Film boiling heat transfer from a round wire to liquid hydrogen flowing upward in concentric annulus

M. Shiotsu[a], Y. Shirai[a], Y. Oura[a], Y. Horie[a], K. Yoneda[a], H. Tatsumoto[b], K. Hata[c], H. Kobayashi[d], Y. Naruo[d], Y. Inatani[d]

[1] Dept. of Energy Science and Technology, Kyoto University, Kyoto, Japan
J-PARC Center, Japan Atomic Energy Agency, Tokai, Ibaraki, Japan
[3] Institute of Advanced Energy, Uji, Kyoto University, Japan
[4] Institute of Space and Astronautical Science, JAXA, Kanagawa, Japan

Abstract

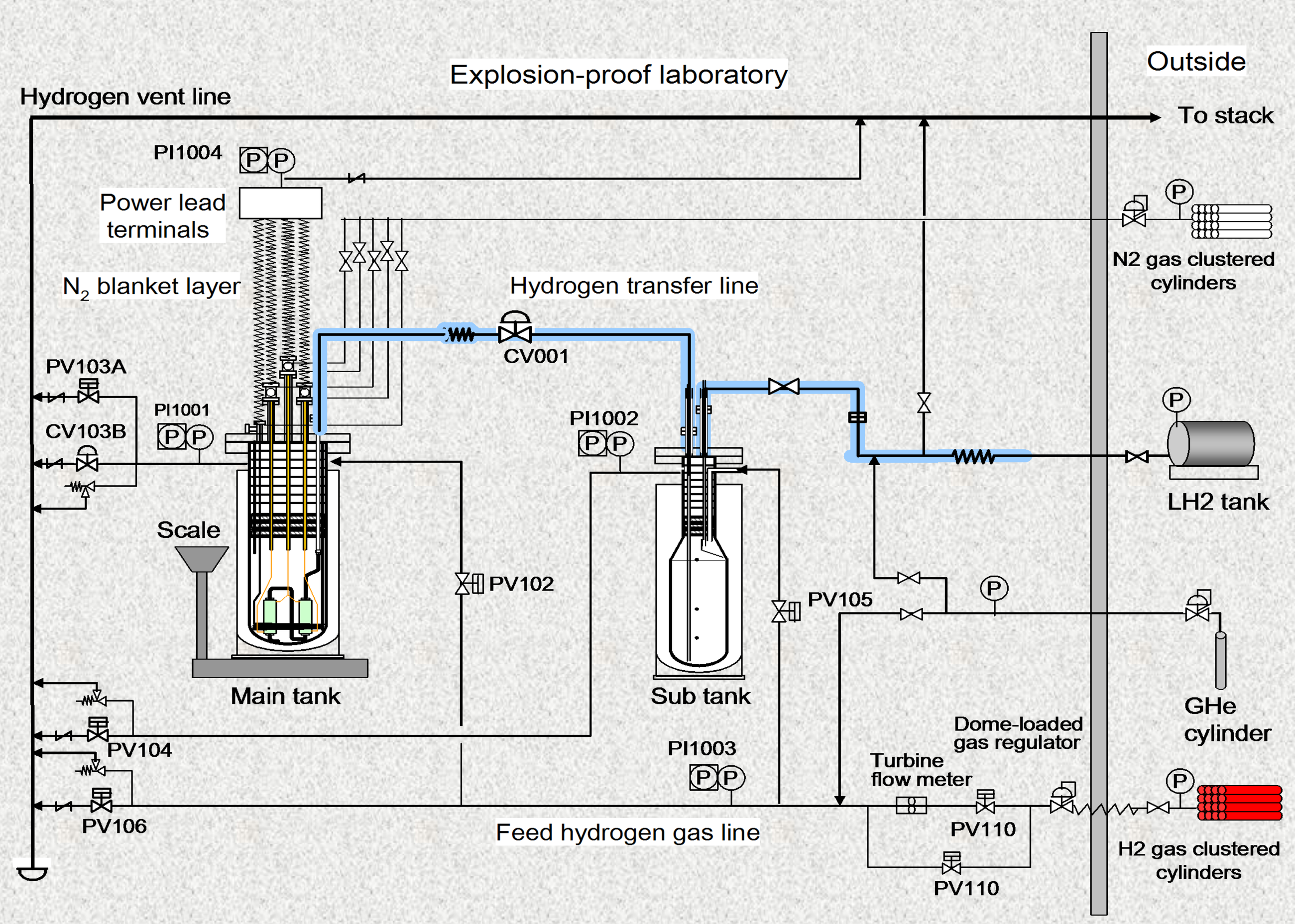
Film boiling heat transfer coefficients were measured for the heater surface superheats up to 400 K under pressures from 400 to 1100 kPa, liquid subcoolings from 0 to 11 K and flow velocities up to 7 m/s. The test wire used was 1.2 mm in diameter and 120 mm in length made of PtCo (0.5 at. %) alloy, which was located at the center of 8 mm diameter conduit made of FRP (Fiber Reinforced Plastics). The heat transfer coefficients were higher for higher pressure, higher subcooling, and higher flow velocity. The heat transfer coefficients were about 1.6 times higher than those predicted by Shiotsu-Hama equation for forced flow film boiling in a wide channel. Discussions were made on the mechanism of difference between them.

