Forced flow heat transfer from a round wire in a vertically-mounted pipe to supercritical hydrogen

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BACKGROUND

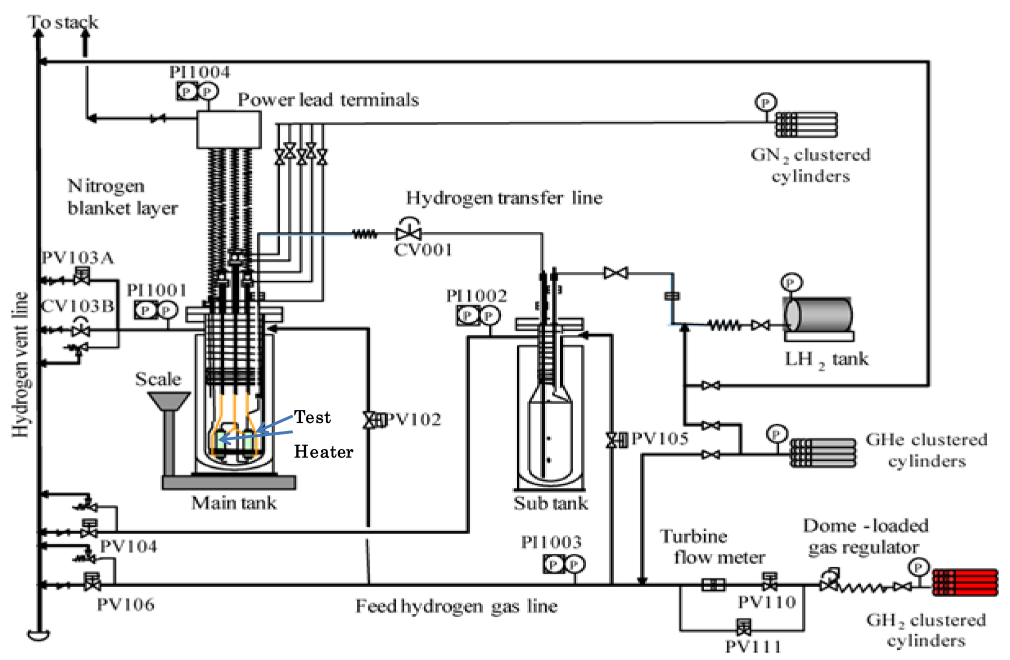
When a superconducting coil wound by cable in couduit conductor (CICC) is cooled by hydrogen under a supercritical pressure, an extraordinary heat at an accidental condition will be cooled smoothly without a jump to film boiling. For a design and safety evaluation of such a superconducting coil, experimental results of forced flow heat transfer under supercritical pressure with inlet fluid temperature lower than the critical temperature is necessary.

INTRODUCTION

Shiotsu et al. [3] studied the heat transfer from inner wall of a vertical tube to forced flow of low temperature hydrogen under supercritical pressures for the test tubes with various inner diameters and lengths. Their experimental results were compared with the equation of forced flow heat transfer under supercritical pressures presented beforehand [4] based on experimental data of helium and conventional data for non-cryogenic fluids. It was confirmed that the equation can be applicable to forced flow of hydrogen in heated tubes with wide ranges of diameter and length.

In case of CICC, heat is transferred not from inner side of a tube but from a round wire to outer flowing fluid. The purpose of this study is firstly to obtain the experimental data of forced convection heat transfer from a round wire to supercritical hydrogen, and secondly to confirm the applicability of the equation with the use of equivalent diameter.

