Experimental study on the pool boiling heat transfer of slush nitrogen under triple point to atmospheric pressure

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Abstract. Slush nitrogen is a solid-liquid two-phase cryogenic fluid, with temperature of about 63.15 K under pressure between the triple point of nitrogen and atmospheric pressure. High-temperature-superconductor (HTS) cables generally require the cryogenic coolant such as subcooled liquid nitrogen. Compared with the subcooled liquid nitrogen, slush nitrogen has lower temperature, higher density and higher heat capacity, and is considered a promising coolant for HTS cables. In order to intuitively understand the boiling heat transfer characteristics of slush nitrogen, a pool of slush nitrogen of 0-30% solid volume fraction was prepared as coolant and was filled into a dewar, and helium was charged to change pressure from triple point to atmospheric pressure. Experiments under different pressure conditions were carried out to obtain the variation of boiling curves. The critical heat flux (CHF) of slush nitrogen was found to be reduced by increasing solid volume fraction, because of denser solid nitrogen with lower heat transfer capacity within the main boiling field. By fitting the result to Kutateladze Correlation which predicts CHF, while considering the influence of subcooling, the improved coefficients applicable for slush nitrogen are obtained with an accuracy of ±10%.

1. Introduction

High-temperature-superconductor (HTS) cables with DC can realize lossless power transmission in theory, however, heat load will occur due to AC loss such as hysteresis loss, eddy-current loss and coupling loss [1], mechanical motion, design defects, accidents and so on. Subcooled liquid nitrogen or slush nitrogen can be used as the coolant for HTS cables. Slush nitrogen is a solid-liquid two-phase cryogenic fluid formed by solid nitrogen particles floating in the liquid nitrogen. The density of slush nitrogen with solid mass fraction of 50% is about 18% higher than that of the subcooled liquid nitrogen [2]. Because of the latent heat of melting, slush nitrogen with the same flow rate can remove a larger heat load than liquid nitrogen. Besides, for homogenous flow, slush nitrogen has comparable fluidity performance with subcooled liquid nitrogen [3]. Therefore, slush nitrogen is considered as a promising HTS cable coolant, thanks to its low temperature, high density and large heat capacity.

Researchers have experimentally studied the pipe flow and pool boiling heat transfer characteristics about the cryogenic solid-liquid two-phase fluids. In terms of pool boiling, Sindt [5] conducted the experiments of liquid hydrogen and slush hydrogen boiling in 1974, and found that the heat transfer coefficients of liquid hydrogen at triple point (TP) (12.5 kPa) and slush hydrogen at TP were almost the same in both natural convection section and nucleate boiling section, while the heat transfer performance of slush hydrogen at atmospheric point (also called normal boiling point, NBP, 101 kPa) at the initial stage of nucleate boiling was significantly better than that at TP. In 2003, the experiments of heat transfer in the pool of slush hydrogen and liquid hydrogen, slush nitrogen and liquid nitrogen were carried out...
by Ohira [6]. The heat transfer coefficients of slush hydrogen and slush nitrogen at TP in high heat flux region decreased to about 0.5 times of those of the liquid hydrogen and liquid nitrogen at NBP, and the critical heat flux (CHF) decreased in the following order: NBP liquid, TP slush and TP liquid.

The above results show that the pressure is an important parameter affecting the heat transfer characteristics of slush nitrogen. However, the experimental data of slush nitrogen under the influence of pressure is not yet sufficient, so further research on the influence of pressure is of great necessity.

2. Research scope and variation law of CHF

As figure 1 shows, the slush nitrogen is located at the junction of the solid and liquid regions, i.e., solid-liquid phase line. According to Clausius Clapeyron relation [7], the variation of melting temperature with pressure is 0.04456 K·MPa⁻¹ near 12.5 kPa (TP). When the pressure of nitrogen on the solid-liquid phase line varies from TP to 101 kPa (NBP), the temperature only rises from 63.151 K to 63.154 K, which can be considered insignificant. In this work, the influence of pressure on the heat transfer characteristics of slush nitrogen pool boiling is studied in the range of TP to NBP as shown in figure 1 (where SlN2 means slush nitrogen).

![Figure 1. Pressure–temperature phase diagram of nitrogen.](image1)

![Figure 2. CHF ratios of saturated liquid nitrogen under different pressures to saturated liquid at TP.](image2)

Since the pool boiling experiment can be affected by the boiling surface conditions, such as material, roughness, area, orientation and liquid flow condition, the method of comparative value analysis of CHF is adopted to reduce these interferences.

Considering the difficulty in directly analyzing the heat transfer characteristics of solid-liquid two-phase fluid, the variation of CHF is expressed by comparing saturated liquid nitrogen, subcooled liquid nitrogen and slush nitrogen, as follows:

1) Comparing CHFs of slush nitrogen at TP and saturated liquid nitrogen at TP, \((q_{sat}^*)_{TP}\) and \((q_{sat}^*)_{TP}\). It can be found that the CHF of liquid nitrogen at TP is slightly higher than that of slush nitrogen at TP. In addition, for different solid volume fractions (1.22-5.90%, 8.06-12.75%, 19.67%-24.70% and 30.64%-35.40%) of slush nitrogen, the CHFs do not vary significantly [8].