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 cooled by liquid hydrogen. However there have been few experimental data as far as we know. Recently, we have performed a series of experimental study for liquid hydrogen cooling Experimental system without using a pump was developed . Steady-state and transient boiling heat transfer in a pool and forced flow boiling heat transfer and its DNB heat flux for wide range of pressures below the critical one were reported.

The purpose of this study is twofold. First is to obtain the experimental data of forced convection heat transfer from a round wire to liquid hydrogen flowing upward in concentric annulus with a narrow gap. Second is to clarify whether the experimental data can be described by conventional correlation.

EXPERIMENTALAPPARATUS



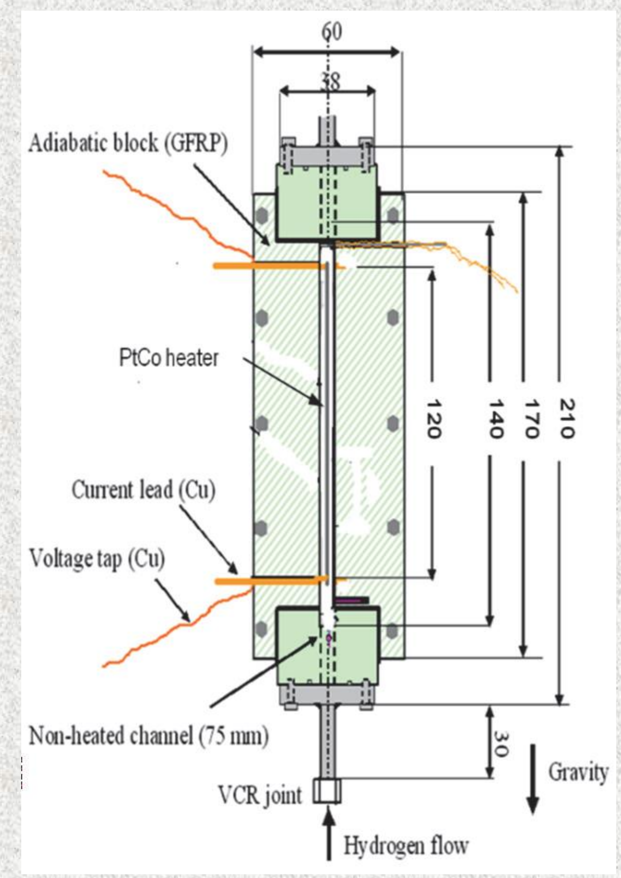


Fig.2 Test heater block.

