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Equation of DNB Heat Flux for Upward Forced Flow of Cryogenic Liquids

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Abstract

Knowledge of departure from nucleate boiling (DNB) heat flux is important for design of superconducting systems cooled by cryogenic liquids. We have already presented the equation of DNB heat flux that can describe the experimental data of liquid hydrogen. To see the applicability of the equation to other cryogenic liquids, similar heat transfer tests in forced flow of liquid nitrogen are performed for wide ranges of conditions in this work. It was confirmed that the DNB heat flux equation derived by the authors can express not only the data for liquid hydrogen but also those for liquid nitrogen.

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Equation of DNB heat flux; Heat transfer; Forced flow; Subcooling; Liquid nitrogen

1. Introduction

The knowledge of forced flow heat transfer in cryogenic liquids is important for design of large scale HTS superconducting magnets and HTS superconducting cable. Heat transfer data in forced flow of

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cryogenic liquids are very few, as far as the authors know. Little is known on the effects of pressure, flow velocity and subcooling on DNB heat flux.

Tatsumoto et al. measured forced convection heat transfer of subcooled liquid nitrogen and supercritical nitrogen in a horizontal tube [1] and in a vertical tube [2] for wide ranges of pressure, inlet temperature and flow velocity. They reported that the departure from nucleate boiling (DNB) heat fluxes in forced flow could not be predicted by a correlation for water given by Hata et al. [3].

Shirai et al. [4,5] and Tatsumoto et al. [6] measured the heat transfer from inner side of a heated vertical pipe to liquid hydrogen flowing upward for wide ranges of flow rates and liquid temperatures. They reported that the DNB equation for water by Hata et al. [3] underestimated the experimental data of liquid hydrogen. Shirai et al. [4] reported that the Hata's equation with the exponent of non-dimensional subcooling term modified from 0.7 to 0.2 described the experimental data of DNB heat flux within $\pm 15\%$ difference. However the equation neglects the latent heat contribution and gives zero heat flux for saturated inlet temperature, because it is aimed for high heat flux cooling.

Shirai et al. [7] presented a new equation of DNB heat flux for forced flow of saturated and subcooled liquid hydrogen based on their assumed mechanism of heat transfer and the experimental data. The equation can describe their data within $\pm 10\%$ difference.

In this work, heat transfer tests in forced flow of liquid nitrogen are performed by using the experimental system for liquid hydrogen to see the applicability of the equation to other cryogenic liquid.

2. Experimental system

Details on the experimental system has been already presented in other paper [8]. It consists of a main cryostat, a sub tank (receiver tank), a connecting transfer tube with a control valve, a feed nitrogen gas line from clustered cylinders and vent lines

A test tube heater, which is shown in Fig. 1, is located at one end of the transfer tube in the main cryostat. The mass flow rate is estimated by the weight change of the main cryostat which is put on a scale (Mettler Toledo WMHC 300s). Two test tubes made of SUS316 are used. These are 3 mm in inner diameter d and 100 mm in length L , and $d=6$ mm, and $L=200$ mm. The outside of the heater is insulated by a Fiber-Reinforced Plastic (FRP) blocks.

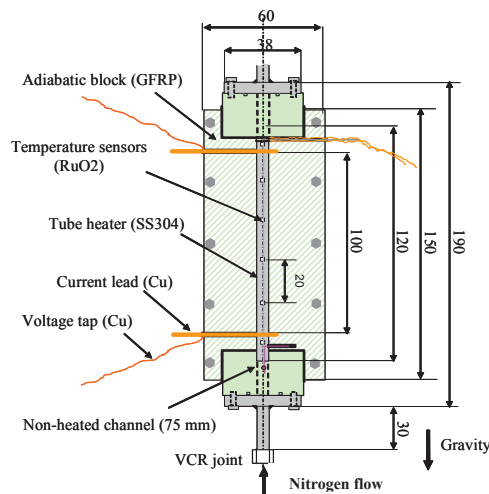


Fig. 1 Schematic of test heater block.

