Transient heat transfer from a wire to a forced flow of subcooled liquid hydrogen passing through a vertically-mounted pipe.

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ABSTRACT

Transient heat transfers from Pt–Co wire heaters inserted into vertically-mounted pipes, through which forced flow subcooled liquid hydrogen was passed, were measured by increasing the exponential heat input with various time periods at a pressure of 0.7 MPa and inlet temperature of 21 K. The flow velocities ranged from 0.3 to 7 m/s. The Pt–Co wire heaters had a diameter of 1.2 mm and lengths of 60 mm, 120 mm and 200 mm and were inserted into the pipes with diameters of 5.7mm, 8.0 mm, and 5.0 mm, respectively, which were made of Fiber reinforced plastic due to thermal insulation. With increase in the heat flux to the onset of nucleate boiling, surface temperature increased along the curve predicted by the Dittus-Boelter correlation for longer period, where it can be almost regarded as steady-state. For shorter period, the heat transfer became higher than the Dittus-Boelter correlation. In nucleate boiling regime, the heat flux steeply increased to the transient DNB (departure from nucleate boiling) heat flux, which became higher for shorter period. Effect of flow velocity, period, and heated geometry on the transient DNB heat flux was clarified.

INTRODUCTION

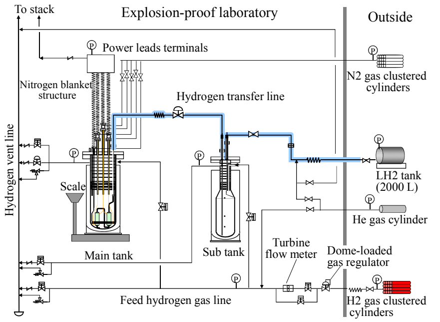
Liquid hydrogen is expected as a coolant for high-T_c superconducting devices because of its boiling point lower than that of liquid nitrogen, higher thermal conductivity, greater specific heat and low viscosity. The knowledge of transient heat transfer to liquid hydrogen in forced flow is necessary for its cooling design and stability during a quench. There has been a lack of systematic experimental data on forced-flow liquid hydrogen, although several workers investigated pool boiling heat transfer of liquid hydrogen [1-5].

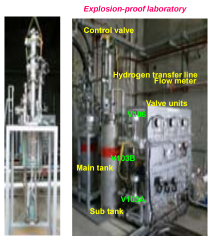
Tatsumoto et al. [6] developed a thermal-hydraulics experimental system for liquid hydrogen to conduct a systematic investigation of the forced-convection heat transfer of liquid hydrogen. They studied steady-state pool boiling [7,8] and forced convection heat transfer of saturated and subcooled liquid hydrogen [9-11]. Shiotsu et al. [12] studied transient heat transfer from a horizontal flat plate in a pool of liquid hydrogen. They reported that, unlike with liquid nitrogen, no direct transition from non-boiling to film boiling was observed. Tatsumoto et al. [13] measured a transient heat transfer from a wire, inserted into a vertically mounted pipe, to a forced flow of subcooled liquid hydrogen with an exponential increase in the heat generation rate at a pressure of 0.7 MPa. They reported that there was no direct transition in forced flow of liquid hydrogen as well as for pool boiling.

In this study,

We measure the transient heat transfer from heated wires with various lengths that were inserted into vertically mounted pipes with various diameters to a forced flow of subcooled liquid hydrogen at a pressure of 0.7 MPa and inlet temperature of 21 K with an exponential increase in the heat generation rate, to clarify the effect of the heating, flow rates, and flow channel geometries on the transient critical heat flux (CHF).