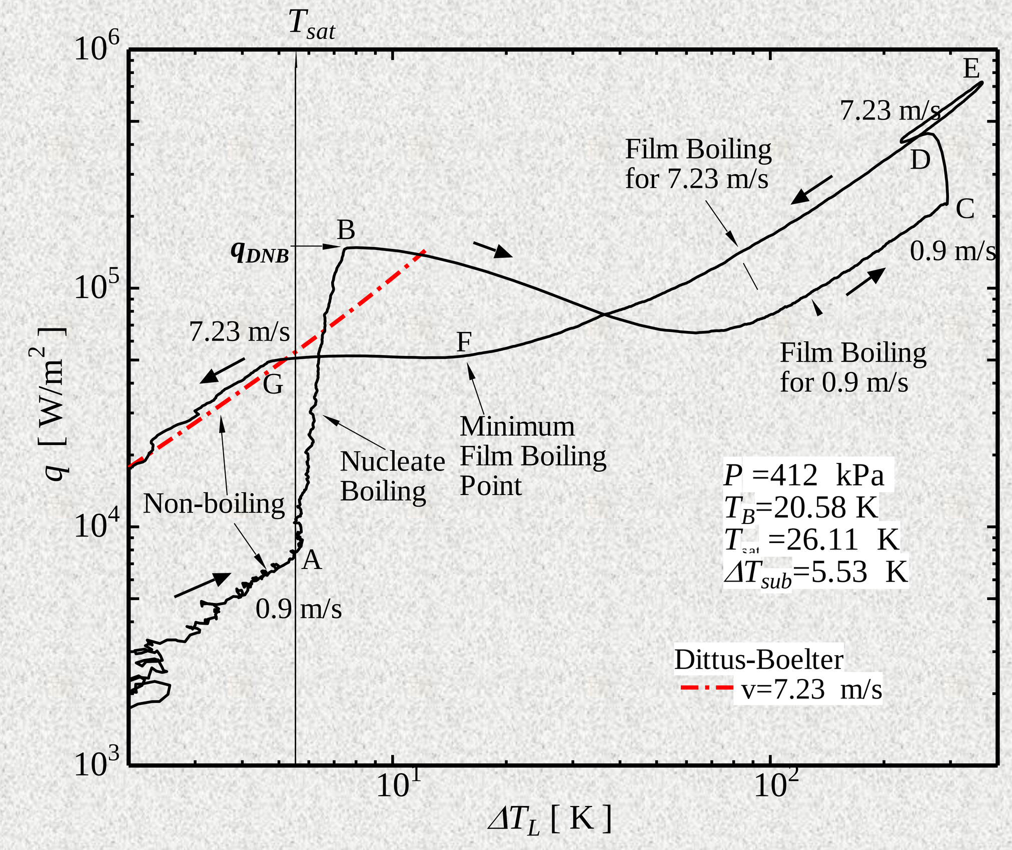
Experimental Conditions

Test Heater: PtCo Wire
1.2mm diameter,120mm-long
Pressure: 400 kPa, saturated condition, subcooling 5 K
700 kPa, saturated condition, subcooling 8 K
1100 kPa, saturated condition, subcooling 11 K

- **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.**
- **The test heater was heated electrically by using a direct current source (max. 400 A at a power level of 4.8 kW).**
- **Average temperature of the test heater was measured by resistance thermometry using a double bridge circuit.**
- **Surface temperature T_w of the wire was calculated by solving the conduction equation in a radial direction of the heater using the measured average temperature and the heat flux.**

RESULTS and DISCUSSION

Typical Heat Transfer Processes



- **This figure shows a typical process to measure film boiling heat transfer without too much thermal shock to the test wire.**
- **Firstly the heat generation rate was gradually increased for a low flow rate (0.9 m/s). Boiling initiates at point A and AB is nucleate boiling regime. When the heat flux reaches the DNB heat flux (point B), heater temperature rapidly increases with a decrease of heat flux to film boiling for 0.9 m/s (point C). Flow velocity is increased to a desired value (here 7.23 m/s). while heating current is continuously increased to the heater temperature around 400 K.**
- **Then the heating current is decreased exponentially and film boiling heat transfer coefficients are measured.**

FILM BOILING HEAT TRANSFER COEFFICIENTS

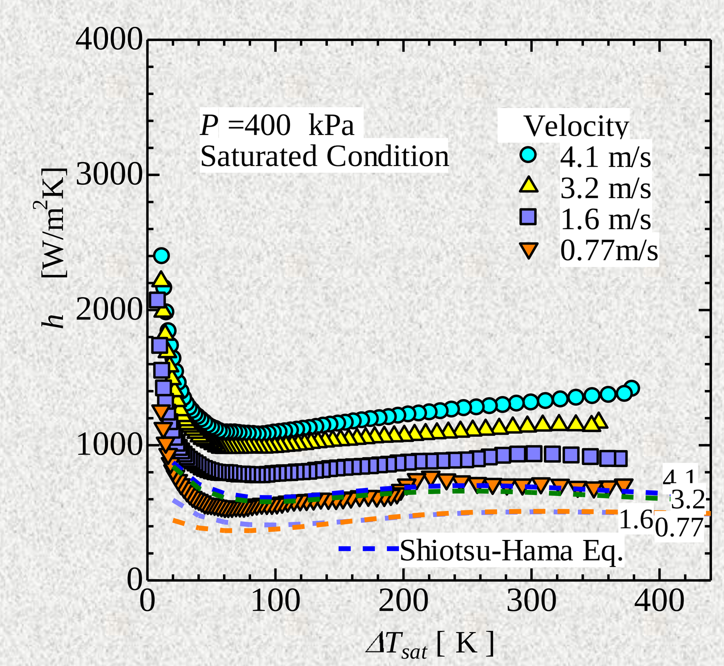


Fig.4 Film boiling heat transfer coefficients for for saturated condition at P=400 kPa.

