Transient heat transfer from a wire inserted into a vertically-mounted pipe to a forced flow of liquid hydrogen.

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ABSTRACT

Transient heat transfer from a PtCo wire heater inserted into a vertically- mounted pipe to forced flow of subcooled liquid hydrogen was measured by increasing exponential heat inputs with various periods at the pressure of 0.7 MPa and the inlet temperature of 21 K. The flow velocities are 0.8 to 5.5 m/s. For shorter period, the non-boiling heat transfer becomes higher than Dittus-Boelter equation due to the transient conductive heat transfer contribution and the transient CHF (critical heat flux) becomes higher than steady-state CHF. Effect of the flow velocity and period on the transient CHF heat flux was also clarified..

INTRODUCTION

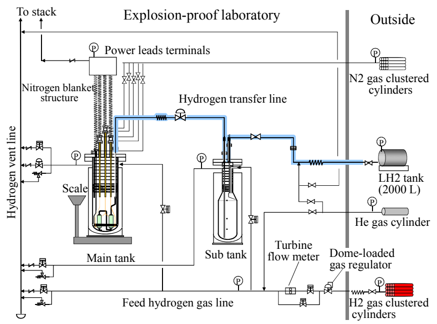
Liquid hydrogen is expected as a coolant for high-*Tc* superconductors because of its boiling point lower than that of liquid nitrogen, high thermal conductivity, large specific heat and low viscosity. It is important for its cooling design and its stability estimation for a quench to understand the transient heat transfer in forced flow of liquid hydrogen as well as steady state one. Coeling et al. [1] measured natural convection heat transfer from a flat disk plate to saturated liquid hydrogen and can be expressed by conventional correlations. Bewilogua et al. [2] measured the critical heat fluxes on a horizontal flat disc plate in a pool of several cryogenic liquids including hydrogen below its critical pressure. They reported that the best coefficient in Kutateladze's correlation was determined to be 0.16 based on their experimental data.

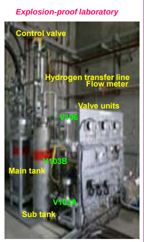
Tatsumoto et al. [3] developed a thermal-hydraulics experimental system for liquid hydrogen in order to systematically investigate pool boiling and force convection heat transfer of liquid and supercritical hydrogen. Shiotsu et al. [4] studied transient heat transfer from a horizontal flat plate in a pool of liquid hydrogen. They reported that no direct transition from non-boiling to film boiling was observed unlike liquid nitrogen. Tatsumoto et al. [5] measured forced convection heat transfer of saturated liquid hydrogen in tubes and derived a correlation of DNB (departure from nucleate boiling) heat flux based on the experimental results.

In this study,

Transient heat transfer from a wire inserted into a vertically-mounted pipe to forced flow of subcooled liquid hydrogen is measured with an exponential increase of the heat generation rate at a pressure of 0.7 MPa to clarify the effect of the heating rate and the flow rate on the transient CHF, q_{cr}.

THERMAL-HYDRAULIC EXPERIMENTAL SYSTEM





Main Tank

- Design pressure : 2.0 MPa
- Maximum hydrogen inventory: 50 L.
- Liquid hydrogen level : weight change of the tank measured by a scale.(max:400 kg 0.002 kg resolution.)
- Pressure control: Pressurized by pure H2 gas controlled by a dome-loaded regulator.
- Temperature control: Sheathed heater (500 W).
- For explosion protection,
  Power cables are covered with nitrogen gas.(the pressure is maintained to be 105 kPa.)