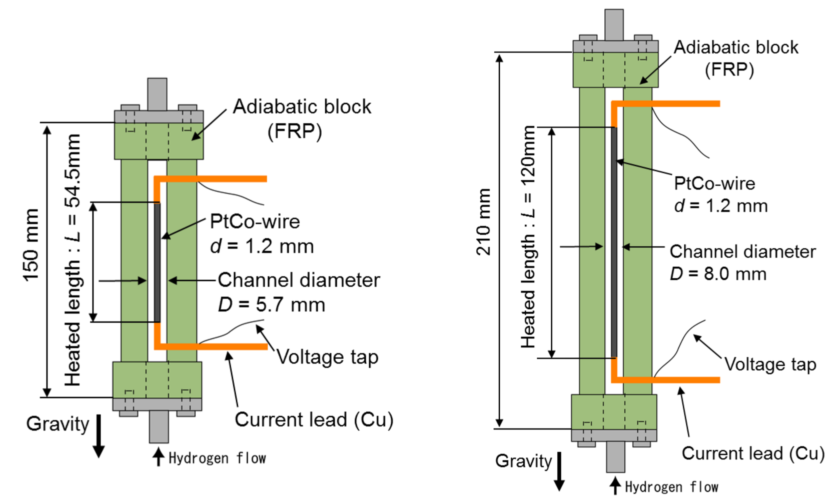
EXPERIMENTAL APPARATUS AND METHODS



- 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.

Experimental Condition

Pressure: 1.5 MPa
Inlet temperature: 21 K
Flow velocity: 0.7 to 12.6 m/s
Test heaters blocks:
Type 1 : PtCo wire 1.2 mm dia, 120 mm long in 8 mm dia. conduit
Type 2 : PtCo wire 1.2 mm dia., 200 mm long in 5 mm dia. conduit

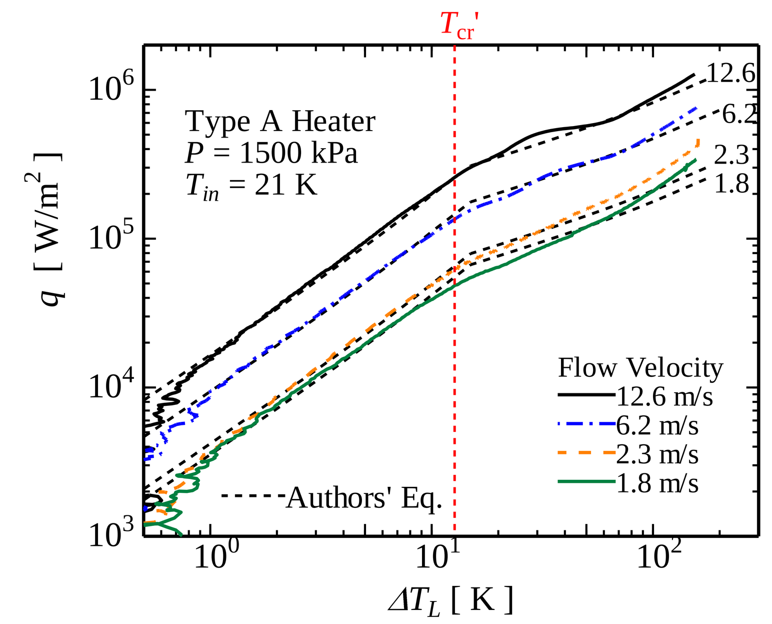


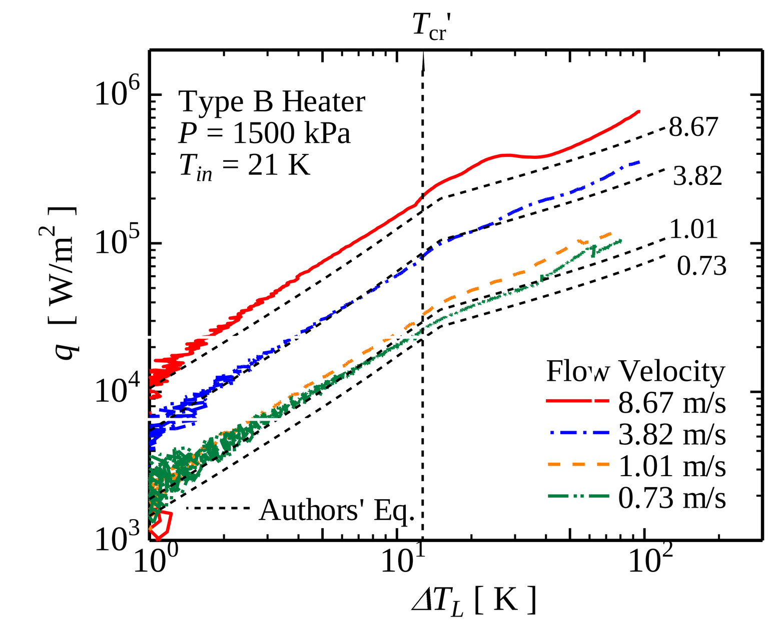
Type A Type B

Schematic of test heater blocks.

