Film boiling heat transfer from a wire to upward flow of liquid hydrogen and liquid nitrogen

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BACK GROUND

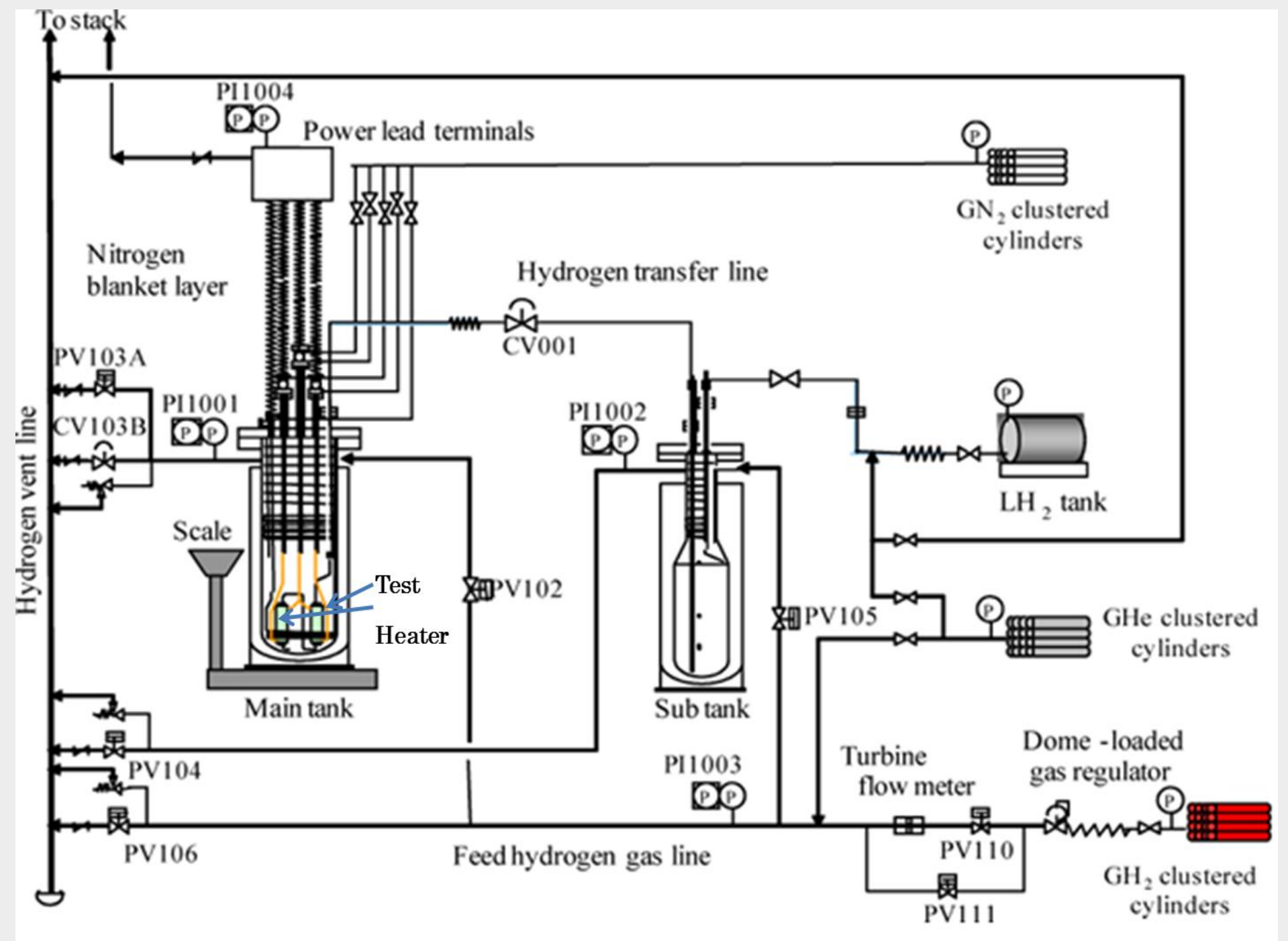
Knowledge of film boiling heat transfer from a heated wire to forced flow of liquid hydrogen in a narrow gap is important for conductor design and quench analysis of superconducting magnets cooled by liquid hydrogen. However there have been few experimental data as far as we know.