Film boiling heat transfer coefficients for each flow velocity gradually decreases or almost constant for wall superheat down to about 80 K. It becomes significantly higher with the decrease of superheat from the value.

The film boiling heat transfer coefficients are higher for higher flow velocity.

For low velocity under saturated condition, small oscillation of heat transfer coefficient was observed at around 220 K.

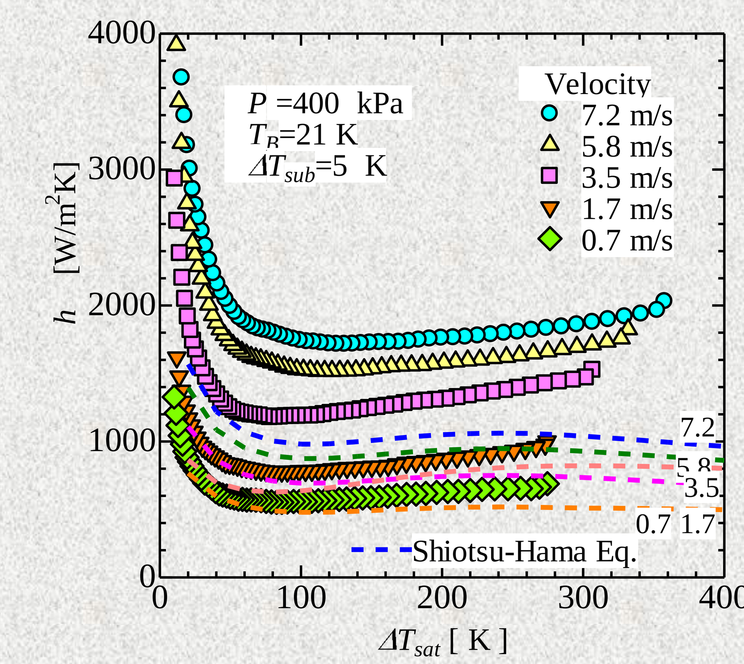


Fig.5 Film boiling heat transfer coefficients for Subcooling of 5 K at P=400 kPa.

Trend of dependence on wall superheat and flow velocity is similar to that for saturated condition.

By comparing the data for 4.1 m/s in Fig.4 with those for 3.5 m/s in Fig.5, we can see that the heat transfer coefficients are higher for higher subcooling.

No oschillation was observed for low velocity under subcooled condition.

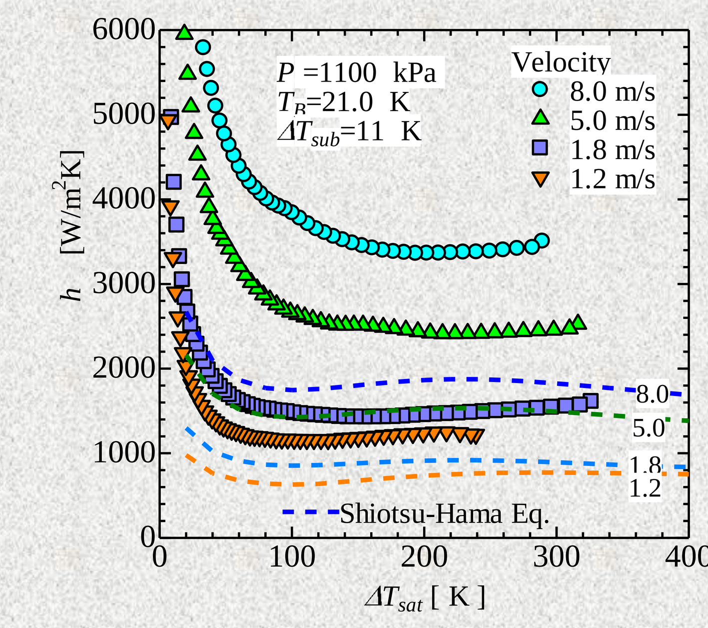


Fig.9 Film boiling heat transfer coefficients for subcooling of 11 K at1100 kPa.

