Forced convection heat transfer from a wire inserted into a vertically-mounted pipe to liquid hydrogen flowing upward

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Abstract. Forced convection heat transfer from a PtCo wire with a length of 120 mm and a diameter of 1.2 mm that was inserted into a vertically-mounted pipe with a diameter of 8.0 mm to liquid hydrogen flowing upward was measured with a quasi-steady increase of a heat generation rate for wide ranges of flow rate under saturated conditions. The pressures were varied from 0.4 MPa to 1.1 MPa. The non-boiling heat transfer characteristic agrees with that predicted by Dittus-Boelter correlation. The critical heat fluxes are higher for higher flow rates and lower pressures. Effect of Weber number on the CHF was clarified and a CHF correlation that can describe the experimental data is derived based on our correlation for a pipe.

1. Introduction

Recently, liquid hydrogen draws attention as a coolant for large-scale HTS superconducting devices, especially MgB_2, because of lower boiling point, higher thermal conductivity, higher specific heat and lower viscosity. There has been a lack of systematic experimental data of forced flow liquid hydrogen, although some experimental data in a pool of liquid hydrogen at around atmosphere pressure have been reported [1-2].

Tatsumoto et al. [3-4] developed a thermal-hydraulics experimental system for liquid hydrogen, which implements explosion-proof measures, and carry out a systematic investigation of the forced convection heat transfer of liquid hydrogen. Tatsumoto et al. [5] measured forced convection heat transfer of saturated liquid hydrogen and clarified the effect of the heated pipe length on the critical heat flux (CHF). They derived a CHF correlation for forced flow of saturated liquid hydrogen. It is considered that a direct-cooled superconducting conductor such as a cable-in-conduit conductor (CICC) is more effective to activate the cooling characteristics of liquid hydrogen as much as possible, although there are some safety issues that need to be solved.

In this study, heat transfer from a wire inserted into a vertically-mounted pipe to forced flow of saturated liquid hydrogen are measured over wide ranges of pressure and flow velocity in order to clarify the effect of the flow rate and the pressure on the CHF. The measured CHF are compared with our CHF correlation for the vertical-mounted pipe [5].

2. Experimental apparatus and method

2.1. Explosion-proof experimental system

Details of the experimental system with the design pressure of 2.1 MPa and the measurement procedure have already been described in a previous paper [3]. The main tank (volume of 50 L), in

which a test tube heater mentioned in 2.2 is vertically mounted at one end of a transfer line, is connected with a receiver tank through a transfer line with a control valve. The main tank is placed on a scale with 0.002-kg resolution. Forced flow through the test tube heater is achieved by pressurizing the main tank to a desired value with pure hydrogen gas (99.99%) and adjusting the valve opening. The mass flow rate is estimated by the weight change and the flow rate of the feed hydrogen gas, which is measured by a turbine flow meter. The flow measurement error is estimated to be within 0.1 g/s [1]. The experimental system is installed in an explosion-proof laboratory and explosion-proof devices such as a valve and a pressure transmitter are used. The power leads that supply the electrical current up to 500 A to the test heater, which is considered as an explosive source, is covered with an enclosure filled with GN2 whose pressure is kept 5kPaG slightly higher than the atmospheric pressure.

2.2. Test heater

A wire heater inserted into a vertical-mounted pipe is shown in Fig.1. The wire heater, which is made of Pt-Co alloy, has a diameter (d) of 1.2 mm and a heated length (L) of 120 mm. The wire heater is located on the central axis of a channel with a diameter (d_p) of 8mm and a length of 210 mm, which is made of a Fiber-Reinforced Plastic (FRP) for thermal and electrical insulation. The hydraulic equivalent diameter (D) is 6.8 mm and the aspect ratio (L/D) is 17.6. The entrance lengths of the tube heaters are set to be more than ten times longer than D. This is because the flow velocities used in this study correspond to Reynolds number, Re, higher than 1.0×10^4 and can be regarded as turbulent flow. The channel with the wire heater is vertically mounted in the main tank and the liquid hydrogen flows upward through it.
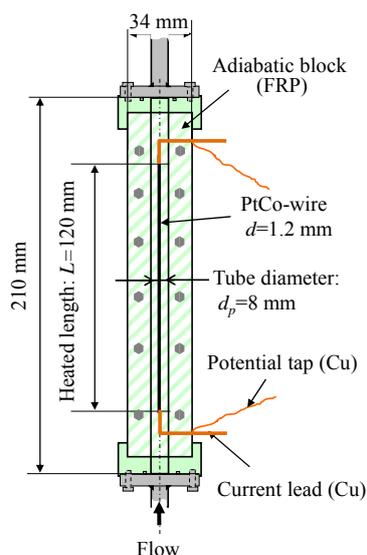

