frac{L}{D_H} \right)^{-0.3} - 0.0034 \quad (5)$$

$$We = \frac{G^2 D_W}{\rho_l \sigma} \quad (6)$$

where We is the Weber number, G is the mass flux, h_{fg} is the latent heat of vaporization, σ is the surface tension, ρ is the density, L is the heated length, $D_H (= (D^2 - d^2)/d)$ is equivalent heated diameter and $D_W (= D - d)$ is equivalent hydraulic diameter. Subscripts l and v indicate liquid and vapour.

In the case of the boiling under subcooled condition, forced convection flow consists of two-phase flow near the surface of the wire heater and subcooled outside flow. Similarly in the case of the boiling under saturated condition, it was assumed that a factor causing the departure from nucleate boiling was the transportation limit of the vapour in two-phase flow. Under subcooled condition, vapour would be cooled and absorbed by subcooled outside flow. Therefore, DNB heat flux under subcooled condition is higher than under saturated condition because the amount of vapour transported in two-phase flow is smaller if other conditions are equal.

From the above consideration, DNB heat flux for subcooled boiling is determined by latent heat contribution in two-phase flow and sensible heat contribution in subcooled flow. The former is supposed to be $q_{DNB,sat}$ and the latter is given by the function of liquid mass flow rate, specific heat at constant pressure and liquid subcooling. Liquid temperature averaged over the flow area becomes higher with an increase of distance from the inlet. Consequently, departure from nucleate boiling occurs first around outlet of the wire heater and liquid subcooling for the correlation of DNB heat flux is given by outlet subcooling, $\Delta T_{sub,out}$.

Based on these consideration and experiment data, the correlation of DNB heat flux for wire heater under subcooled condition was derived.

$$q_{DNB,sub} = q_{DNB,sat} (1 + ASC_{out}) \quad (7)$$

$$A = 1.4 \left(\frac{\rho_v}{\rho_l} \right)^{-0.43} E^{-0.1} \left(\frac{L}{D_H} \right)^{0.25} \quad (8)$$

$$E = \frac{D_W}{\sqrt{\sigma/g(\rho_l - \rho_v)}} \quad (9)$$

$$Sc_{out} = \frac{c_{pl}\Delta T_{sub,out}}{h_{fg}} \quad (10)$$

where g is gravitational acceleration, c_{pl} is specific heat at constant pressure and ΔT_{sub} is subcooled temperature. Subscript *out* indicates outlet of flow path.

Here, $\Delta T_{sub,out}$ is given by the function of $q_{DNB,sub}$, so not known in advance. From the energy balance, $\Delta T_{sub,out}$ is given by the following expression.

$$\Delta T_{sub,out} = \Delta T_{sub,in} - 4q_{DNB,sub} \frac{(L/D_H)}{Gc_{pl}} \quad (11)$$

Subscript *in* indicates inlet of flow path. From Eq. (10), Eq. (11) expressed as

$$Sc_{out} = Sc_{in} - 4q_{DNB,sub} \frac{(L/D_H)}{Gh_{fg}} \quad (12)$$

$$Sc_{in} = \frac{c_{pl}\Delta T_{sub,in}}{h_{fg}} \quad (13)$$

By substituting Eq. (12) into Eq. (7), the following correlation is given.

$$q_{DNB,sub} = q_{DNB,sat} \frac{1 + AS_{in}}{1 + ABq_{DNB,sat}} \quad (14)$$

$$B = 4 \frac{(L/D_H)}{Gh_{fg}} \quad (15)$$

From Eq. (14), DNB heat flux for subcooled condition can be estimated. Next subsection, predicted DNB heat flux is the value obtained from Eq. (14).

3.4. Comparison of DNB heat flux of the correlation with the experimental data

Figure 5 shows the DNB heat flux data obtained from experiment and the value of correlation. It can be said that most of the experimental data are within plus or minus 15 % of the predicted values.

Figure 6 shows the DNB heat flux versus flow velocity at pressure of 700 kPa with inlet subcooling as a parameter and dotted line shows the correlation of DNB heat flux presented at previous subsection. These figures indicate that the correlation and experimental data match with good accuracy for both test heaters.

