Film boiling heat transfer properties of liquid hydrogen flowing inside of heated pipe

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Abstract. The knowledge of heat transfer properties of liquid hydrogen is important for designing and developing superconducting devices. In this study, film boiling heat transfers of liquid hydrogen flowing inside of heated pipe were measured under saturated conditions at the absolute pressures of 700 kPa for various mass flow rates. Test pipe heater made of SS310S with a diameter of 8 mm and a length of 200 mm was used. The test heater was once heated up to the film boiling regime with exponential heat generation rate. And then, while the heat generation rate was decreased exponentially down to the minimum heat flux, the film boiling heat transfer coefficient, mass flow rate per unit area and the degree of superheat of pipe length direction were measured. It was observed that though the mass flow rate decreased according to increase of the heat generation rate, the heat transfer coefficient increased. Discussions on the experimental results of various conditions were carried out to clarify the phenomenon of film boiling of liquid hydrogen flowing inside of heated pipe. It was considered that since the void fraction in the flow path was high, the effect of improving the heat transfer rate was also observed in the film boiling region due to the acceleration of the liquid phase.

1. Introduction
Liquid hydrogen has good physical properties for cooling, like a low boiling point, high latent heat, high specific heat and low viscosity properties. When liquid hydrogen is used as a refrigerant of a superconductor, it is important to understand the whole range of heat transfer characteristics of liquid hydrogen up to film boiling region.

Shiotsu et al. [1] measured forced convection film boiling heat transfer of liquid hydrogen for a wire heater and presented a correlation modifying the Shiotsu-Hama equation [2] derived for water as a coolant. This correlation assumes cooling of the superconducting wire inside a conduit.

In the past, many researches had been conducted experiments to obtain liquid hydrogen heat transfer characteristics applied for a rocket engine cooling with a high heat load. For example, Hendricks et al. [3] conducted experiments on liquid hydrogen forced convection through some pipe heaters in steady-state condition with a constant heat input and mass flow rate. Graham et al. [4] also conducted experiments for obtaining the steady-state heat transfer of film boiling with liquid hydrogen flowing through a heated pipe with the diameter of 8.5 mm and the length of 305 mm. They measured the pipe inner surface temperature at several points in the longitudinal direction. The surface temperature decreased from inlet to exit along the flow path under the condition that the exit quality was 0.2 to 0.7. On the contrary, in case of the wire heater in a conduit where the exit quality is low, the wire surface
temperature increases from inlet to exit. It is supposed that the quality of hydrogen may affect the heat transfer phenomena. Hollow conductors such as superconducting cables or CIC conductors are forced convection cooled with liquid hydrogen flowing through the central hollow path. The heat load of the conductors is only very small intrusion heat and AC loss of the conductor in normal operation (natural convection regime), however, if a local quench occurs in the superconducting conductor for some reasons, boiling form changes abruptly to film boiling regime beyond the DNB heat flux due to ohmic heat generation by a large transport current. The temperature rise and hence the electric resistance increase of the conductor occur depending on the transient heat transfer characteristics of the forced flow (fluctuations in mass flow rate and quality are expected), and at the same time, the heat generation of the conductor changes with the conductor resistance and the transport current. The cooling conditions described above is quite different from those for the rocket engine.

In this paper, film boiling heat transfers of liquid hydrogen flowing inside of a heated pipe were measured under exponential heat input with a continuous record of mass flow rate of liquid hydrogen, which was calculated directly from the weight scale data of the cryostat. In a higher void fraction case, it was observed that the heat transfer coefficient became high although the mass flow rate decreased. In order to clarify the phenomena, detailed data such as boiling curve, heat transfer coefficient, mass flow rate per unit area, quality, and temperature longitudinal distribution of heated pipe are presented.

2. Experimental apparatus and method

2.1. Experiment system
Details on experimental system have been reported in a previous paper [5]. Forced convection experiment system for liquid hydrogen consists of a main cryostat, a sub cryostat and a transfer line with a control valve connecting two cryostats. The main cryostat is mounted on a digital scale for measuring mass flow rate. Test bodies were installed vertically in a main cryostat and one end of flow line was connected to the inlet of transfer line.

Liquid hydrogen in the main cryostat was pressurized with pure hydrogen gas (99.999 %) to a desired pressure value with dome-loaded regulator. The sub cryostat was of atmospheric pressure. The temperature of liquid hydrogen was set to the desired value by a sheathed heater (~500 W) that was mounted at the bottom of the main cryostat. The initial mass flow rate (before heat input) can be set by the control valve in the transfer line. Heat transfer characteristics for a wide range of liquid temperature (21 ~32 K), mass flow rate per unit area (0.0~400 kg/m² s) and pressure (0.1~1.1 MPa) can be investigated by the system.