Fig. 1. Test heater

2.3. Experimental procedure

The wire heater is electrically heated by using a fast response direct current source (24 V, 500 A max.), which is controlled by a digital computer so as to give a desired time function for the heat input. Exponential heat generation of $Q = Q_0 \exp(t/\tau)$, for $\tau = 10$ s, where the heat transfer phenomenon can be regarded as a continuous series of steady-state, is applied to the heater. The average temperature of the heater is estimated by temperature-dependence of the electric resistance, which had been previously calibrated ranging from 20 K to ambient temperature. The electric resistance of the heater is measured using a double-bridge circuit including the heater as a branch of the bridge. The double bridge circuit is balanced at a bath temperature. The output voltage of the bridge circuit caused by the heater resistance deviation with the current heating, the voltage drop across the potential taps of the heater and that across a standard resistance, are amplified and are simultaneously sampled at a constant time interval. The heat generation rate in the heater is calculated from the measured voltage

drops across the heater and the standard resistance. The surface heat flux, q, is the difference between the heat generation rate and the time rate of change of energy storage in the heater. The average surface temperature of the heater, T_w, is calculated from the average temperature and the surface heat flux by solving a conduction equation in the radius direction of the wire. The double-bridge circuit to measure the heater resistance has the accuracy of 1×10^{-4}. The temperature deviation of about 0.1 K can be measured by the bridge. The bath temperature and the inlet temperature are measured by Cernox sensors with the accuracy of 10 mK. Only the temperature increment of the heater from the inlet temperature is necessary for the analysis. Accordingly, experimental error is estimated to be within the heater surface temperature of 0.1 K and the heat flux of 2 %.

Heat transfer from the wire located at the center axis of the vertically-mounted tube to forced flow of saturated liquid hydrogen at the pressures of 0.4, 0.7 and 1.1 MPa was measured with a quasi-steady increase of the heat generation rate, $Q_0\exp(t/\tau)$, with $\tau = 10.0$ s for various flow velocities.

3. Results and Discussion

3.1. Forced convection heat transfer characteristics

Fig.2 shows forced convection heat transfer characteristics at the pressures of 0.7 MPa under saturated condition. The transverse axis is the wall superheat, ΔT_{sat} ($=T_w - T_{sat}$), that indicates the temperature difference between the heated wall temperature, T_w, and the saturated temperature, T_{sat}. With an increase in the heat input quasi-steadily, the heat flux, q, gradually increases along the curves predicted by the Dittus-Boelter correlation [6], where hydraulic equivalent diameter is used as representative length. The nucleate boiling occurs at the wall superheat slightly higher than the saturated temperature and the heat flux steeply increases up to a certain upper limit heat flux, which is called a critical heat flux (CHF), q_{cr}, with relatively little increase in the wall superheat. Above q_{cr}, it seems that the heat transfer characteristic continuously changes to film boiling regime, because the averaged heated wall temperature is used in the figure although the wire heater has a temperature distribution along a longitudinal direction. Although the heat transfer in the developed nucleate boiling regime is not affected by the flow velocity, the non-boiling heat transfer and the CHF are higher for higher flow velocities. With increase in the pressure, the heat transfers of the developed nucleate boiling get better but the CHF becomes lower, like pool boiling of saturated liquid hydrogen [7].