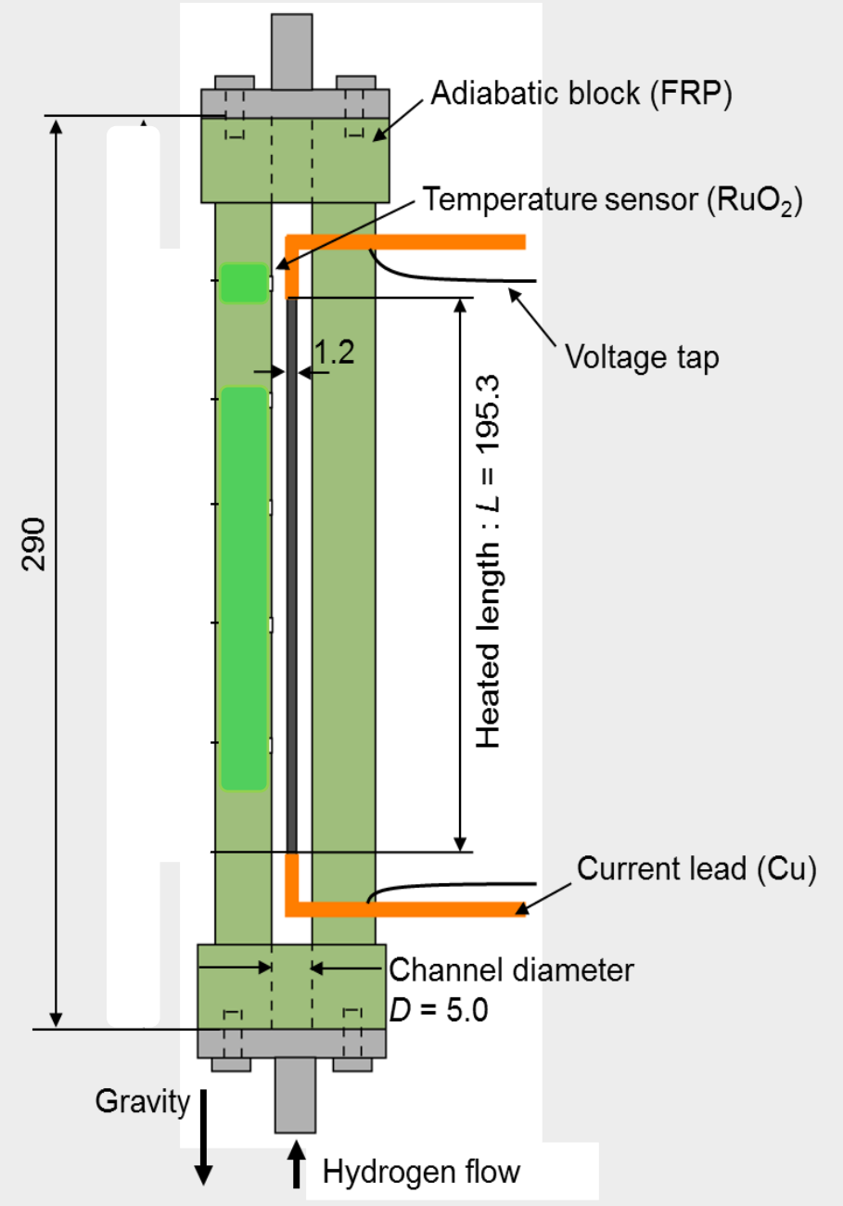
INTRODUCTION

Recently, Shiotsu et al.[2] have measured the forced convection film boiling heat transfer from a round wire to liquid hydrogen flowing upward in concentric annulus with a narrow gap. They reported that the values predicted by a conventional equation for a wide conduit were about 1.7 times higher than the predicted values, although the trend of dependence on flow velocity was similar to that predicted by the equation. They suggested that vapor film layer around the wire heater may be made thinner by a narrow gap.

The purpose of this study is firstly to obtain the experimental data of film boiling heat transfer from a heater wire to forced flow of liquid hydrogen and liquid nitrogen in round conduits with different gaps and secondly to present a film boiling heat transfer equation based on the experimental data.

EXPERIMENTAL APPARATUS





Type 2 Heater

Type 1 Heater: PtCo wire 1.2 mm dia, 120 mm long in 8 mm dia. conduit
Type 2 Heater: PtCo wire 1.2 mm dia., 200 mm long in 5 mm dia. conduit