With the increase of pressure and subcooling, film boiling heat transfer coefficients increase significantly. At the pressure of 1100 kPa and liquid subcooling of 11K for instance, the film boiling heat transfer coefficients for velocities are about 70 % higher than those for the pressure of 400 kPa.

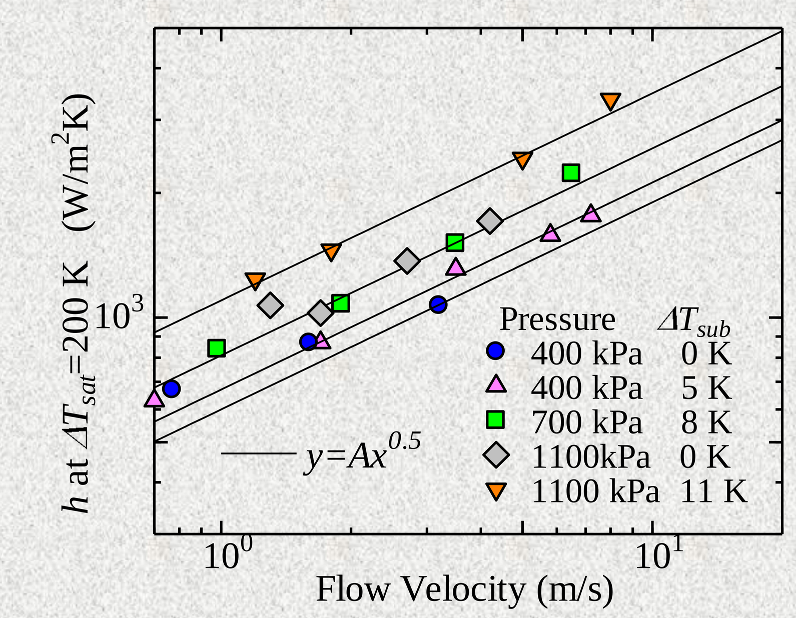


Fig.10 Film boiling heat transfer coefficients at wal superheat of 200 K versus flow velocity.

The heat transfer coefficients at each pressure and subcooling increase proportional to square root of the flow velocity.

Comparison with Conventional Correlation

Shiotsu and Hama studied the saturated and subcooled film boiling heat transfer from a vertical cylinder in forced flow of water and R113 in 40 mm dia. cylindrical conduit. They derived the following correlation of forced convection film boiling heat transfer based on their experimental data.

$$\frac{\overline{Nu}}{\sqrt{\mathrm{Re}_z}}\frac{\mu_v}{\mu_l}=0.53\left[\frac{Sp}{R^2}\left(1+\frac{E_2}{2\,\mathrm{Pr}_l\,Sp}\right)\left(1-0.7\frac{Sc}{E_2}\right)\right]^{-1/3} z'^{1/4} \qquad \text{for} \quad \mathrm{Re}_z \ge F_v \qquad (1)$$

$$\overline{Nu}=0.52 z'^{1/4} M_z^{1/4} \qquad \text{for} \quad \mathrm{Re}_z < F_v \qquad (2)$$

where

$$F_v=0.96 M_z^{1/2}\left(\mu_v/\mu_l\right)^2\left[\left(Sp/R^2\right)\left\{1+E_2/\left(2\,\mathrm{Pr}_l\,Sp\right)\right\}\left(1-0.7Sc/E_2\right)\right]^{2/3}$$

E_2 is a positive root of

$$E_2^3+(5\,\mathrm{Pr}_l\,S_p-S_c)E_2^2-5\,\mathrm{Pr}_l\,S_p S_c E_2-(15/2)\,\mathrm{Pr}_l^2\,S_p^2 R^2=0$$

The values predicted by the equation are shown in Figs. 4,5 and 9 for comparison. The experimental data are about 1.7 times higher than the predicted values, although the trend of dependence on flow velocity is similar as shown in Fig.10. Shiotsu-Hama equation is based on the experimental data for large conduit . Vapor film layer around the wire heater may be made thinner by a very narrow gap of 3.4 mm in this study.

CONCLUSIONS

- **Film boiling heat transfer coefficients are higher for higher pressure, flow velocity and subcooling.**
- **Film boiling heat transfer coefficients are about 1.7 times higher than those predicted by Shiotsu and Hama equation based on experimental data for water and R113 in 40 mm dia. cylindrical conduit.**
- **Vapor film layer around the wire heater may be made thinner by a very narrow gap of 3.4 mm in this study. Modification of the equation to include the effect of gap length is a future problem and now in progress.**

ACKNOWLEDGMENTS

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