2.2. Test heater
Figure 1 shows a cross-sectional view of the test body. A pipe of SS310S with an inner diameter of 8 mm and a heated length of 200 mm was attached into a Fiber Reinforced Plastic (FRP) body for thermal insulation. The test body was vertically mounted in the main cryostat and liquid hydrogen flowed upward through the cylindrical path. The pipe heater was equipped with ten potential voltage taps with 20 mm length and the tap with 200 mm of the both ends for whole heated area.

2.3. Experimental procedure
The experimental procedure is described briefly here, and details have been reported in a previous paper [1]. The pipe heater was heated by a direct current source (~500 A at ~12 V). The source current I was controlled by a digital computer to give a desired heat generation rate Q . Here, exponential heat generation rate of \( Q = Q_0 e^{t/\tau} \) : \( 0 \leq t \leq t_m \) and \( Q = Q_0 e^{-(t-t_m)/\tau} \) : \( t_m < t \) was applied to the test body as shown in figure 2 where \( \tau =10.0 \) s. It was confirmed by the former experiments that the heat transfer phenomenon with \( \tau >5 \) s can be considered as continuous sequence of steady-state.

The heater average temperature \( T_A \) of whole heater (200 mm) was measured by electrical resistivity of the pipe heater dependent on its temperature. The resistance of the test heater was calibrated
beforehand at various temperatures ranging from 20 K to ambient temperature. The electrical resistance of the test heater was measured by four-terminal method. The surface heat flux, \( q \) was obtained from the heat generation rate and the heat capacity of the heater. The average inner surface (wall) temperature, \( T_{WA} \) of the heater was calculated from \( T_A \) and \( q \) by solving a conduction equation. The mass flow rate per unit area, \( v_{mass} \) were obtained by weight change of the main cryostat, which was put on a scale (Mettler Toledo WMH C 300s) that can measure up to 200 kg within 0.002 kg resolution and 0.2 s measurement period. Thermodynamic equilibrium quality at the exit of the flow path, \( x_{exit} \) was obtained from \( Q \) and \( v_{mass} \) (Range over one). Heat transfer characteristics of liquid hydrogen were measured under saturated conditions at absolute pressures of 700 kPa for \( v_{mass} \) in the range of 15 - 340 kg m\(^{-2}\) s\(^{-1}\).

3. Results and Discussion

3.1. Typical experimental data of heat transfer characteristics

Figures 3 shows forced convection heat transfer characteristics under saturated condition at 700 kPa with the initial \( v_{mass} \) (\( \approx 140 \) kg/m\(^2\) s). The left side figure shows boiling curves, with the vertical axis is \( q \) and the transverse axis is the temperature difference, \( \Delta T_{satA} \) (= \( T_{WA} - T_{sat} \)) (inlet saturated liquid hydrogen temperature, \( T_{sat} \)). Because inlet liquid hydrogen is in saturated condition, nucleate boiling occurs soon after the heating starts. In nucleate boiling regime, the heat flux steeply increases up to a certain upper limit heat flux, called DNB (Departure from Nucleate Boiling) heat flux, \( q_{DNB} \). When the heat flux exceeds \( q_{DNB} \), film boiling occurs and the \( \Delta T_{satA} \) rises greatly. In the film boiling regime, \( Q \) continuously increased to the \( \Delta T_{satA} \) around 300 K (point A). After reaching point A, \( Q \) was decreased exponentially. The heat transfer in film boiling regime was measured from point A to B of the minimum heat flux, \( q_{min} \) where the transition occurred from the film boiling to the nucleate boiling.

In the central figure, \( \Delta T_{satA} \), \( v_{mass} \) and \( x_{exit} \) are taken as the vertical axis and the time after starting of heat input is taken on the horizontal axis. \( v_{mass} \) decreased and then recovered according to \( \Delta T_{satA} \) increased and decreased. \( x_{exit} \) has clear negative correlation with \( v_{mass} \). \( x_{exit} \) increased up to almost 2.0 around point A and then \( v_{mass} \) decreased to almost 1/4 of initial condition. \( x_{exit}>1.0 \) shows the superheated condition.)

Figure 4 shows forced convection heat transfer characteristics under saturated condition at 700 kPa with the initial \( v_{mass} \) (\( \approx 340 \) kg/m\(^2\) s). \( q \) was higher than that in figure 3 throughout the test. As shown in the central figure, the peak value of \( x_{exit} \) was almost half of that in figure 3 and then \( v_{mass} \) decreased to only 1/2 of initial condition. It is considered that \( v_{mass} \) was deeply affected by exit side pressure depending on the void fraction in the flow path due to heat input.