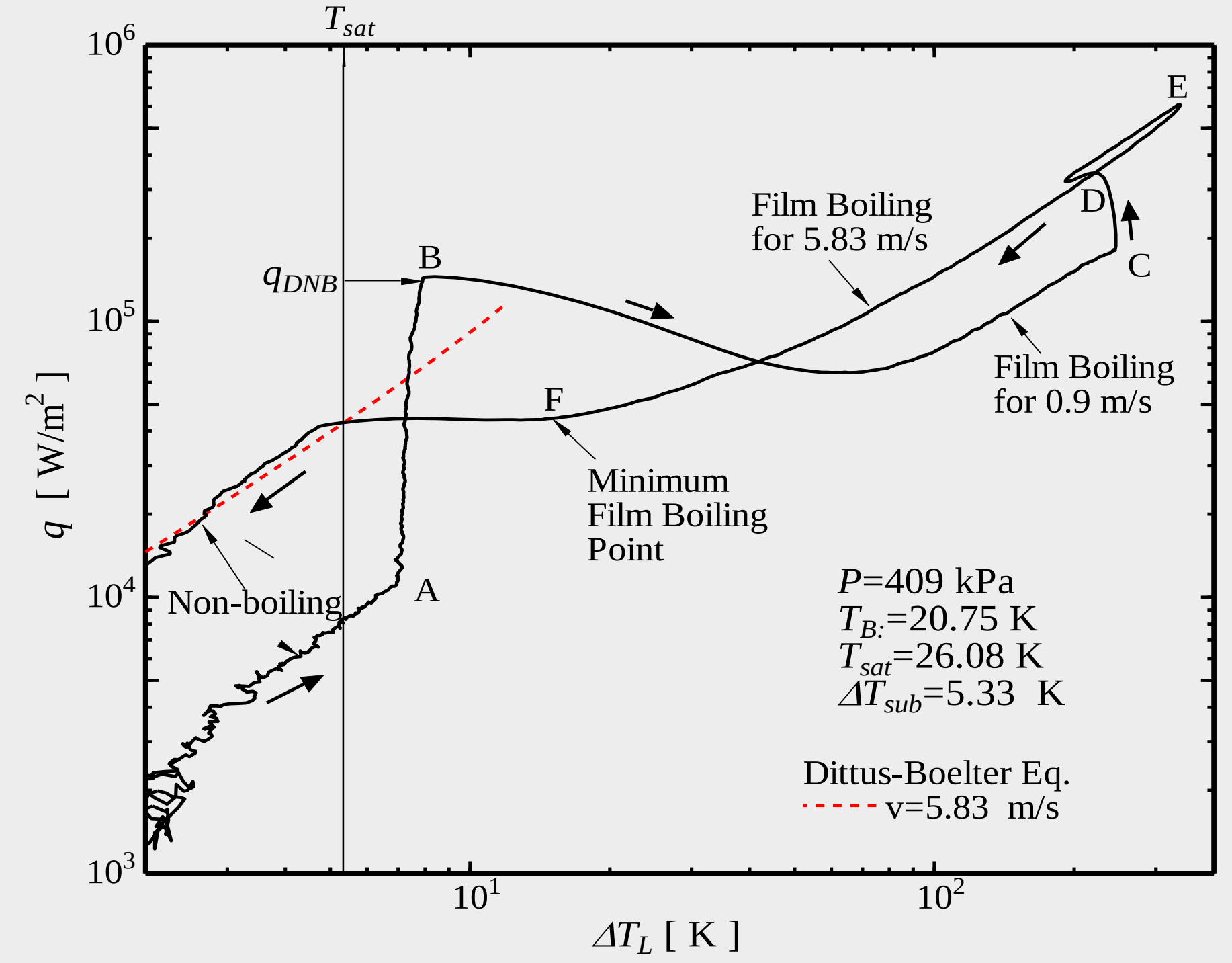
- **The mass flow rate is estimated by the weight change of the main tank, which is put on a scale that can measure up to 400 kg within 0.002 kg resolution.**
- **The test heater was heated electrically by using a direct current source (max. 400 A at a power level of 4.8 kW).**
- **Average temperature of the test heater was measured by resistance thermometry.**
- **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.**

Liquid Hydrogen Experiments
Pressure: 400 kPa, saturated condition,
subcooling 5 K
700 kPa, saturated condition,
subcooling 8 K
1100 kPa, saturated condition,
subcooling 11 K

Liquid Nitrogen Experiments
Pressure: 550 kPa, subcooling 16 K
Pressure: 1000 kPa, subcooling 25 K

