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Film Boiling Heat Transfer from a Wire to Upward Flow of Liquid Hydrogen: Effect of Wire Diameter

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Abstract. Film boiling heat transfer coefficients were measured for the test wires of 0.5 and 0.7 mm in diameters and 200mm in length located at the centre of 8 mm diameter conduit with upward flow of liquid hydrogen. Pressures are ranged from 0.4 to 1.1 MPa, liquid subcoolings from 0 to 11 K and flow velocities up to 5 m/s. The experimental data were compared with the authors' correlation for forced flow film boiling already presented based on the data for 1.2 mm diameter test wire. The experimental data are higher than the predicted values by the correlation. Discussion is made on the effect of wire diameter observed and a new correlation was presented.

1. Introduction

Knowledge of film boiling heat transfer from a heated wire to forced flow of liquid hydrogen in a narrow gap is important for conductor design and quench analysis of superconducting magnets wound with high-Tc superconducting cable in conduit conductor (CICC). However, there have been few experimental data as far as we know.

Shiotsu et al. [1] measured the forced convection film boiling heat transfer from a round wire to liquid hydrogen flowing upward in a concentric annulus with a narrow gap. They reported that the experimental data were about 1.7 times higher than the values predicted by the Shiotsu-Hama equation [2], which is derived based on the film boiling data for a vertical cylinder in forced flow of water and R113 in 40 mm dia. conduit. They suggested that vapour film layer around the wire heater may be made thinner by a narrow gap.

Shiotsu et al. [3] measured the film boiling heat transfer from a heater wire to forced flow of liquid hydrogen and liquid nitrogen in round conduits. They made clear the effect of heater length and conduit inner diameter (gap of heater and conduit wall). They modified the Shiotsu-Hama equation to express the gap effect by introducing the equivalent diameter $D_e (=d_1-d_2)$; d_1 :conduit diameter, d_2 :heater wire diameter) and presented the film boiling heat transfer equation for liquid hydrogen and nitrogen based on their data.

The purpose of this study is first to obtain the experimental data of film boiling heat transfer from heater wires with the diameters of 0.5 and 0.7 mm to forced flow of liquid hydrogen and secondly to make clear the effect of heater diameter by comparing the data with the former correlation [3].



2. Apparatus and method

Experimental system consists of a main cryostat, a sub tank (receiver tank), a connecting transfer tube with a control valve. Liquid hydrogen in the main tank is forced to flow into the transfer tube by the pressure difference between the cryostat and the sub tank. Test heater block is located at the end of the transfer tube in the main tank. Liquid hydrogen flows upward through the conduit of test heater blocks. The mass flow rate is estimated by the weight change of the main tank, which is put on a scale (MettlerToledo WMHC 300s) that can measure up to 400 kg within 0.002 kg resolution. Details on the apparatus and method are shown in [1].

A test wire, 0.5 or 0.7 mm in diameter, 200 mm in length is supported at the centre of 8 mm diameter conduit in a block made of fibre reinforced plastic (FRP). The 0.5 mm-dia one is called Type A and the other is called Type B. The heating current to the test wire is supplied by a power amplifier (max. 400 A at a power level of 4.8 kW). The input signal of the power amplifier is controlled so that the heat generation rate in the test wire agreed with a desired value. In this study, exponential heat generation rate of $Q = Q_0 e^{t/\tau}$ with $\tau = 10$ s up to a certain value Q_m at $t = t_m$ and $Q = Q_m e^{(t_m - t)/\tau}$ for $t > t_m$ are applied to the test wire (see figure1). 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 average temperature of the heated wire T_{av} was estimated using its electrical resistance. Temperature characteristics of the heater resistance had been obtained previously. The surface heat flux q was obtained from the difference between the heat generation rate Q and the time rate of energy storage. The surface temperature of the heater T_w was calculated by solving steady-state conduction equation in a radial direction of the heater wire using T_{av} and Q (that is T_w is given as the boundary condition that satisfies measured T_{av} for Q).