Supposing that the forced convection cooling of CIC superconducting conductors during its normal transition, a pulse heat input may be applied like this experiment. It is assumed that the heat transfer is greatly influenced by \( v_{mass} \) change due to the void fraction of hydrogen flow.
3.2. Results of film boiling heat transfer properties of liquid hydrogen

Figure 5 shows the relations between the heat transfer coefficients, \(h\) and \(\Delta T_{sat}\) during film boiling regime (point A to B) at 700 kPa under saturated condition with the initial \(v_{mass}\) as a parameter. \(h\) decreased as \(\Delta T_{sat}\) decreased from 250 K~ to around 50 K, and then increased steeply since the vapour film near the heater became thinner and shifted to the nucleate boiling regime. It is found that \(h\) was larger as \(\Delta T_{sat}\) was higher in the film boiling region, although \(v_{mass}\) was lower as \(\Delta T_{sat}\) was higher as mentioned in the previous subsection.

Shiotsu et al. [1] measured forced convection film boiling heat transfer of liquid hydrogen with a wire heater. They showed the relationship between \(h\) and \(\Delta T_{sat}\) obtained from the experimental results. It is understood that \(h\) does not change much with respect to \(\Delta T_{sat}\) in the film boiling region. In case of the wire heater in the conduit, \(x_{exit}\) is not so large and so \(v_{mass}\) does not decrease so much.

It is supposed that there is some mechanism related to \(x_{exit}\) of the flow in the film boiling for the heated pipe to improve \(h\) as \(\Delta T_{sat}\) increases though \(v_{mass}\) decreases.

Right side graphs in figures 3 and 4 show \(x_{exit}\), the superheat, \(\Delta T_{sat}\) of each voltage tap area (\(P_1\)~\(P_4\): each position is shown in figure 1) during the film boiling regime (point A to B). \(T_{w_{px}}\) is wall surface temperature of each tap area (20 mm length). The superheat of all section decreases as the heat generation rate decreased. The temperature distribution (ascending order of \(\Delta T_{sat}\)) had the following three cases. With respect to figure 3, the temperature distribution was of \(\Delta T_{sat2} < \Delta T_{sat3} < \Delta T_{sat4}\) at around point A (case III : \(1.05 > x_{exit}\)). \(x_{exit}\) also decreased and reached a certain value (1.05), then the temperature distribution changed to \(\Delta T_{sat4} < \Delta T_{sat2} < \Delta T_{sat3}\) (case II : \(0.05 < x_{exit} < 1.05\)). With much smaller \(x_{exit}\), it switched to \(\Delta T_{sat2} < \Delta T_{sat3} < \Delta T_{sat4}\) (case I : \(x_{exit} < 0.05\)).

To understand the boiling state in each region, a schematic views of the cross section of the flow path in each cases are shown in figure 6. In lower quality, \(\Delta T_{sat}\) increases along the longitudinal direction of the flow path as the thickness of the vapor film increases (Region 1). In higher quality, the effect of the velocity increase of the two-phase flow due to the increase in the void fraction becomes apparent (Region 2). Here, in the film boiling region, turbulent exchange between the vapor film and the liquid phase is an important in the heat transfer. So the heat transfer is promoted and the higher the quality, the better the heat transfer characteristic in region 2. When \(x_{exit}\) exceeds a certain value, the gas...
phase occupies (Region 3) and heat transfer mechanism is dominated by single gas phase cooling. The heat transfer coefficient becomes worse. In case I, only region 1 exists. Region 1 and 2 exist in case II and region 1, 2 and 3 in case III.

In addition to \( x_{\text{exit}} \) and \( v_{\text{mass}} \), various factors such as flow path diameter, flow path length, pressure, liquid temperature etc. could be considered as factors that change to each cases. It is necessary to clarify these relationships to present a correlation of heat transfer characteristics of liquid hydrogen.

4. Conclusion

Film boiling heat transfer of liquid hydrogen flowing inside a heated pipe was measured under saturated conditions at the absolute pressures of 700 kPa for various mass flow rates.

The heat transfer coefficient is higher for the higher superheat in the film boiling region, although the mass flow rate is lower due to increase of the void fraction in the flow path. Since the void fraction in the flow path is high, the effect of improving the heat transfer coefficient would be due to the acceleration of the gas-liquid phase.

The correlation of heat transfer properties of liquid hydrogen in film boiling regime with a wire heater set in the center of the pipe flow path was already presented [1], however, the above mentioned phenomena were not observed with the wire heater case. Therefore, it is necessary to clarify the influence of each phenomena to present a correlation for the film boiling heat transfer characteristic of liquid hydrogen flowing inside of heated pipe assuming hollow superconducting conductors cooling.

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