RESULTS AND DISCUSSION

Typical Heat Transfer Processes

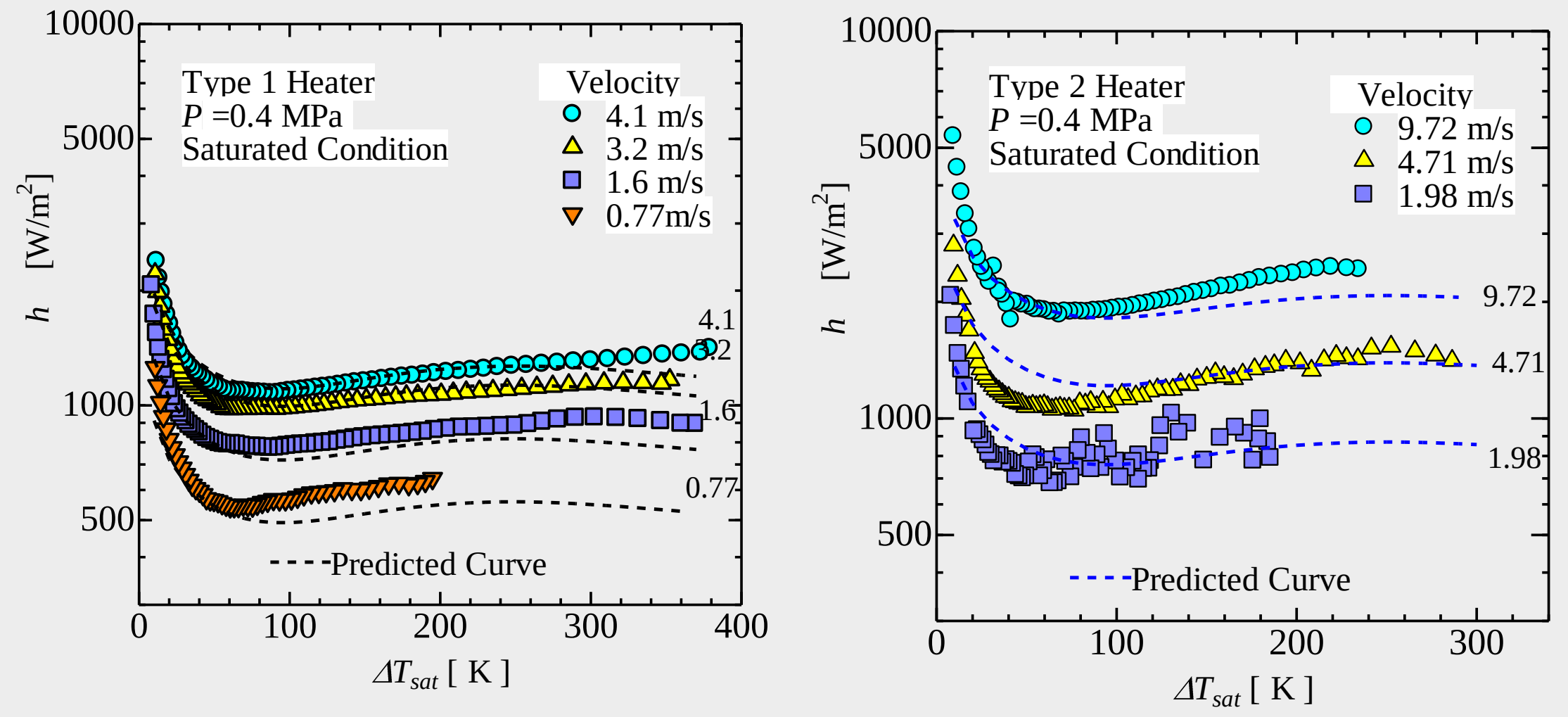


Heat transfer process to measure film boiling heat transfer

- **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.**

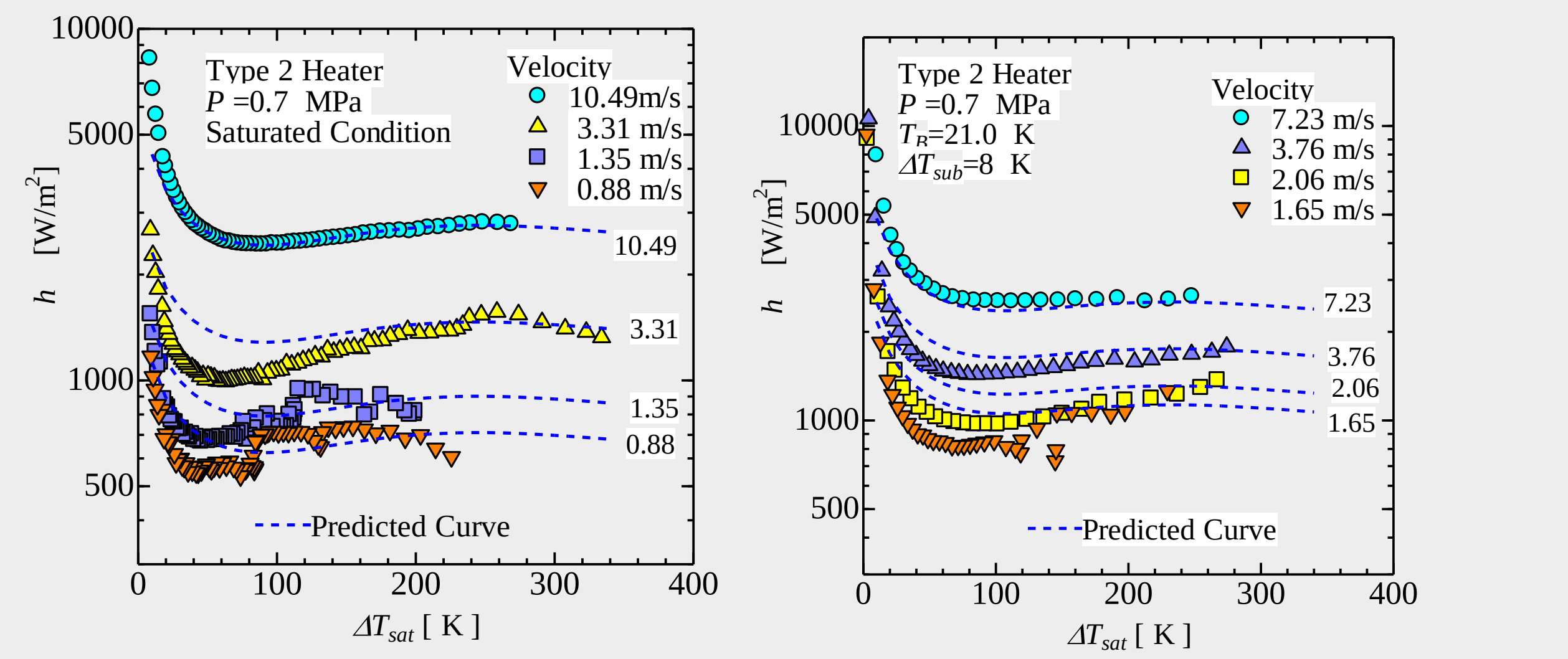
FILM BOILING HEAT TRANSFER COEFFICIENTS

Liquid Hydrogen Results



Comparison of the film boiling heat transfer coefficients for Type 1 with those for Type 2 at *P*=0.4 MPa under saturated condition.

