Experimental Study on Pool Boiling Heat Transfer Characteristics of Slush Nitrogen

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Abstract. Slush nitrogen is a cryogenic two-phase fluid with solid nitrogen particles suspended in liquid nitrogen, which can be a potential coolant for high temperature superconductor thanks to its high density and large heat capacity. The present work focuses on the pool boiling heat transfer characteristics of slush nitrogen. The freeze-thaw method was used to produce slush nitrogen and the capacitance-type density meter was adopted to determine the solid volumetric fraction of slush nitrogen. The experimental results show that the heat transfer characteristics of slush nitrogen matches with typical nucleate boiling heat transfer. The heat transfer of slush nitrogen can be enhanced by increasing the solid fraction. The applicability of Rohsenow equation to the nucleate pool boiling heat transfer of slush nitrogen was analyzed, and then a heat transfer correlation for nucleate pool boiling heat transfer of liquid nitrogen and slush nitrogen, considering the effect of solid volumetric fraction, was summarized.

1. Introduction

Superconducting devices have broad application prospect in the field of energy conservation. As a cheap and environmentally friendly cryogenic refrigerant, liquid nitrogen is commonly used in high temperature superconducting cables, transformers, fault current limiters and other equipment. Slush nitrogen is a two-phase cryogenic fluid with small solid nitrogen particles suspended in liquid nitrogen. In recent years, slush nitrogen is considered a potential coolant for some HTS devices thanks to its high density and large heat capacity [1, 2]. Using slush nitrogen as coolant in HTS device can reduce the volume of cryogenic system and improve the operation stability of the system. As a cryogenic refrigerant, it would encounter various heat transfer conditions in its working environment. It is an important practical issue to obtain experimentally the boiling heat transfer characteristics of slush nitrogen. The
experimental investigation of pool boiling heat transfer characteristics of cryogenic slurry fluid is limited. Sindt et al. [3] studied the pool boiling heat transfer of slush hydrogen and analyzed the influence of the orientation of heat transfer surface. The heat transfer data they obtained was in a region of relatively small heat flux. Ohira et al. [2] also studied the heat transfer characteristics of slush hydrogen, as well as slush nitrogen, by varying the orientation of heat transfer surface in the nucleate boiling region.

The heat transfer characteristics and the influence of solid fraction on the boiling heat transfer of slush nitrogen are still relatively undefined. There is still no effective prediction method for the boiling heat transfer of slush nitrogen. In this paper, the pool boiling heat transfer characteristics of slush nitrogen and the influence of solid fraction were observed experimentally. Slush nitrogen was produced by freeze-thaw method, the solid volumetric fraction was determined by capacitance-type density meter and the steady-state boiling conditions were obtained by heat flux control method. The applicability of empirical correlation to the nucleate pool boiling heat transfer of slush nitrogen was analyzed, and then a heat transfer correlation for nucleate pool boiling heat transfer of liquid nitrogen and slush nitrogen, considering the effect of solid volumetric fraction, was summarized.

2. Test apparatus and experiment method

2.1 Test apparatus

The freeze-thaw method is employed to produce slush nitrogen. Fig. 1 presents an overview of the test apparatus, consisting of the slush nitrogen generator with visual windows, the pressure control system, the stirring system, the measurement system and the heat transfer unit. The pressure control system, which can accurately control the pressure in the dewar during the production of slush nitrogen, is composed of a rotary mechanical pump, a vacuum gauge and an intelligent control valve. To obtain homogeneous slush nitrogen, an agitator with three blades is installed on the top flange. The blades are at 100 mm from the bottom of the dewar.

![Figure 1. Experimental setup of pool boiling for slush nitrogen](image-url)
The fluid temperature in the dewar is measured by Pt100 resistance thermometers located in the tank along the vertical direction. The pressure in the tank is measured by a pressure sensor. The solid fraction (density) of the slush nitrogen is measured by means of a capacitance-type densimeter, which is comprised of one square flat-plate electrode and two cylindrical electrodes. The measurement error of the capacitance-type densimeter is ±0.16%. More details about the capacitance-type densimeter can be found in our earlier work [4].