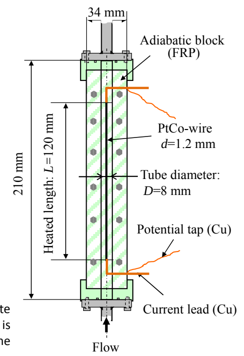
Sub Tank

- Design pressure : 2.0 MPa
- Hydrogen inventory: 60 L larger than that of main tank.
- Liquid hydrogen level: three thermocouples (type T)

- ***Forced flow is produced by the pressure difference between the tanks and the valve opening.***
- ***The mass flow rate is estimated by the weight change and the feed hydrogen gas flow rate, which is measured by a turbine flow meter.***
- ***It is confirmed that flow measurement error is estimated to be within 0.1 g/s .***

TEST HEATER

- Wire heater: made of Pt-Co alloy
  Diameter (d) of 1.2 mm heated length (l) of 120 mm.
- Wire heater is located on the central axis of the pipe with a diameter (d_p) of 8mm and a length of 210 mm, which is made of a Fiber-Reinforced Plastic (FRP)
- Entrance lengths of the pipe heaters are set to be more than ten times longer than hydraulic equivalent diameter (D).
  - ➡ This is because the flow velocities used in this study correspond to Reynolds number, Re, higher than 1.0 x10^4 and can be regarded as turbulent flow.
- The channel with the wire heater is vertically mounted in the cryostat and the liquid hydrogen flows upward through it.



How to heating

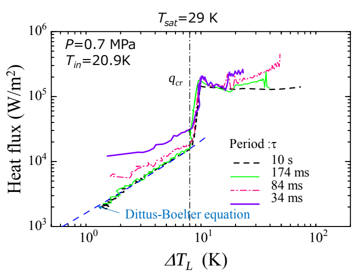
- Exponential heat generation of $Q = Q_0 e^{t/\tau}$ with the period τ of 19 ms to 10.0 s
- The input signal of the power amplifier is controlled so that the heat generation rate of the test heater agrees with a desired value. The heating current to the heater is supplied by a power amplifier, which can supply a direct current up to 400 A at the power level of 4.8 kW.

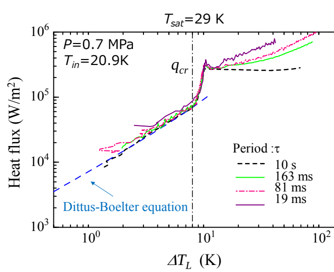
How to measuring heat transfer

- Average temperature of the heater is measured by resistance thermometry using a double-bridge circuit.
- Heat generation rate in the heater is calculated from the measured voltage drops across the heater and the standard resistance.
- Surface heat flux, q, is the difference between the heat generation rate and the time rate of change of energy storage in the heater.
- Average surface temperature of the heater, T_w, is calculated from the average temperature and the surface heat flux by solving a conduction equation in the radius direction of the tube.

Transient heat transfer from the wire located on the center axis of the vertically-mounted tube to forced flow of subcooled liquid hydrogen at the pressure of 0.7 MPa and a inlet temperature of 20.9 K was measured by exponentially increasing heat input, $Q_0 exp(t/\tau)$. The exponential period of the heat input was changed from 10.0 s to 19 ms.

TRANSIENT HEAT TRANSFER CHARACTERISTICS IN FORCED FLOW OF SUBCOOLED LIQUID HYDROGEN





- Non boiling heat transfer
  - For relatively slow heating, it agrees with Dittus-Boelter equation.
  - With decrease in τ, the non-boiling heat transfer becomes higher than Dittus-Boelter equation because of the transient conductive heat transfer contribution, which appears for shorter τ with increase in flow velocity..
- Nucleate boiling
  - With relatively little increase in ΔT_L, the heat flux steeply increases up to a certain upper limit heat flux of the nucleate boiling, which is called a critical heat flux (CHF).
  - Transient nucleate boiling heat transfer is almost unaffected by the period of the exponential heating.
  - The transient CHFs become higher for shorter τ.
- Transient critical heat flux: q_{cr}
  - Transient CHFs become higher for shorter τ.