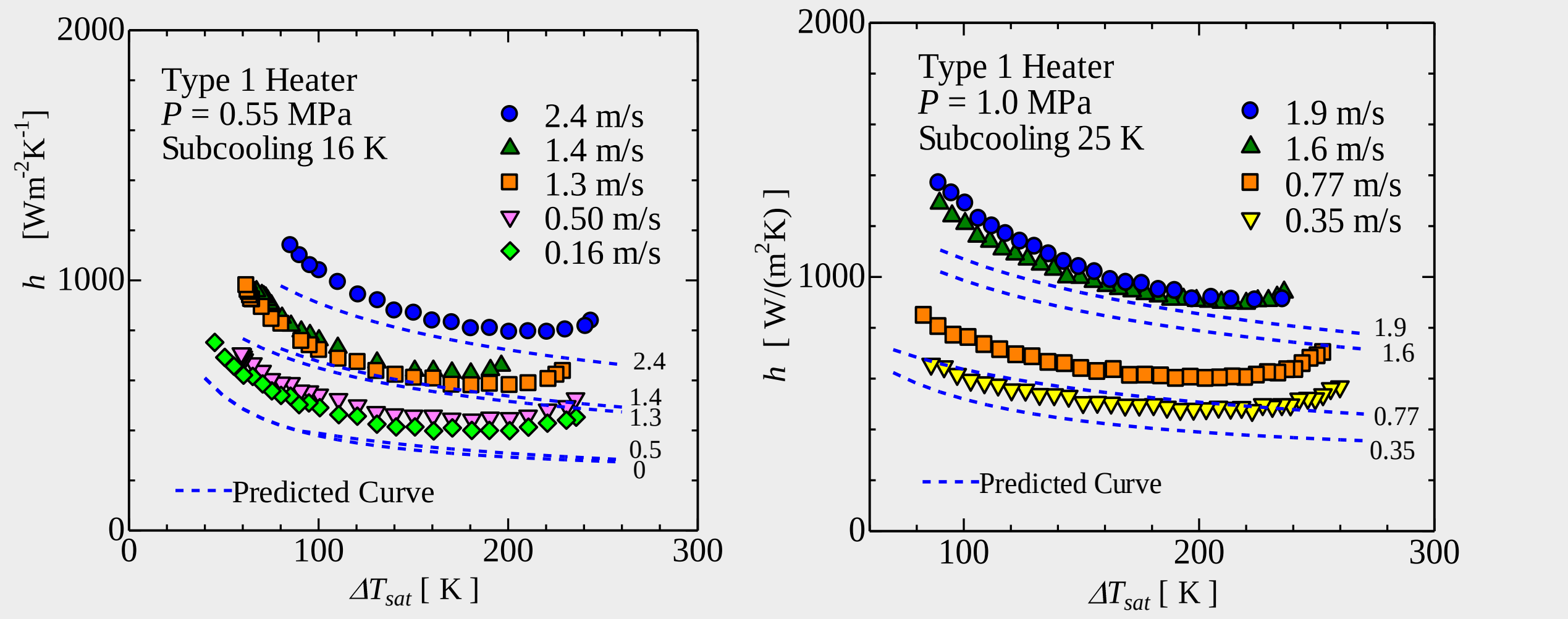
- **The length *L* and the equivalent diameter D_e of the Type 2 heater are about 1.67 times and 0.56 times as long as those of Type 1, respectively.**
- **The heat transfer coefficients for the Type 1 and Type 2 heaters for nearly the same velocities are almost the same. Namely the heat transfer coefficients are higher for shorter length and equivalent diameter.**



Film boiling heat transfer coefficient for the Type 2 heater at *P*=0.7 MPa and liquid subcooling of 0 K and 8 K with flow velocity as a parameter.

- **The heat transfer coefficients are higher for higher pressure and liquid subcooling.**

Liquid Nitrogen Results



As the viscosity of liquid nitrogen is about 15 times higher than liquid hydrogen, maximum flow velocity attained for the Type 2 test heater is far lower than that for liquid hydrogen.