3 Results and discussion

3.1 Typical heat transfer processes

Film boiling heat transfer coefficients are measured for the pressures from 0.4 to 1.1 MPa, liquid subcoolings to 11 K, and flow velocities to 8 m/s. Figure 1 shows a procedure to obtain film boiling heat transfer. Vertical axis is the heat flux q and horizontal axis is the excess heater temperature beyond liquid temperature ΔT_L . Firstly the heat generation rate is gradually increased for a low flow rate (0.95 m/s). Boiling initiates at the heater surface temperature slightly higher than the saturation temperature T_{sat} (point A). The process from A to B is nucleate boiling regime. When the heat flux reaches the DNB (Departure from Nucleate Boiling) heat flux (point B), heater temperature jumps to film boiling regime for 0.95 m/s (point C). Transient heat transfer process during the jump is shown in the figure. Then flow velocity is increased to a desired value (here 3.8 m/s, process CD) while heating current is continuously increased to the ΔT_{sat} around 300 K. Then the heating current is decreased and film boiling heat transfer coefficients are measured down to the minimum heat flux q_{min} (point E to F).

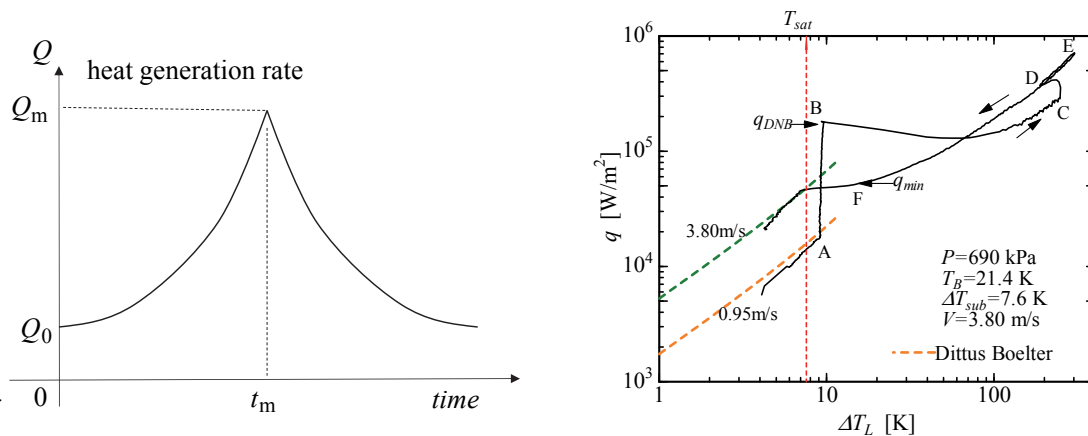


Figure 1. Heat generation rate pattern and measurement process of film boiling heat transfer.

3.2 Results of film boiling heat transfer

Figure 2 shows the film boiling heat transfer coefficients, $h = q / \Delta T_{sat}$, for the Type A heater under saturated condition at $P=400$ kPa versus ΔT_{sat} with flow velocity as a parameter. As the heat flux is reduced from a high ΔT_{sat} near 400 K, the heat transfer coefficient h decreases gradually down to about 80 K. For further decrease of wall superheat, the coefficient h increases steeply, since the vapour film becomes thinner drastically near the minimum film boiling heat flux q_{min} shown in figure 1. The film boiling heat transfer coefficients for the same ΔT_{sat} are higher for higher flow velocity.

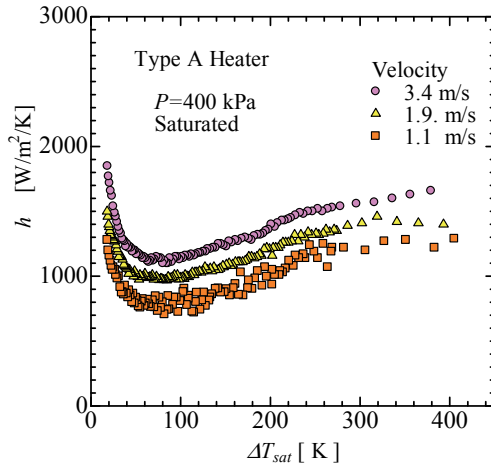


Figure 2. Film boiling heat transfer coefficient for Type A heater at $P=400$ kPa vs. heater surface superheat under saturated condition with flow velocity as a parameter