3.2. Critical heat flux

Fig.3 shows the effect of the flow velocity on the measured CHF at the pressures of 0.4 to 1.1 MPa. It seems that the CHFs increase in proportion to the flow for lower flow velocity. For higher flow velocity, the increasing rate is smaller. With increase in the pressure, the threshold value of the flow velocity becomes lower and the CHFs also become smaller, like that for a pool boiling [7]. For comparison, the CHF data for a tube heater with the diameter of 6 mm and the length of 100 mm
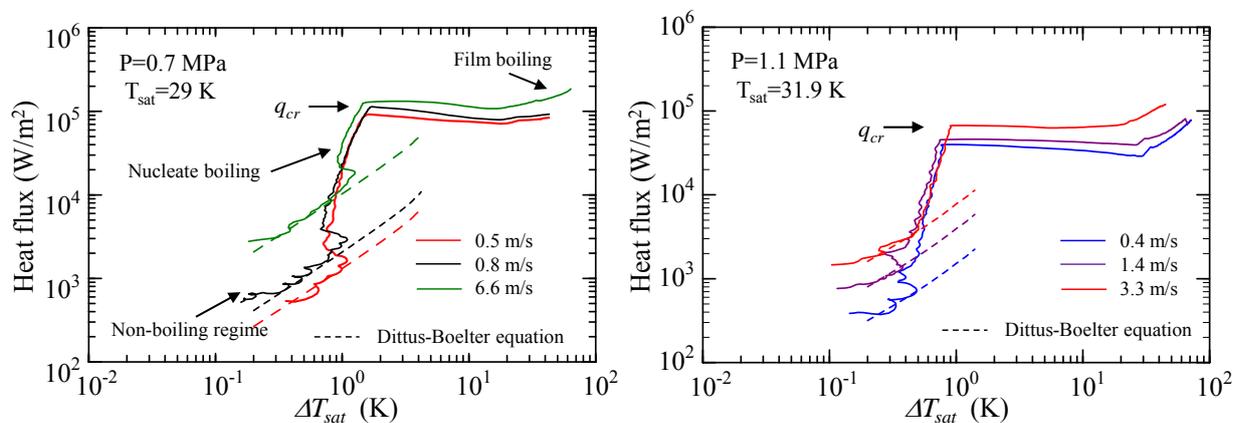

Fig. 2. Typical forced convection heat transfer characteristics of liquid hydrogen.
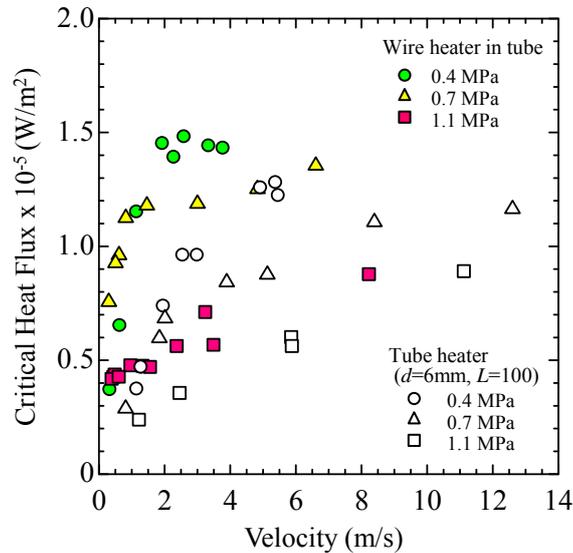
Fig. 3. Effect of flow velocity on critical heat flux.

measured by Tatsumoto et al. [5] are also plotted in the figure. The aspect ratio of L/D is 16.6, which is exactly similar to that used in this experiment. The CHFs for the wire heater inserted in the tube are higher than those for the heated tube, although they are affected by the flow velocity and the pressure as well as those for the heated tube.

3.3. Comparison with our CHF correlation for a vertically-mounted heated pipe

Tatsumoto et al. [5] have measured heat transfers from the inner side of vertically-mounted heated pipes with various heated lengths and diameters to forced flow of saturated liquid hydrogen at the pressures of 0.4 to 1.1 MPa and have presented the following CHF correlations for forced flow of saturated liquid hydrogen.

$$q_{cr} = Gh_{fg}\left(\frac{\rho_v}{\rho_l}\right)^{0.43}\left(\frac{L}{D}\right)^{-0.35}F_b \tag{1}$$

$$F_b = 0.038\left(\frac{L}{D}\right)^{-0.45} \quad \text{for} \quad We < We_b \tag{2}$$

$$F_b = 0.32We^{-0.45} + 0.0017 \quad \text{for} \quad We \geq We_b \tag{3}$$

$$We_b^{-0.45} = 0.118\left(\frac{L}{D}\right)^{-0.45} - 0.0053 \tag{4}$$

$$We = \frac{G^2 D}{\rho\sigma} \tag{5}$$

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 and L is the heated length. Subscripts l and v in eq. (1) indicate liquid and vapor.