FILM BOILING CORRELATION

By introducing the equivalent diameter *De* to express the gap effect, we have derived the following equation by extending the Shiotsu-Hama equation based on the experimental data of hydrogen and nitrogen obtained in this work.

$$\overline{Nu_{D_e}} = 0.63\left(zD_e^{-1}\right)^{-1/4} Re_{D_e}^{0.55}(\mu_l \mu_v^{-1}) M^{-1/3} F_p \qquad \text{for} \quad Re_{D_e} \geq F_v \qquad (1)$$

where

$$M = (SpR^{-2})[1+\{E_2(2\,\mathrm{Pr}_l\,Sp)^{-1}\}][1-0.7ScE_2^{-1}] \qquad (2)$$

$$F_p = 1.0 + 0.7(PP_{cr}^{-1})^{0.9} \qquad (3)$$

***E_2* is a positive root of the following equation**

$$E_2^3 + (5\,\mathrm{Pr}_l\,S_p - S_c)E_2^2 - 5\,\mathrm{Pr}_l\,S_p S_c E_2 - 7.5\,\mathrm{Pr}_l^2\,S_p^2 R^2 = 0 \qquad (4)$$

$$\overline{Nu_{D_e}} = 0.52\left(z^{-1}D_e\right)\left[z\{g(\rho_l-\rho_v)\sigma^{-1}\}^{1/2}\right]^{1/4} M_z^{1/4} \qquad \text{for} \quad Re_{D_e} < F_v \qquad (5)$$

where

$$M_z = [Gr_z Sp^{-1}]\left[E^3\{1+E(Sp\,\mathrm{Pr}_l)^{-1}\}^{-1}\right](R\,\mathrm{Pr}_l\,Sp)^{-2} \qquad (6)$$

$$E = \left(A+CB^{1/2}\right)^{1/3} + \left(A-CB^{1/2}\right)^{1/3} + (1/3)Sc^* \qquad (7)$$

$$A = (1/27)Sc^{*3} + (1/3)R^2 Sp\,\mathrm{Pr}_l\,Sc^* + (1/4)R^2 Sp^2\,\mathrm{Pr}_l^2 \qquad (8)$$

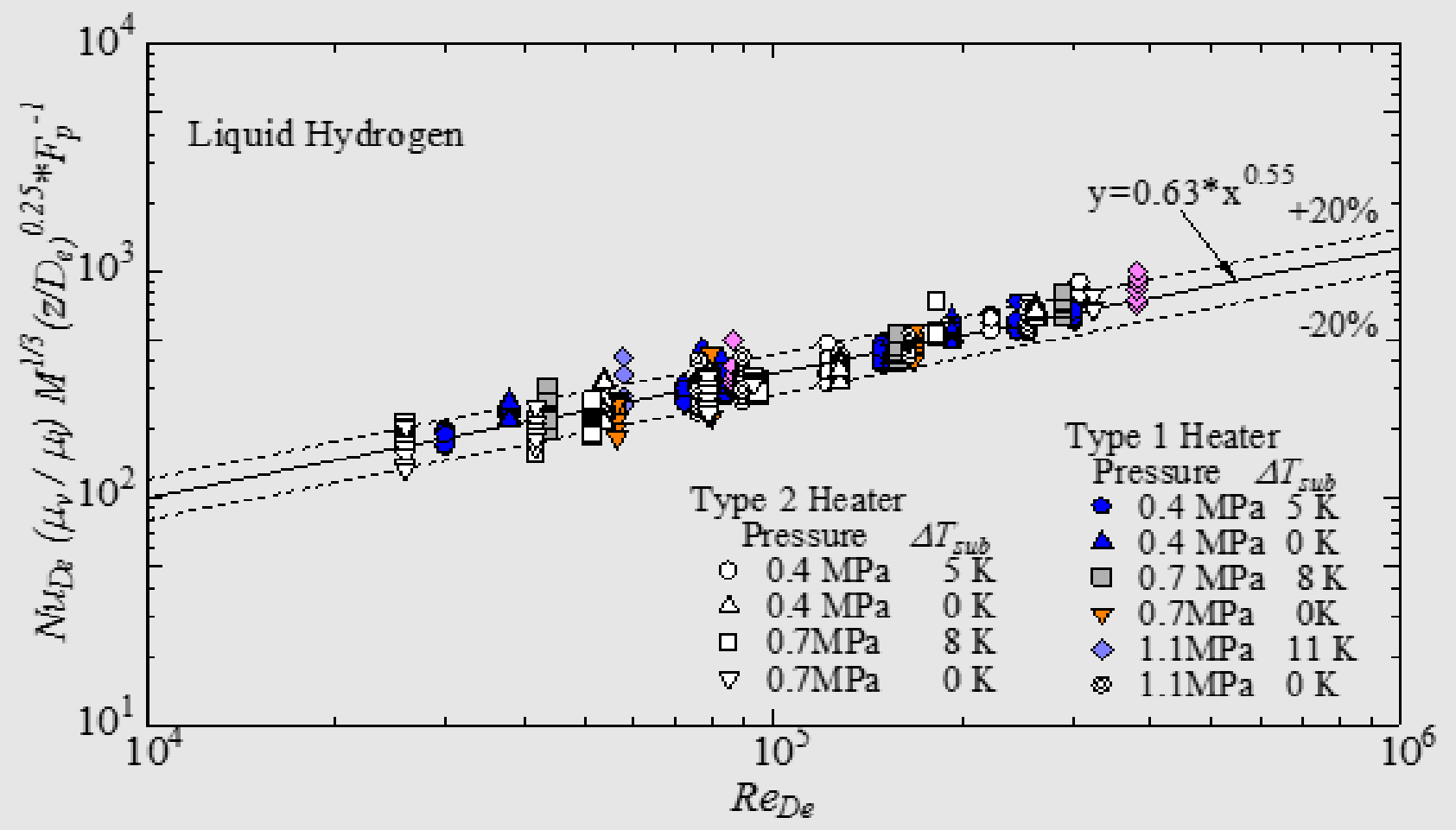
$$B = (-4/27)Sc^{*2} + (2/3)Sp\,\mathrm{Pr}_l\,Sc^* - (32/27)Sp\,\mathrm{Pr}_l\,R^2 + (1/4)Sp^2\,\mathrm{Pr}_l^2 + (2/27)Sc^{*3}/R^2 \qquad (9)$$