Nomenclature

$\overline{Nu}_{De} = hD_e / \lambda_v$: average Nusselt number with De

z : test heater length [m]

$Re_{De} = uDe / \nu_l$: Reynolds number with De

$Sp = \frac{c_{pv}}{h'_{fg} Pr_v} \Delta T_{sat}$: Non- dimensional superheat

$Sc = \frac{c_{pl}}{h'_{fg}} \Delta T_{sub}$: Non- dimensional subcooling

$h'_{fg} = h_{fg} + c_{pv} \Delta T_{sat} / 2$: modified latent heat [Jkg^{-1}]

$R = \sqrt{(\rho_v \mu_v) / (\rho_l \mu_l)}$

$Pr_v = c_{pv} \mu_v / \lambda_v$; Prandtl number

P : Pressure [kPa], P_{cr} : critical pressure [kPa]

subscript l, v : liquid, vapour

4. Correlation of Film Boiling Heat Transfer

4.1 Previous correlation by the authors

We have presented the following correlation of film boiling heat transfer from a vertical wire in forced flow of liquid hydrogen [3].

$$\overline{Nu}_{De} = 0.63 (zD_e^{-1})^{-1/4} Re_{De}^{0.55} (\mu_l / \mu_v) M^{-1/3} F_p \quad (1)$$

where $M = (SpR^{-2})[1 + \{E_2(2Pr_l Sp)^{-1}\}][1 - 0.7ScE_2^{-1}]$, $F_p = 1.0 + 0.7(PP_{cr}^{-1})^{0.9}$, $D_e (=d_1 - d_2)$ is the equivalent diameter and E_2 is a positive root of the following cubic equation.

$$E_2^3 + (5Pr_l Sp - Sc)E_2^2 - 5Pr_l Sp Sc E_2 - 7.5Pr_l^2 Sp^2 R^2 = 0 \quad (2)$$

Explanation on other parameters in these equations are shown in [3] and listed above. The film boiling heat transfer coefficients predicted by Eq. (1) decrease with the decrease in flow velocity, but do not become lower than those of pool film boiling heat transfer. The experimental data on vertical wires of diameter $d_2=1.2$ mm with the lengths from 50 to 300 mm in various diameter conduits for wide ranges of pressure, inlet subcooling and flow velocity were expressed within ± 20 % error by the equation (1) [3].

The film boiling heat transfer coefficients predicted by the correlation are compared with the experimental data for the Type A heater ($d_2=0.5$ mm, $d_1=8$ mm) in figures 3 and 4, and Type B heater ($d_2=0.7$ mm, $d_1=8$ mm) in figures 5 and 6. Broken lines in these figures are those by equation (1). We can see that the experimental data are higher than the predicted curve. Maximum deviation is about 60 %. Dashed lines in these figures are by a new correlation described later.

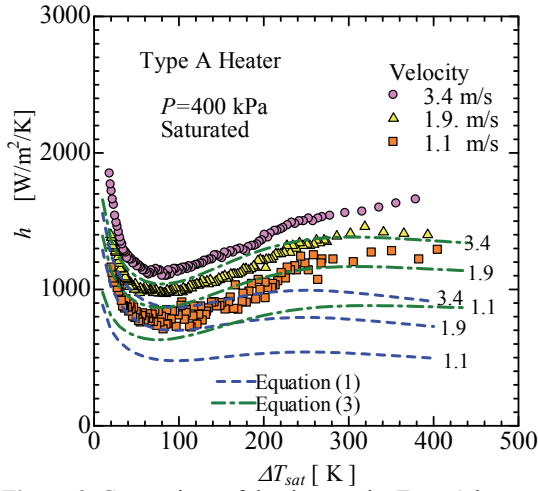


Figure 3. Comparison of the data on the Type A heater for $P=400$ kPa saturated condition with the correlations.