The heating current to the test heater is supplied by a power amplifier which can supply a direct current of up to 400 A. Exponential heat generation rate $Q = Q_0 e^{t/\tau}$ with $\tau = 10.0$ s is 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 forced convection heat transfer characteristics were measured at the pressure of 0.5 and 1.0 MPa. The inlet temperature T_{in} was varied from 77 K to saturated temperature T_{sat} and the flow velocities increased up to 11 m/s for 3 mm-tube and 6 m/s for 6 mm-tube.

3. Results and discussion

3.1 Typical heat transfer characteristics

Figure 2 shows the heat transfer characteristics on inner surface of the heater for inlet subcoolings of 14 K at the pressure of 1.0 MPa with flow velocity as a parameter. The y axis is the heat flux and x axis is the excess heater surface temperature beyond inlet temperature $\Delta T_L = T_w - T_{in}$.

The heat flux increases gradually proportional to ΔT_L with an increase in the heat input (non-boiling regime). The heat transfer coefficients in the non-boiling regime are higher for higher flow velocity. The curves predicted by the Dittus-Boelter's equation are also shown in the figure for comparison. The heat transfer coefficients in the non-boiling regime almost agree with the Dittus-Boelter equation. The nucleate boiling occurs at the wall temperature slightly higher than the saturation temperature T_{sat} . The heat flux increases with a steep gradient on this graph up to a certain value, where the wall temperature increases significantly with a slight increase in heat flux. The heat flux at the break point is called in this work the DNB heat flux. It is seen from the figure that the heat flux at the inception of boiling and the DNB heat flux are higher for higher flow velocity.

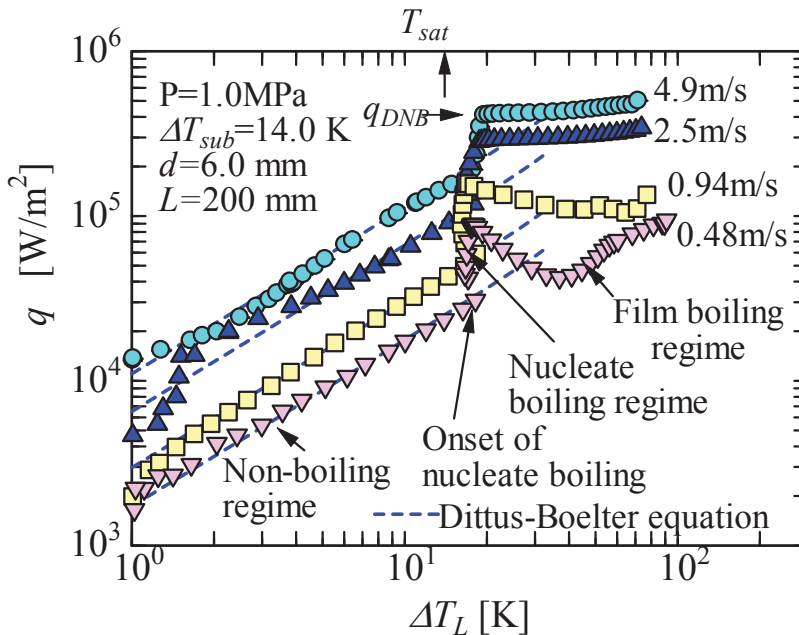


Fig. 2 Heat transfer curves for various flow velocities at 1.0 MPa.

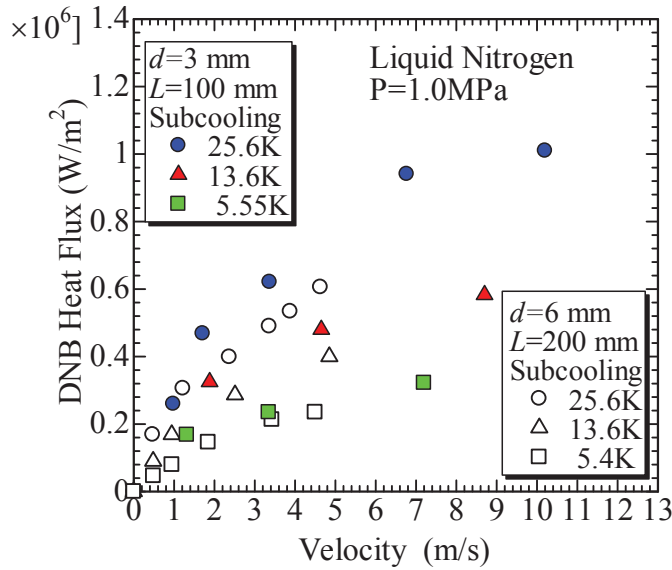


Fig. 3 DNB heat flux data versus flow velocity. Effect of tube diameter with subcooling as a parameter.