THERMAL-HYDRAULIC EXPERIMENTAL SYSTEM





Main Tank

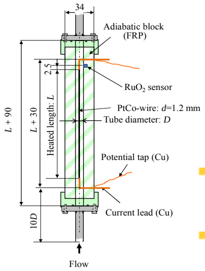
- Design pressure : 2.0 MPa
- Maximum hydrogen inventory: 50 L.
- Liquid hydrogen level : weight change of the tank measured by a scale.(max:400 kg 0.002 kg resolution.)
- Pressure control: Pressurized by pure H2 gas controlled by a dome-loaded regulator.
- Temperature control: Sheathed heater (500 W).
- 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



D_e :hydraulic equivalent diameter
D_h :equivalent heated diameter

No.	d	L	D	D_e	D_h	L/D_e	L/D_h
1	1.2	60	5.7	4.5	25.9	13.3	2.3
2	1.2	120	8.0	6.8	52.1	17.6	2.3
3	1.2	200	5.0	3.8	19.6	52.6	10.2

- Entrance lengths of the pipe heaters are set to be more than ten times longer than hydraulic equivalent diameter.
  - 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.

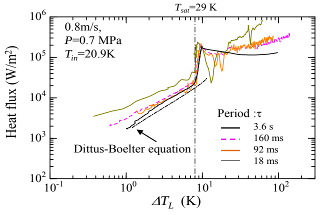
How to measuring heat transfer

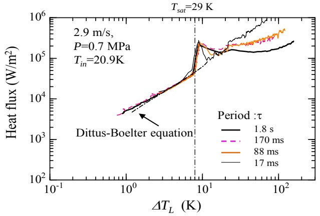
- Average temperature of the heater is measured by resistance thermometry using a double-bridge circuit.
- Heat generation rate in the heater is calculated from the measured voltage drops across the heater and the standard resistance.
- Surface heat flux, *q*, is the difference between the heat generation 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.

We measured the transient heat transfer from the wire located on the center axis of the vertically mounted pipes to the forced flow of the subcooled liquid hydrogen at a pressure of 0.7 and inlet temperature, T_{in}, of 20.9 K, by exponentially increasing the heat input, $Q_0 exp(t/t)$. The exponential periods of the heat input were changed from 10.0 s to 19 ms. The inlet temperature corresponds to a subcooling temperature of 8 K. The flow velocities changes from 0.3 m/s to 7 m/s.

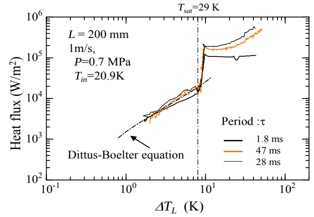
TRANSIENT HEAT TRANSFER CHARACTERISTICS IN FORCED FLOW OF SUBCOOLED LIQUID HYDROGEN

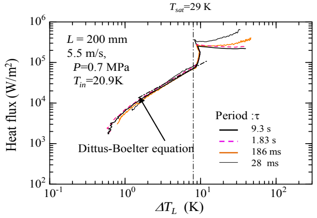
For *L* = 60 mm at 0.7 MPa under subcooled condition.





For *L* = 200 mm at 0.7 MPa under subcooled condition.





**Through the experimental data,
we confirmed that, unlike with liquid nitrogen, forced convection heat transfer of subcooled liquid hydrogen has no direct transition from non-boiling to film boiling for shorter *t* value as well as pool boiling of it.**

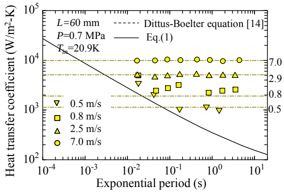
TRANSIENT NON-BOILING HEAT TRANSFER

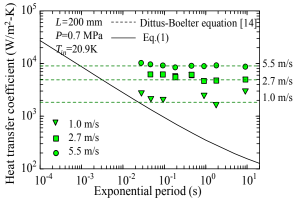
- Transient conductive heat transfer coefficients, h_c, with $Q_0\exp(t/\tau)$, is given as follows.

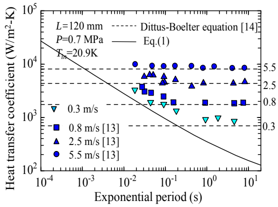
$$h_c = \left(\frac{k\rho C_p}{\tau}\right)^{0.5} \frac{K_1(\mu d/2)}{K_2(\mu d/2)} \quad (1)$$

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

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.