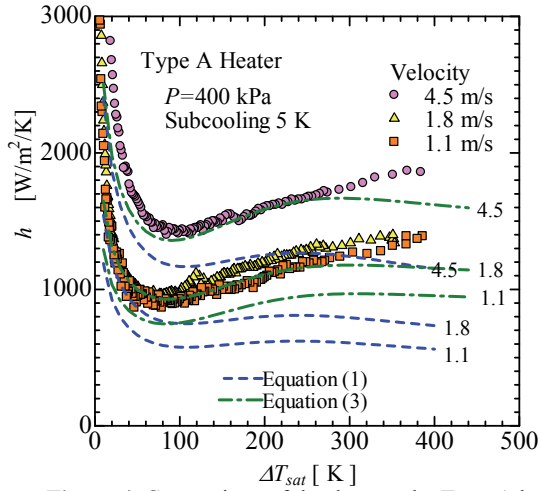


Figure 4. Comparison of the data on the Type A heater for $P=400$ kPa, subcooling 5 K with the correlations.

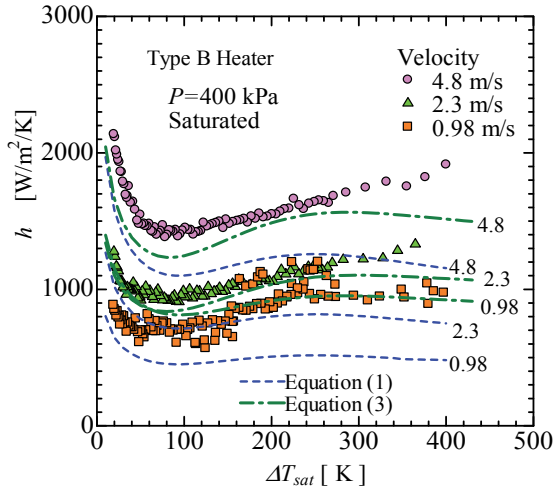


Figure 5. Comparison of the data on the Type B heater for $P=400$ kPa saturated condition with the correlations.

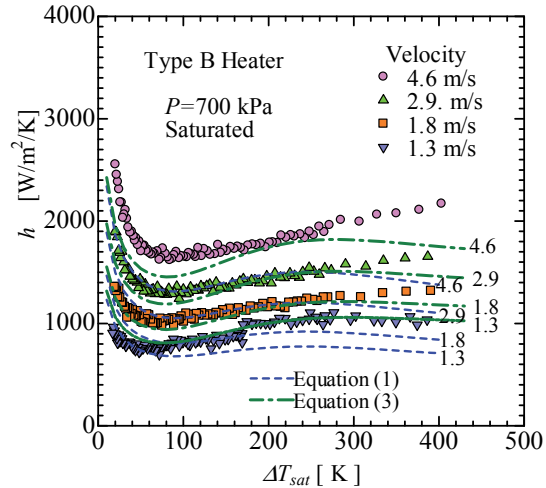


Figure 6. Comparison of the data on the Type B heater for $P=700$ kPa saturated condition with the correlations.

4.2 New correlation

The large deviation from the correlation may be due to the curvature effect of the test wire. When the diameter of the test wire is small, surface area of the vapour film cannot be regarded as that of the test wire. Sakurai et al. [4] reported in their study of pool boiling on a horizontal cylinder that this effect can be expressed by a correction factor, $(1 + 2 / \overline{Nu}_{d_2})$, where d_2 is the wire diameter. If the radial temperature distribution in the vapour film around the heater is supposed to be linear, heat flux q is approximately expressed as $q = \lambda_v \Delta T_{sat} / \delta$, where δ is vapour film thickness. Inserting this expression of q into \overline{Nu}_{d_2} , the correction factor $(1 + 2 / \overline{Nu}_{d_2}) = (d_2 + 2\delta) / d_2$. This is the ratio of the vapour film surface area to the heater surface area. The value of \overline{Nu}_{d_2} is obtained from the equation (1) as $\overline{Nu}_{d_2} = \overline{Nu}_{De} (d_2 / D_e)$. The modified correlation is

$$f = \frac{\overline{Nu}_{d_2}}{1 + 2 / \overline{Nu}_{d_2}} = 0.63 (d_2 / D_e) (z / D_e)^{-1/4} Re_{De}^{0.55} (\mu_l / \mu_v) M^{-1/3} F_p \quad (3)$$

From the quadric formula, $\overline{Nu}_{d_2} = 0.5 \times \left(f + \sqrt{f^2 + 8f} \right)$.