$$C = 0.5R^2 Sp\mathrm{Pr}_l \qquad (10)$$

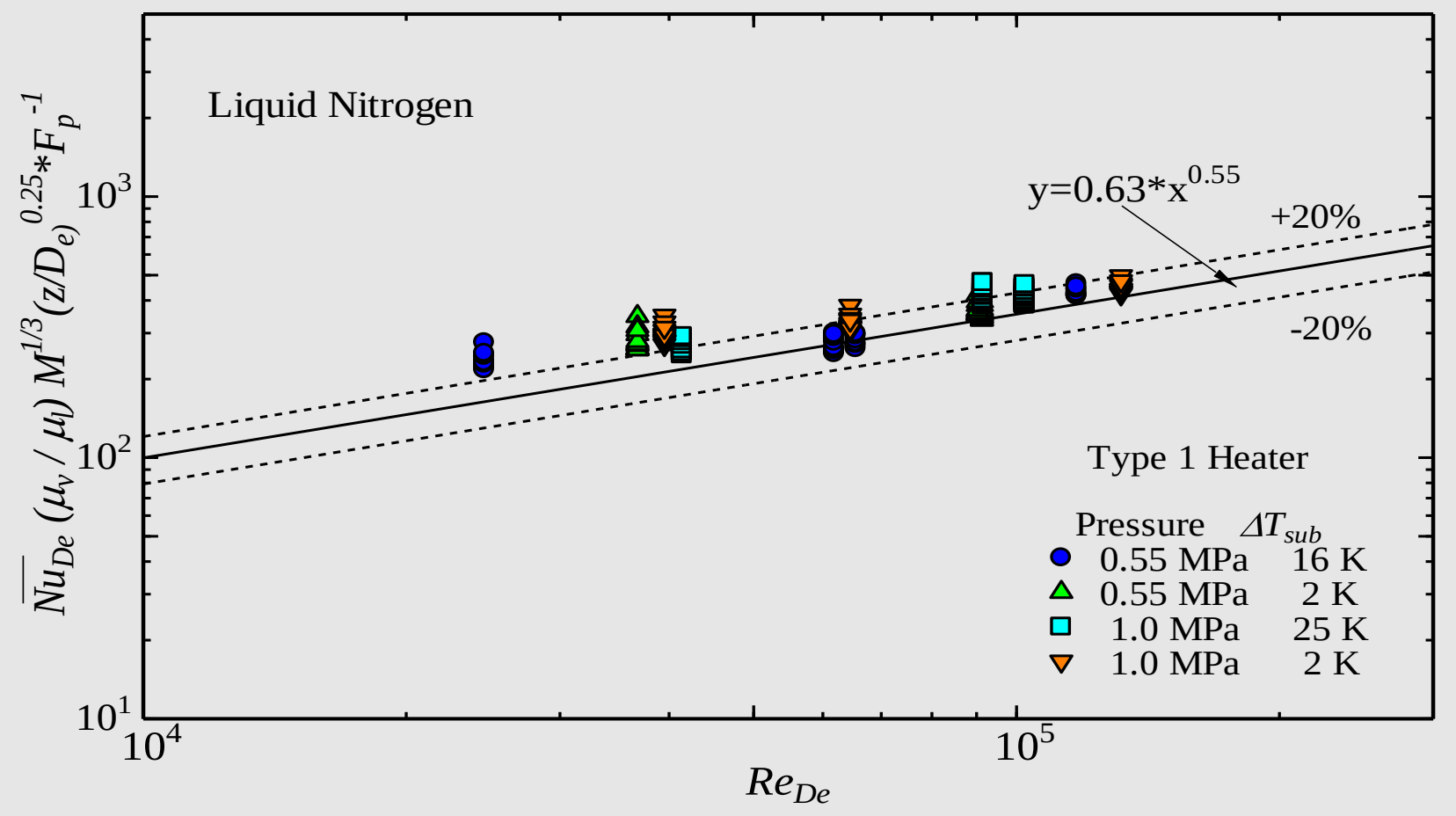
$$Sc^* = 0.93\,\mathrm{Pr}_l^{0.22}\,Sc \qquad (11)$$

$$F_v = 0.71(z^{-1}D_e)^{1.364}\left[z\{g(\rho_l-\rho_v)\sigma^{-1}\}^{1/2}\right]^{0.455} M_z^{0.455}\left(\mu_v \mu_l^{-1}\right)^{1.818} M^{0.606} F_p^{-1.818} \qquad (12)$$