As shown in Fig.3, the measured CHFs for the wire heater are different from those for the heated pipe with almost the same L/D. An equivalent heated diameter, D_H ($= (d_p^2 - d^2)/d$), is applied to eqs.(1) to (3) instead of the equivalent hydraulic diameter, D. Comparison of the measured CHF for the wire inserted into the pipe with the correlations is plotted in Fig.4. It is confirmed that the correlations can also describe the measured CHFs for the wire heater as well as those for the heated tube.
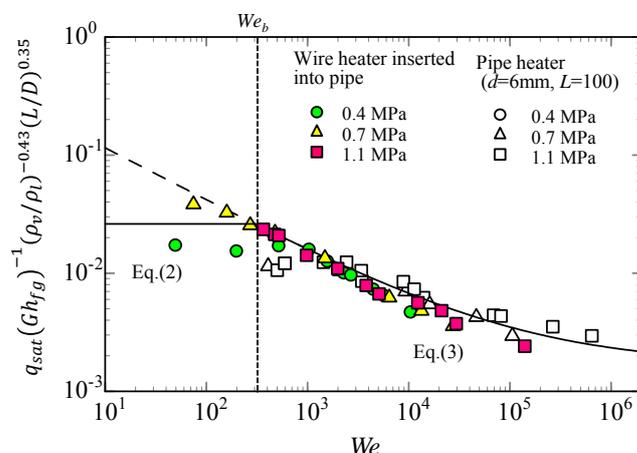
Fig. 4. Comparison of the CHF for the wire inserted into the pipe with authors' correlations.

4. Conclusion

The heat transfers from PtCo wire heater with a length of 120 mm and a diameter of 1.2 mm that was inserted into a vertically-mounted pipe with a diameter of 8.0 mm to forced flow of saturated liquid hydrogen were measured by quasi-steadily increasing the heat input for various flow rates at pressures of 0.4, 0.7 and 1.1 MPa. The experimental results lead to the following conclusions.

The non-boiling heat transfer coefficients agree with those predicted by Dittus-Boelter's equation and are higher for higher flow velocity, although the heat transfer in the developed nucleate boiling regime is not affected by the flow velocity under the same pressure.

For lower flow velocity, the CHF increases in proportion to the flow velocity. For higher flow velocity, the increasing rate of the CHF is smaller. With increase in the pressure, the CHF decreases like that for a pool boiling. The measured CHFs for the wire heater are higher than those for the heated pipe with almost the same L/D. It is confirmed that the measured CHFs for the wire heater can be described by our correlation for the heated tube by means of equivalent heated diameter, instead of the equivalent hydraulic diameter.

Acknowledgements

References

[1]   Coeling K J and Merte JR H 1969 *J. Eng. Indu.* **91** 513-524
[2]   Steward W G 1990 *Adv. in Cryo. Eng.* **35**, 403-412.
[3]   Tatsumoto H, Shirai Y, Shiotsu M, Hata K, Kobayashi H, Naruo Y and Inatani Y 2010 *J.Phys:Conf. Seri.* 234, 032056
[4]   Tatsumoto H, Shirai Y, Shiotsu M, Hata K, Kobayashi H, Naruo Y Inatani Y Narita N 2013 *Proc. Int. Cryo. Eng. Conf. 24* 157-160
[5]   Tatsumoto H, Shirai Y, Shiotsu M, Hata K, Naruo Y, Kobayashi H and Inatani Y 2014 *Adv. in Cryo. Eng.* 1573 59A, 403-412
[6]   Van Sciver S W 1986 *Helium Cryogenics* Plenum Press New York USA p. 251
[7]   Shirai Y, Tatsumoto H, Shiotsu M, Hata K, Kobayashi H, Naruo Y, Inatani Y 2010 *Cryogenics* **50** 410-416