2.2 Heat transfer unit
The heat transfer unit is immersed in slush nitrogen pool inside the dewar. Details of the heat transfer unit are shown in Fig. 2, consisting of a copper block, a stainless steel container and a Teflon plate. The boiling surface, which is a circular flat plate with 25 mm diameter, is finished with 1000# emery paper before each test. Four equally spaced holes are drilled at the bottom of the copper block to install the heating rods, as illustrated in Fig. 2. Six calibrated copper-constantan thermocouples with the accuracy of 0.1 K are used to measure the temperature distribution along the copper block. Three of them are embedded at the locations of 10, 15 and 20 mm away from the boiling surface while the rest are embedded at the locations of 5 mm and 120° apart from each other. To improve the thermal conduction, the thermocouples and the heating rods are embedded in thermal grease. The expanded perlite is filled into the empty space of container to minimize the heat leak from the heating source to the areas other than the boiling surface.

![Figure 2. Heat transfer unit](image)

The heat flux can be calculated from the temperature difference between two adjacent temperature measuring points by inverse heat conduction method [5], with the known thermal conductivity and the distance of the thermocouples. The surface temperature can be obtained with the calculated heat flux from the same method. The uncertainty of measurement has been analyzed in term of the principle for error transfer. In our experiment, the indirect measurements are applied for heat flux, wall superheat and boiling heat transfer coefficient. For example, when the heat flux reaches 90.641 kW/m², the relative uncertainties of heat flux, wall superheat and heat transfer coefficient are 4.18%, 0.99%, and 4.3%, respectively, as listed in Table 1.
Table 1 Uncertainty for the parameters by indirect measurements (Heat flux $q=90.641$ kW/m$^2$)

| Parameter            | Heat flux | wall superheat | Heat transfer coefficient |
|----------------------|-----------|----------------|--------------------------|
| Uncertainty          | 4.18%     | 0.99%          | 4.3%                     |

2.3 Experiment method

Slush nitrogen in the dewar is produced by freeze-thaw method. Triple point state liquid nitrogen is evacuated intermittently to form solid nitrogen particles. The production process will be suspended when the needed solid fraction is reached. The triple-point pressure is maintained with the pressure control system during the heat transfer test. And then, power is supplied to the heating rods in increasing increments to heat the boiling surface. The temperatures measured by thermocouples are monitored to determine whether the heat transfer reaches a steady state, i.e., when the temperatures remain unchanged within five minutes, the heat transfer process is considered to be stable. After the temperatures turn to stabilize, the data of temperature, pressure and solid fraction are collected. Since the solid in the slurry cannot remain long time, the test will be stopped when the solid fraction is out of the control range or the critical heat flux is reached.

3. Results and discussion

3.1 Boiling curves

Because of the existence of solid particles, the slush nitrogen showed an appearance of turbidity. Thus, the bubbles formed during boiling cannot be visualized clearly in many cases. The photos of the slush nitrogen with fine and uniform solid nitrogen particles are shown in Fig. 3. The solid fraction of slush nitrogen in Fig. 3(a) is relatively low, in which condition the pool boiling phenomenon can be observed through visual window with the help of cold light source. However, the visualization of slush nitrogen pool in Fig. 3(b) is poor due to the large numbers of solid particles.

![Figure 3. Image of slush nitrogen](image-url)
Figs. 4-5 shows experimental results of slush nitrogen. In this series of the experiments, the mean solid volumetric fractions of slush nitrogen are low enough (in the range from 1.22 to 5.9%) to provide a clear observation of the behaviour of bubbles merged from boiling surfaces to judge the boiling state. In order to obtain a complete boiling curve and ensure the reliability, the experimental results consist of several groups of experiment data. The results of different experiments show good consistency, which means the experiments in this work are reproducible.