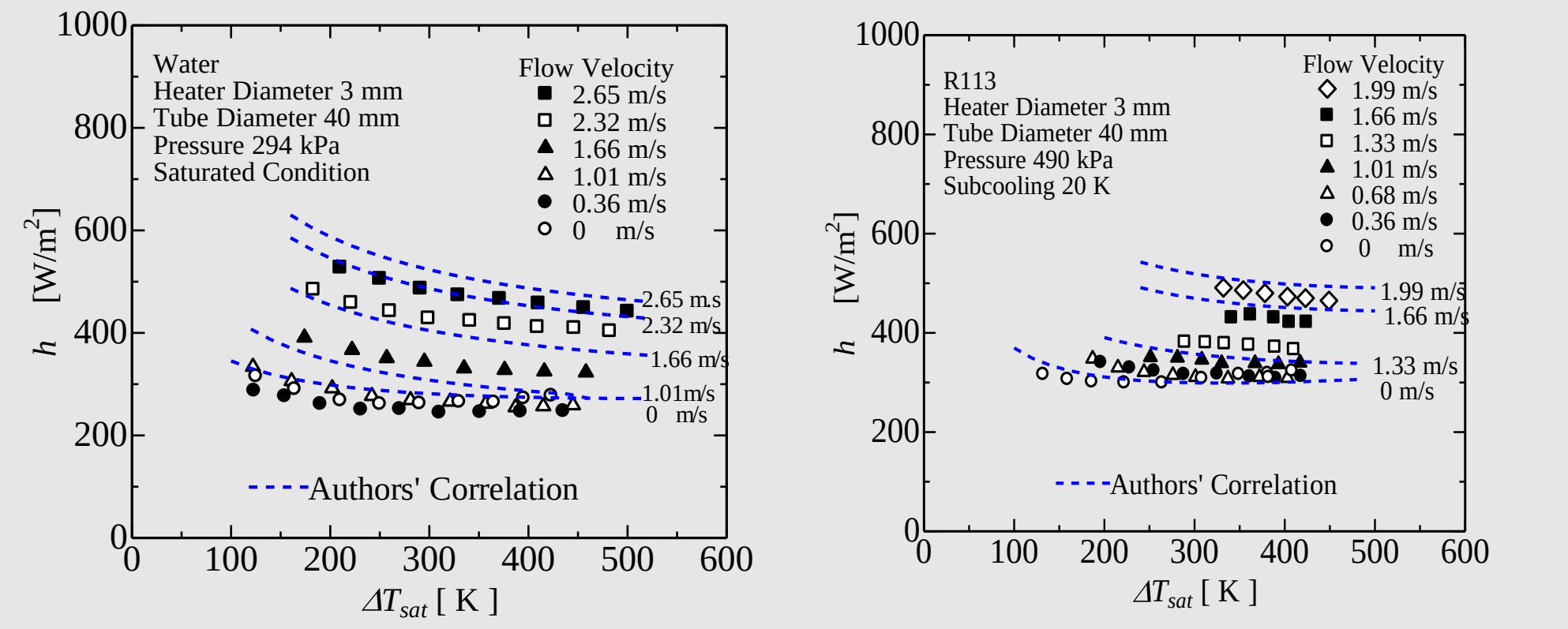
Comparison with the Experimental Data



Comparison of all the experimental data of liquid hydrogen with the new correlation.



Comparison of all the experimental data of liquid nitrogen with the new correlation.



Comparison of water and R113 data [2] for *L*=180 mm, D_e=37 mm with the new correlation.

CONCLUSIONS

Film boiling heat transfer coefficients were measured for the two types of heater blocks with the same diameter of the heater wire and different heater lengths and gaps of the conduit. Experimental results lead to the following conclusion.

- **The heat transfer coefficients are higher for higher pressure, subcooling and higher flow velocity.**
- **The heat transfer coefficients for the Type 1 and Type 2 heaters for nearly the same flow velocities are almost the same, though the length *L* and equivalent diameter D_e of the Type 2 heaters are about 1.7 times and 0.56 times as long as those of Type 1, respectively.**
- **We have assumed that the vapor film layer around the heater wire would be made thinner by a very narrow gap. A new correlation was presented by extending the Shiotsu-Hama equation by introducing D_e to express the gap effect.**
- **The experimental data of liquid hydrogen and liquid nitrogen are expressed well by the new correlation.**
- **It can be expected that this correlation can express forced flow film boiling heat transfer of cryogenic and non-cryogenic liquids for a round wire in conduits.**