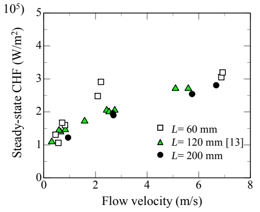


- For long τ values, the non-boiling heat transfer coefficients agree with those predicted by the Dittus-Boelter equation.
- For slow flow velocity, the heat transfer coefficient increases with a decrease in τ values due to the transient conductive heat transfer contribution,
- It seems that the effect would appear for even shorter τ values and the heat transfer coefficient is not affected by τ values in this experimental measurement range.

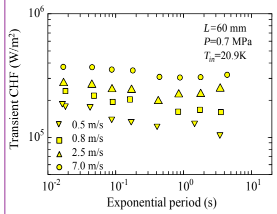
TRANSIENT CRITICAL HEAT FLUX

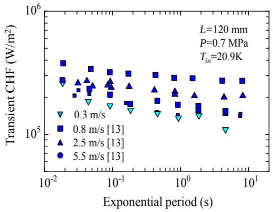
Steady-state CHF

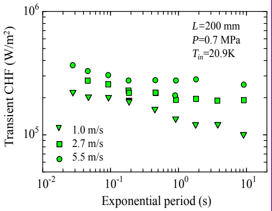
- The steady-state CHFs increase, with an increase in flow velocity.
- CHFS are higher for shorter *L* and smaller *D,* although the test heaters for *L* = 60 mm and 120 mm have the same aspect ratios *L/D*



Transient CHF

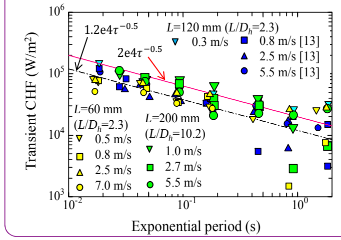






- For the flow velocities higher than 1.0 m/s, the transient CHFs are almost unaffected by *t* value for *t* > 2 s, and agree with the steady-state CHF.
- With a decrease in τ value from 2 s, the transient CHFs increase from q_{st}.

At flow velocity lower than 1 m/s, although the transient CHFs are slightly affected by exponential heating rate for τ > 2 s, they seem to approach the steady-state CHF.



- The values of $q_{cr} - q_{st}$ are independent of the flow velocity for the same wire heater, and increases along the same curve with the gradient of $\tau^{-0.5}$ with a decrease in τ.
- For the same L/D_h, it seems that they exist on the same curve, although the steady-state CHFs are different.
- For larger L/D_h, although the value of $q_{cr} - q_{st}$ is larger, they seem to exist on the curve with the same gradient of $\tau^{-0.5}$.

CONCLUSIONS

We measured the transient heat transfer from wires inserted into vertically-mounted pipes with various aspect ratios of L/D_h to forced flow of subcooled liquid hydrogen by increasing the exponential heat inputs. The flow rates were varied from 0.3 m/s to 7.0 m/s at a pressure of 0.7 MPa and inlet temperature of 21 K, which corresponds to a subcooling of 8 K. Experimental results lead to the following conclusions:

- For relatively slow heating, the non-boiling heat transfers agree well with the values predicted by the well-known Dittus–Boelter equation. In the nucleate boiling regime, with relatively little increase in DT_L, the heat flux steeply increases to the CHF, where the heat transfer transitions to film boiling regime. Accordingly, the heat transfer can be regarded as steady-state.

- For faster heating, the non-boiling heat transfer is enhanced because of the transient conductive heat transfer contribution for relatively low flow velocity, and the transient CHFs increase. The nucleate boiling heat transfer is unaffected by the heating rate and flow velocity. At higher flow rate, the transient CHFs become higher, and the transient convective heat transfer contribution in the non-boiling region diminished in this experimental measurement ranges of *t* values. We confirmed that no direct transition from non-boiling to film boiling appear for shorter *t* value, unlike with liquid nitrogen.

- The increment rates of the transient CHF from the steady-state CHF would be independent of the flow velocity for the same test heater. For the same aspect ratio of L/D_h, the increment seems to be expressed by the same curve with the gradient of $\tau^{-0.5}$. For larger L/D_h, it is clarified that, although the increments are larger, they would be expressed by a curve with the same gradient of $\tau^{-0.5}$.