3.2 DNB heat flux

Forced flow DNB heat fluxes are obtained for various subcoolings and flow velocities at the pressures of 0.5 and 1.0 MPa.

Figure 3 shows the relation between the DNB heat flux and flow velocity on inner surface of 3 mm and 6 mm diameter tube with inlet subcooling as a parameter. We can see that the DNB heat fluxes are higher for higher flow velocity and higher subcooling. Length to diameter ratio (L/d) for 6 mm diameter tube was taken to be the same as that for 3 mm diameter tube (L/d=33.3). The DNB heat fluxes under subcooled condition for 3 mm diameter tube are clearly higher than those for 6 mm tube. The difference becomes smaller with the decrease in subcooling and the data for subcooling of around 5.5 K are almost in agreement with each other. It seems that the DNB heat flux under saturated condition can be expressed by the combined parameter of L/d. However, the DNB heat fluxes under subcooled conditions are higher for shorter tube even if the L/d value is the same.

3.3 Equation of DNB Heat Flux

We [7] have presented the following equation for DNB heat flux under saturated condition $q_{DNB,sat}$ and that under subcooled condition $q_{DNB,sub}$ for forced flow of liquid hydrogen with mass flow rate G .

$$q_{sat} = Gh_{fg} (\rho_v/\rho_l)^{0.43} (L/d)^{-0.35} (0.32We^{-0.45} + 0.0017) \text{ for } We > 1700 \tag{1}$$

$$q_{sat} = 0.013Gh_{fg} (\rho_v/\rho_l)^{0.43} (L/d)^{-0.35} \text{ for } We \leq 1700 \tag{2}$$

$$q_{sub} = q_{sat} [1 + 4.3(\rho_v/\rho_l)^{-0.43} E^{-0.35} F_c Sc_{in}^{1.2}] \tag{3}$$

where $G = \rho u$, $We = G^2 d \rho_l^{-1} \sigma^{-1}$, $Sc_{in} = C_{p,av} \Delta T_{sub,in} / h_{fg}$, $E = d(\sigma/g(\rho_l - \rho_v))^{-0.5}$, $C_{p,av} = \Delta h_{sub,in} / \Delta T_{sub,in}$,

$F_c = \exp[-(L/d)/(0.53Re^{0.4})]$, We is the Weber number, Sc_{in} is the non-dimensional inlet subcooling, E is the non-dimensional heater diameter, F_c is the compensation factor to estimate outlet subcooling, $C_{p,av}$ is the average specific heat, G is the mass flux, h_{fg} is the latent heat of vaporization, σ is the surface tension, g is the acceleration of gravity, ρ is the density, $\Delta T_{sub,in}$ is the inlet liquid subcooling. Subscripts l and v denote liquid and vapor and in denotes inlet, respectively. All the thermo-physical properties except $C_{p,av}$ are taken at saturation temperature.

3.4 Comparison with the DNB heat flux data for liquid nitrogen

Experimental data of DNB heat flux in forced flow of liquid nitrogen are compared with the predicted values by Eq.(3). Figure 4 shows the comparison for 3 mm and 6 mm diameter tubes under pressures of 0.5 and 1.0 MPa. Effects of flow velocity for various subcoolings at the pressures are expressed well by the equation. It was confirmed that the equation can describe not only the q_{DNB} for liquid hydrogen but also that for liquid nitrogen.