RESULTS AND DISCUSSION

Typical Heat Transfer Curves

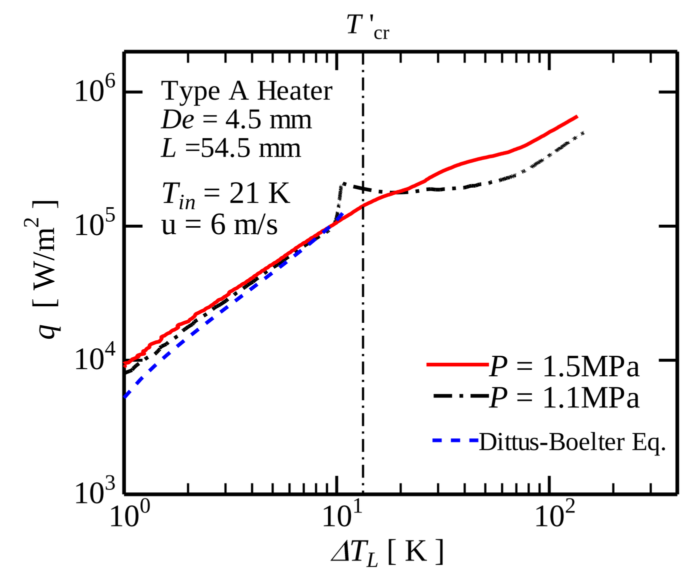


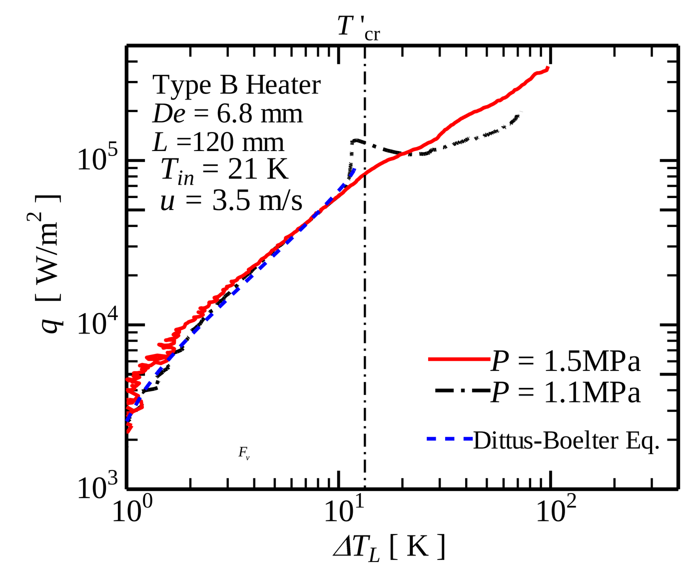


- The heat transfer curve for each flow velocity consists of a region with a higher gradient and that with a lower gradient.
- The highest temperature limit of the former region is slightly higher than T'_{cr}.
- Heat transfer curve tends to oscillate and becomes better at the ΔT_L of approximately 100 K.

- Thermo-physical properties of fluids remarkably change for the fluid temperature higher than T'_{cr}.
- Thermal boundary layer with $T > T'_{cr}$ would graw near the inner surface of the test wire. The growth of the boundary layer would be the cause of the degradation of heat transfer.

Comparison of the Heat Transfer under Supercritical Pressure with that under a Pressure Lower than P_{cr}





Typical heat transfer curve of super-critical hydrogen for the Type A (upper) and Type B (lower) heater in comparison with those under below critical pressure.