All the measurements are observed in boiling conditions. Fig. 4 shows the boiling curve. With the increase of heat flux, the wall superheat of the boiling surface increases continuously till the critical heat flux (CHF), where the abrupt wall temperature rise occurs. Fig. 5 shows the relation between heat flux and heat transfer coefficient. The heat transfer coefficient increases along a line with the gradient of around 2/3.

Although there are suspended solid nitrogen particles in slush nitrogen, the heat transfer on the boiling surface shows the features of typical nucleate boiling heat transfer, and the heat transfer curve of slush nitrogen is a typical nucleate boiling curve.

3.2 Effect of solid concentration
To further explore the influence of solid particles on the boiling heat transfer of slush nitrogen, three groups of experiments of slush nitrogen with solid volumetric fractions ranging from 8.06-12.75%, 19.67-24.70%, and 30.64-35.40% respectively were conducted. The trend of boiling curves for slush nitrogen with different solid fractions shows a similar trend and no significant difference is observed. With the increase of heat flux, the superheat of boiling surface increases. The critical heat flux condition also exists in slush nitrogen with relatively high solid fraction.

Fig. 6 shows the heat transfer coefficients of slush nitrogen with different solid fractions. The heat transfer coefficients of slush nitrogen are slightly higher than that of liquid nitrogen under the same pressure. Moreover, the nucleate boiling heat transfer coefficient of slush nitrogen increases with the increase of solid fraction, but this effect is not significant. The effect of solid fraction on the boiling heat transfer is relatively obvious in low heat flux region, while in high heat flux region, the heat transfer coefficients of the slush nitrogen with different solid fractions and the liquid nitrogen under the same
pressure tend to be same. One reason for the enhancement of the heat transfer for slush nitrogen can be that the presence of suspended solid particles in slurry will increase the disturbance of the fluid near the boiling surface, which then enhances the micro-convection near the heat transfer surface.

Fig. 7 presents the average value of $h/q^{2/3}$ for the slush nitrogen with different solid fractions, where the value of $h/q^{2/3}$ for the liquid nitrogen at triple-point pressure is also presented for comparison. The effect of solid fraction is shown intuitively. For the figure, we can find that the data of $h/q^{2/3}$ increases with the rise in solid fraction and the value of slush nitrogen is obviously higher than that of liquid nitrogen.

![Figure 6. Heat transfer coefficient of slush nitrogen with different solid fraction](image)

![Figure 7. Solid fraction dependence of nucleate boiling heat transfer of slush nitrogen](image)

### 3.3 Heat transfer correlation

There have been many correlations for the nucleate boiling heat transfer in a pool. In this work, the empirical correlation given by Rohsenow is selected to compare with the experimental results [6]

$$Cp_l \Delta t = C_{wl} \left( \frac{q}{\mu h_{fg} g \left( \rho_l - \rho_g \right)} \right)^{1/3} Pr^s$$

where the exponent $s$ of $Pr$ is usually set as 1.7. The parameter $C_{wl}$ is the experimental empirical coefficient, depending on the combination of the heater surface condition and the fluid, and is usually set between 0.0025 and 0.013.

When the combination remains unchanged, the coefficient $C_{wl}$ will also remain the same value [2]. Thus, the pool boiling experiments of liquid nitrogen under different saturation pressures have been carried out to obtain the coefficient $C_{wl}$, which is 0.0115, with the help of least square method. The comparison of experimental data and Rohsenow equation with $C_{wl}=0.0115$ is shown in Fig. 8. The deviation between experimental data and calculated value is within ±20%.