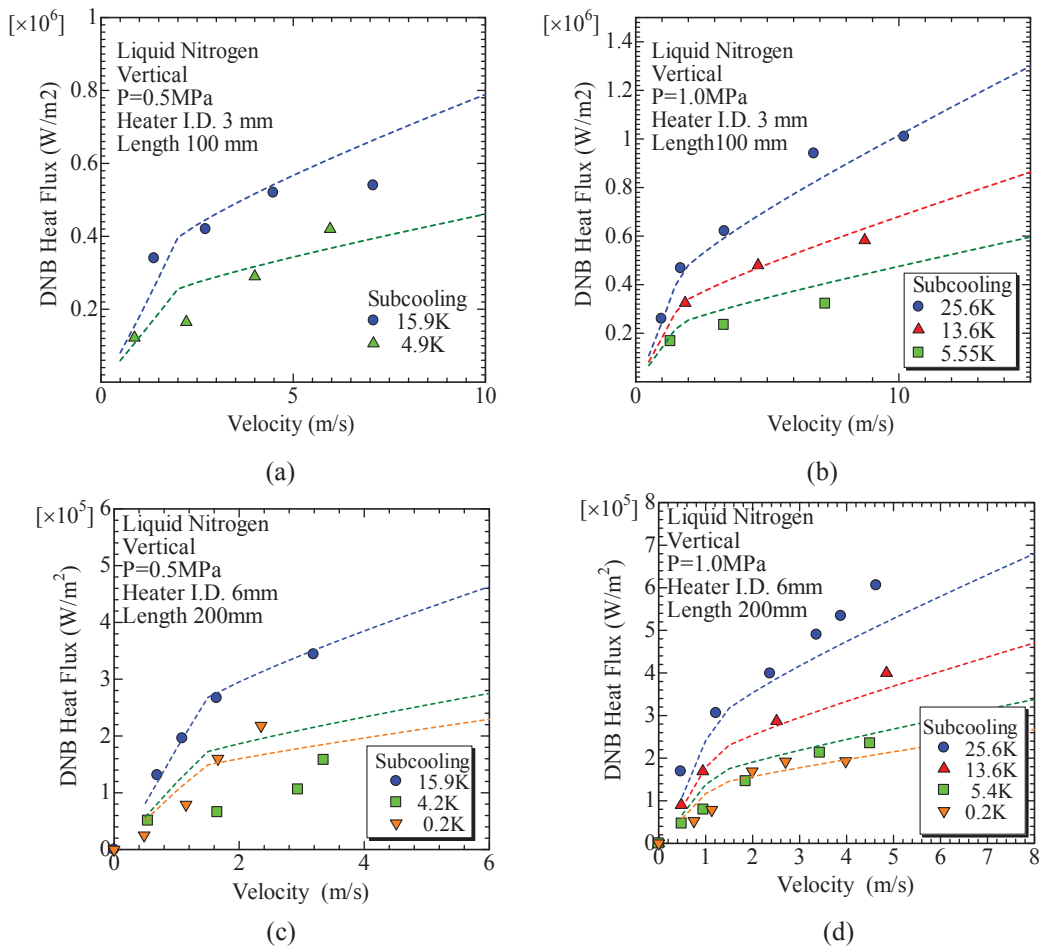


Fig. 4 Comparison of the DNB heat flux data for 3 mm diameter heater at (a) 0.5 MPa and (b) 1.0 MPa and those for 6 mm diameter heater at (c) 0.5 MPa and (d) 1.0 MPa with the predicted values by Eq. (3).

4. Conclusions

Heat transfer from inner side of a heated tube with upward flow of liquid nitrogen was measured for 3 mm inner diameter and 100 mm long and 6 mm inner diameter and 200 mm long tubes at pressures of 0.5 and 1.0 MPa. The results led to the following conclusions.

The nonboiling heat transfer coefficient is higher for higher flow velocity. The heat transfer coefficients in non-boiling region agree with Dittus-Boelter's equation.

The heat fluxes at the inception of boiling and the DNB heat fluxes are higher for higher flow velocity and subcooling.

The DNB heat flux under saturated condition for the test tubes with different length and the same value of L/d are almost in agreement with each other. However, the DNB heat fluxes under subcooled conditions are higher for shorter tube even if the L/d value is the same.

The data of DNB heat flux were compared with the authors' equation. Most of the experimental data under saturated and subcooled conditions are expressed within plus or minus 10 % of the predicted values by the equation.

It was confirmed that the equation can describe not only the q_{DNB} for liquid hydrogen but also those for liquid nitrogen.

Acknowledgements

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