4.3 Comparison of the new correlation with the experimental data

The dashed lines in figures 3 to 6 are by the new correlation, equation (3). It seems that the prediction error has become very much smaller. All the experimental data obtained in this work are plotted on $\{\overline{Nu}_{d_2}/(1+2/\overline{Nu}_{d_2})\}(D_e/d_2)(z/D_e)^{1/4}(\mu_v/\mu_l)M^{1/3}F_p^{-1}$ vs. Re_{De} graph in figure 7. Figure 8 shows the similar comparison of the data for the test heaters Type 1 ($d_2=1.2$ mm, $d_l=8$ mm, $z=120$ mm) and Type 2 ($d_2=1.2$ mm, $d_l=5$ mm, $z=200$ mm) presented by the authors [3]. We can see from these figures that most of the experimental data for $d_2=0.5$, 0.7 and 1.2 mm are within $\pm 30\%$ of the predicted values.

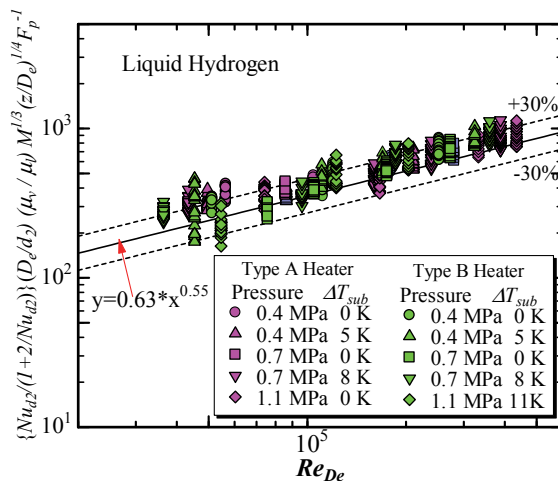


Figure 7. Experimental data for Type A and Type B heaters compared with the new correlation.

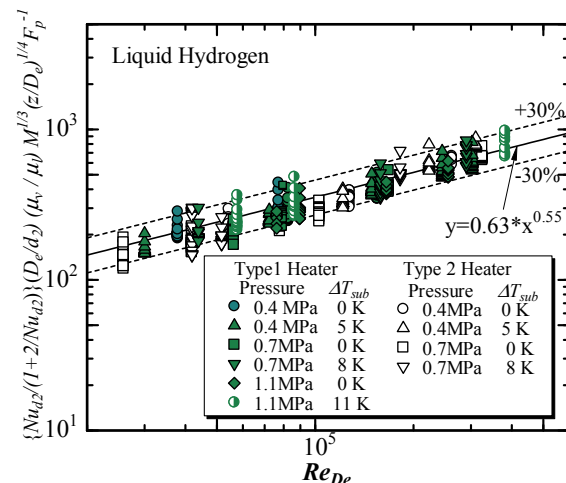


Figure 8. Experimental data for 1.2 mm-dia heaters [3] compared with the new correlation.

5. Conclusions

Film boiling heat transfer coefficients were measured for the test wires of 0.5 and 0.7 mm in diameters and 200 mm in length located at the centre of 8 mm diameter conduit with upward flow of liquid hydrogen.

The experimental data are higher than those predicted by the previous correlation given by the authors based on the experimental results for 1.2 mm diameter test heater. Maximum deviation is about 60 %.

New correlation of film boiling heat transfer was given modifying the conventional one to extend for the smaller heater diameter. Experimental results for the Type A and Type B heater and the former results for 1.2 mm diameter heater [3] are expressed by the correlation within $\pm 30\%$ error.

Acknowledgments

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