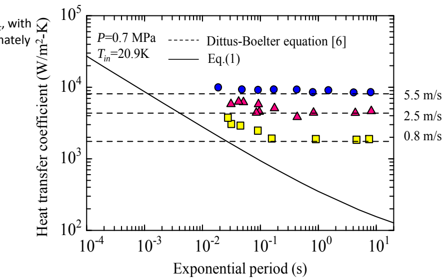
TRANSIENT NON-BOILING HEAT TRANSFER

- Transient conductive heat transfer coefficients, h_c, with exponential heat generation, $Q_0 \exp(t/\tau)$, is approximately given as follows.

$$h_c = \left(\frac{k\rho C_p}{\tau}\right)^{0.5} \frac{K_1(\mu d/2)}{K_2(\mu d/2)} \quad (1)$$

$$\mu = \left(\frac{\rho C_p}{k\tau}\right)^{0.5} \quad (2)$$

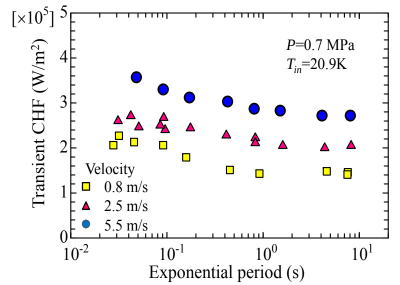
k : thermal conductivity
ρ : density
C_p : specific heat.
Subscript of l : liquid.
K_1 and K_0 : modified Bessel functions of the second kind of zero and first orders.



- For long τ, the non-boiling heat transfer coefficients agree with those for steady-state, which are predicted by Dittus-Boelter equation.
- For shorter τ, it appears that it becomes higher and approaches to the curve by Eq.(1).
- For higher flow velocity, that for steady-state becomes larger and the transient conductive heat transfer contribution appears at shorter τ.

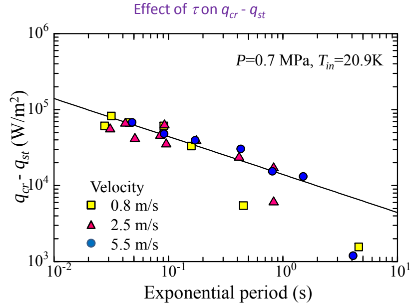
TRANSIENT CRITICAL HEAT FLUX

Transient CHF by the exponential heating



- For flow velocity of 0.8 m/s, the transient CHFs almost agree with steady-state CHF, q_{st}, for τ > 0.92 s.
- For τ < 0.92 s, it becomes larger than q_{st}.
- For v =2.5 m/s and v = 5.5 m/s, transient CHFs become higher than q_{st} for τ < 2 s and τ < 5 s, respectively.
- For higher flow velocity, the enhancement of the CHF caused by the exponential heating appears for longer τ.
- It seems that the increasing rate of q_{cr} from q_{st} is the same independent of the flow velocity.

Effect of τ on q_{cr} - q_{st}



- It is found that the measured values of q_{cr} - q_{st} exist on the same curve with the gradient of -0.5 independent of v, although q_{cr} for longer τ agrees with q_{st} that depends on v.

CONCLUSIONS

The transient heat transfer from a wire inserted into a vertically-mounted pipe to forced flow of subcooled liquid hydrogen are measured by increasing exponential heat inputs for various flow rates at a pressure of 0.7 MPa and the inlet temperature of 21 K, which corresponds to the subcooling of 8 K. The experimental results lead to the following conclusions.

- For relatively slow heating (τ > 1 s), the non-boiling heat transfer agrees with that for the steady-state, which is predicted by Dittus-Boelter equation. For faster exponential heating (shorter τ), it becomes higher due to the transient conductive heat transfer contribution. For higher flow velocity, it becomes larger and the transient conductive heat transfer contribution appears for shorter τ.
- The transient nucleate boiling heat transfer is almost unaffected by τ. The transient CHF becomes larger than q_{st} for shorter τ. For higher flow velocity, the enhancement of the CHF caused by the exponential heating appears for longer τ. It is found that the increase in the transient CHF from the steady-state CHF can be expressed by the same curve with $\tau^{-0.5}$ independent of the flow velocity.