The calculated value for $h/q^{2/3}$ from Rohsenow equation is also given in Fig.7, which shows that the calculated values are obviously lower than the experimental results. This indicates that the calculation of the boiling heat transfer of slush nitrogen directly using Rohsenow equation would result in large errors. Introducing the effect of solid fraction into the empirical coefficient $C_{wl}$ to describe the influence of solid particles on fluid-surface interaction, the formula can be modified into the following form
where \( h_{fg,s} \) is the latent heat of vaporization including the heat of fusion of the solid. The coefficient \( a \) is chosen to be 0.0115 corresponding to the result of liquid nitrogen. The experimental data of pool boiling heat transfer of slush nitrogen are fitted by least square method, and the values of coefficient \( b \) and \( c \) were obtained as -0.01866 and 0.51931, respectively. \( C_{psl} \) and \( Pr_{sl} \) are the specific heat capacity and the Prandtl number of slush nitrogen, respectively, as shown below [7]

\[
C_{psl} = \frac{\alpha_l (\rho_s / \rho_l)(C_{ps} / C_{pl}) + (1 - \alpha_s)}{\alpha_s (\rho_s / \rho_l) + (1 - \alpha_s)} C_{pl}
\]

(3)

\[
Pr_{sl} = \frac{\mu_{ls} C_{psl}}{\kappa_{sl}}
\]

(4)

where \( \mu_{ls} \) and \( \kappa_{sl} \) represent the viscosity and thermal conductivity of slush nitrogen, respectively, which are defined as below [7]

\[
\mu_{ls} = \left[ 1 - (\alpha_s / 0.6)^{-1.8} \right] \mu_l
\]

(5)

\[
\kappa_{sl} = \frac{2\kappa_s + \kappa_l - 2\alpha_s (\kappa_l - \kappa_s)}{2\kappa_l + \kappa_s + \alpha_s (\kappa_l - \kappa_s)} \kappa_l
\]

(6)

Thus, the modified equation of nucleate boiling heat transfer of slush nitrogen can be obtained:

\[
\frac{C_{psl} \Delta t}{h_{sl}} = (0.0115 - 0.01866 \alpha_s^{0.51931}) \left[ \frac{q}{\mu_{ls} h_{fg,s}} \sqrt{\frac{\sigma}{g(\rho_s - \rho_l)}} \right]^{1/3} Pr_{sl}^{s}
\]

(7)

Fig. 9 illustrates the comparison between the experimental results and calculated values of slush nitrogen, which shows good agreement with the fluctuation of ±20%.
4. Conclusions

A visual experimental apparatus was built for studying the pool boiling of slush nitrogen. The characteristics of pool boiling heat transfer of slush nitrogen, as well as the effects of the solid fraction on the heat transfer, were observed and analyzed.

The experimental results show that the heat transfer characteristics of slush nitrogen matches with typical nucleate boiling heat transfer. The heat transfer coefficients of slush nitrogen are slightly higher than those of liquid nitrogen under the same pressures. With the increase of solid fraction, the nucleate boiling heat transfer coefficient of slush nitrogen increases, but the effect of the solid fraction is not significant. The applicability of Rohsenow equation to the nucleate pool boiling heat transfer of slush nitrogen was analyzed. A heat transfer correlation for nucleate pool boiling heat transfer of liquid nitrogen and slush nitrogen, considering the effect of solid volumetric fraction, was also summarized.

The thermophysical parameters of slush nitrogen were used in the correlation to calculate the nucleate pool boiling heat transfer of slush nitrogen.

NOMENCLATURE

| Symbol | Description       | Units     |
|--------|-------------------|-----------|
| $c_p$  | specific heat, J/kg·K |           |
| $g$    | gravitational acceleration, m²/s |         |
| $h_{fg}$ | latent heat, kJ/kg    |           |
| $q$    | heat flux, W/m²   |           |
| $Pr$   | Prandtl number    |           |
| $\Delta t$ | superheat, K      |           |

Greek Letters

| Symbol | Description       | Units     |
|--------|-------------------|-----------|
| $\alpha$ | volume fraction, % |           |
| $\rho$  | density, kg/m³  |           |
| $\kappa$ | thermal conductivity, W/m K |     |
| $\sigma$ | surface tension, N/m |       |
| $\mu$   | fluid viscosity, Pa·s |         |

Subscripts

| Symbol | Description       | Units     |
|--------|-------------------|-----------|
| $l$    | liquid phase      |           |
| $sl$   | slush             |           |
| $s$    | solid phase       |           |

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