- The boiling curve with the same flow velocity at the pressure of 1.1 MPa, which is slightly lower than P_{cr}, are shown in comparison with the those under supercritical pressure, 1.5 MPa.
- In the region where ΔT_L is lower than the pseudo-critical temperature T'_{cr}, the heat flux at supercritical pressure increases with an increase of heat input along with the curve predicted by Dittus-Boelter equation. It agrees well with that under below criitical pressure.
- In the regions where ΔT_L is higher than T'_{cr}, the heat flux at supercritical pressure is higher than that at below critical pressure

HEAT TRANSFER CORRELATION

We have already presented the following correlation which consists of the Dittus-Boelter equation with a correction factor F_c to express the degradation of heat transfer due to the growth of thermal boundary layer.

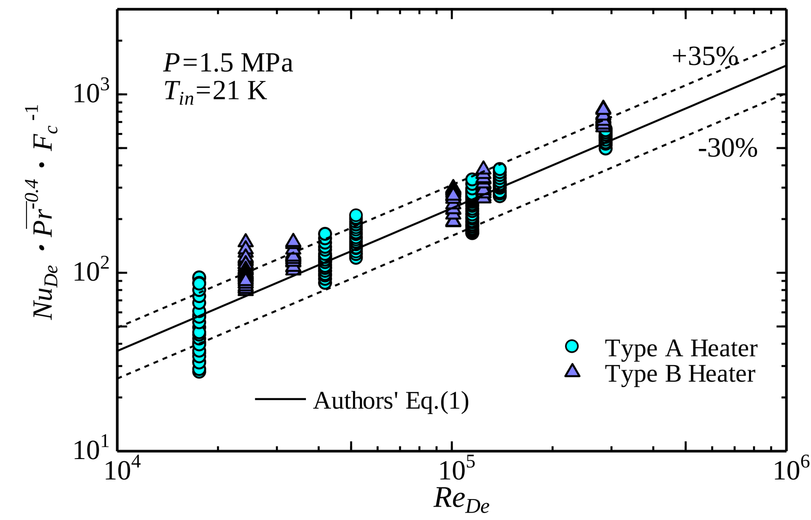
$$Nu_{De} = 0.023 Re_{De}^{0.8}\,\overline{Pr}^{0.4} F_c \qquad (1)$$

$$F_c = [1.0 + 108.7(L/D_e)^{-2}]^{0.25}[1 + 0.002(\Delta T_L / T'_{cr})] \times (\rho_w/\rho_{in})^{0.34}(\mu_{in}/\mu_w)^{0.17} \qquad (2)$$

where

$\overline{Pr} = \overline{c_p}\mu_{in}/\lambda_{in}$, $\overline{c_p} = (h_w - h_{in})/(T_w - T_{in})$, D_e: equivalent diameter, L: heated length, h: enthalpy, ρ: density, μ: viscosity, subscripts w and in mean at wall and inlet.

To see the applicability of our correlation, all the experimental data are shown on $Nu_{De} \cdot \overline{Pr}^{-0.4} \cdot F_c^{-1}$ vs. R_eD_e graph in comparison with the equation (1). These data are for the Reynolds numbers ranging from about 1.8×10^4 to 2.9×10^5. Most of the data are within +35 % and -30 % of the equation. Though the error band is relatively wide due to the fluctuation, this correlation would be useful for a cooling design of HTC systems where relatively low temperature range is important.



Comparison of the correlation with the experimental data.

CONCLUSIONS

- The heat transfer coefficients are higher for higher flow velocity. The heat transfer curve for each flow velocity consists of a region with a higher gradient and that with a lower gradient. The highest temperature limit of the former region is slightly higher than T'_{cr} of the fluid at the pressure.
- The heat transfer in the former region agrees well with the Dittus-Boelter equation and becomes lower than the equation with further increase in wall temperature.
- The experimental results were compared with the authors' equation of forced flow heat transfer under supercritical pressures. Mostl of the data for Re_{De} from 1.8×10^4 to 2.9×10^5 are within +35 % and -30 % of the equation.
- It was confirmed that the equation can be applicable for a central wire heater in a conduit. This would be useful for a cooling design of HTC systems where relatively low temperature range is important.