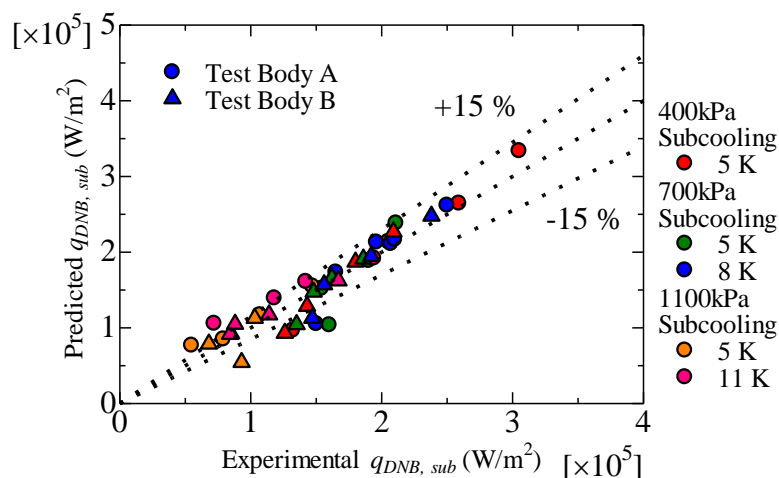


Figure 5. Comparison with predicted and experiment value of DNB heat flux.

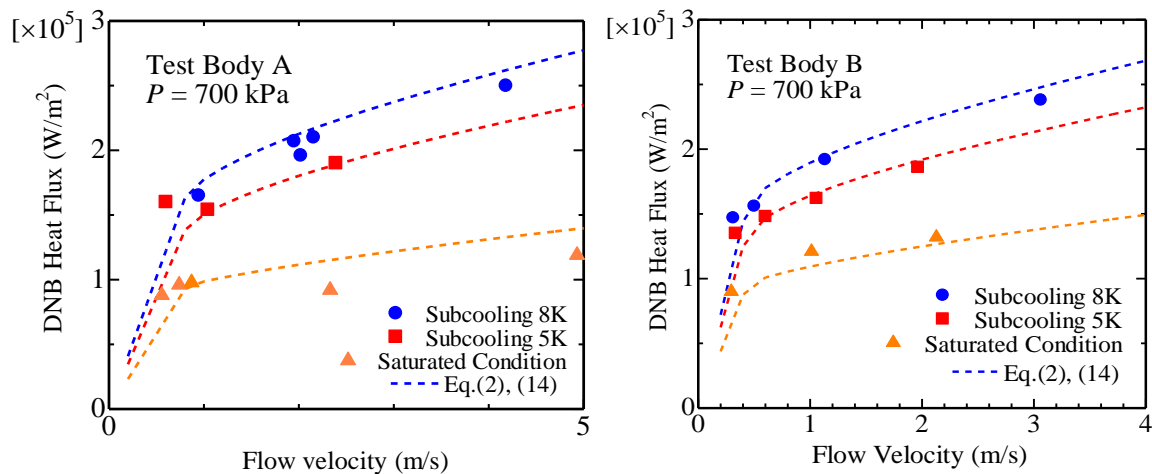


Figure 6. DNB heat flux versus flow velocity at pressure of 0.7 MPa with inlet subcooling as a parameter.

4. Conclusion

DNB heat flux of liquid hydrogen under saturated and subcooled condition were measured for various flow velocities and pressures and test bodies. The test bodies consist of FRP pipe and Pt-Co wire heater inserted into FRP pipe. From the experimental data, we got following conclusion.

- DNB heat flux under the same subcooled temperature were lower for higher pressure within the experimental range of pressures.
- DNB heat flux increased as both subcooled temperature and flow velocity increased.
- DNB heat flux under saturated condition was higher for larger flow channel diameter.

From the experimental data and consideration, new correlation of DNB heat flux of liquid hydrogen under saturated and subcooled condition was presented. Most of the experimental data were within plus or minus 15 % of the predicted values. So it can be said that the value of correlation and experimental data match with good accuracy.

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