2) Comparing CHFs of saturated liquid nitrogen at TP and under different pressure, \((q_{sat}^*)_{P}\) and \((q_{sat}^*)_{TP}\). The CHFs of saturated state can be calculated by Helmholtz instability [9]:

\[
q^* = kh_{lv}\rho_v \left( \frac{\sigma (\rho_l - \rho_v)g}{\rho_v^2} \right)^{\frac{1}{2}} \left( \frac{\rho_l}{\rho_l + \rho_v} \right)^{\frac{1}{2}}
\]

where k is a constant with a value of \(\pi^2 h_{lv} \rho_v\) is the latent heat of gas-liquid phase transition, \(\sigma\) is the surface tension. As shown in figure 2, the CHF of saturated liquid nitrogen increases with the pressure increasing from TP to NBP. When the pressure rises to NBP, the CHF becomes 2.36 times of that at TP.
3) Comparing CHFs of saturated liquid nitrogen and subcooled liquid nitrogen, \( (q_{\text{sub}})_{P} \) and \( (q_{\text{sat}})_{P} \). Kutateladze attributed the CHF of subcooled liquid exceeding that of saturated liquid to the extra heat needed for the subcooled liquid near the wall to reach the saturation temperature. Based on this notion, the following correlation was proposed [10]

\[
\frac{q_{\text{sub}}^*}{q_{\text{sat}}^*} = 1 + A \left( \frac{\rho_{l}}{\rho_{v}} \right)^{m} \left( \frac{c_{pl} \Delta T_{\text{sub}}}{h_{lv}} \right)
\]

(2)

where \( c_{pl} \) is the heat capacity of liquid, \( A \) and \( m \) are the constants determined by experimental measurement and values of them widely used are given by Kutateladze (\( A=0.065 \) and \( m=0.8 \)) and Ivey and Morris (\( A=0.1 \) and \( m=0.7 \)).

4) Comparing CHFs of subcooled liquid nitrogen on solid-liquid phase line and slush nitrogen, \( (q_{\text{sl}})_{P} \) and \( (q_{\text{sub}})_{P} \). At present, there is not yet enough detailed data to directly support this comparative analysis. Based on the comparison of slush nitrogen and saturated liquid nitrogen at TP, it can be speculated that the CHF of subcooled liquid nitrogen on solid-liquid phase line and the CHF of slush nitrogen do not differ much.

Based on the above comparison, the CHF of slush nitrogen should increase significantly with the increasing pressure.

3. Experimental system

The experimental system of slush nitrogen pool boiling is shown in figure 3. The dewar has a volume of 70 L, an inner diameter of 380 mm and a height of 1041 mm, and its interlayer is vacuumized by molecular pump to about 10^{-5} Pa. There are five layers of 50 mm spacing radiation screens on the top of dewar, and the designed static evaporation rate is 1.2 L/h. The solid volume fraction is measure by a capacitance-type densimeter at real time [11].

The structure of heating device is shown in figure 4. The upper cover plate is made of PTFE, with high strength at low temperature, and the thermal conductivity is about 0.2 W/(m·K). The heating element is made of oxygen free copper, and the thermal conductivity is calculated by \( k_{Cu} = 2830.53 \times T^{-0.384} \) W/(m·K). The upper cylindrical part of heating element has a diameter of 25 mm and a height of 65 mm, with six temperature measuring holes for installing thermocouples. The lower cylindrical part of heating element has a diameter of 75 mm and a height of 10 mm, with four symmetrical deep holes for installing heating rods. The heating element installed in the heating device, only the upper surface of the upper cylindrical part is exposed to the ambient slush nitrogen. The surface diameter is designed as 25 mm and the surface roughness is about 0.1 μm.

Figure 3. Experimental apparatus for pool boiling test of slush nitrogen

(1. LN₂/GHe inlet  2. Vacuum gauge  3. Motor  4. Glass window  5. Heating device  6. Cold light source  7. Main dewar  8. Densimeter  9. Agitator  10. Control valve  11. NI data acquisition board  12. Capacitance digital converter  13. Computer acquisition system  14. Vacuum pump  15. Self-pressurized liquid nitrogen tank  16. High-purity helium cylinder  17. Precooling dewar).
4. Results and analysis

In the experiments of saturated/subcooled/slush nitrogen, the stirring rate of agitator was controlled at 190-200 r/min. Figure 5 shows the nucleate boiling curves of slush nitrogen at 12.5 kPa, 25 kPa, 50 kPa, 75 kPa and 101 kPa, respectively. The onset of boiling (ONB) is the beginning of boiling curve, while the critical heat flux (CHF) is the end of boiling curve, also known as “burnout” point. If the heat flux continues to increase from the “burnout” point, the transition from nucleate boiling to film boiling will occur and cause a jump of superheat. At the same time, the heat transfer coefficient will drop greatly, and the wall temperature will rise sharply.

4.1. Onset of nucleate boiling (ONB)

With the increase of pressure, the degrees of superheat of ONB $\Delta T_{onb}$ increase significantly. The degrees of subcooling $\Delta T_{sub}$ are calculated by subtracting the slush nitrogen temperature $T_{sl}$ from $T_{sat}$. By comparison, the variations of $\Delta T_{onb}$ and $\Delta T_{sub}$ are almost equal, as listed in table 1.

The explanation for the consistently close connection between $\Delta T_{onb}$ and $\Delta T_{sub}$ lies in the boundary layer near the wall, which must be heated to the saturation temperature at the corresponding pressure for reaching boiling state. At this time, if the heat flux of heating wall continues to be increased, bubbles will appear at the vaporization cores.
The observation through the visual window, the liquid application of slush nitrogen is concerned, $q_{\text{sl}}$ with the higher solid volume fraction of slush nitrogen is lower with the higher solid volume fraction of slush nitrogen liquid nitrogen.

The thermal conductivity of solid nitrogen is much lower than that of liquid nitrogen. Therefore, the convection heat transfer coefficient $h_{\text{nc}}$ slightly decreases with the increase of solid volume fraction. The reason is that the solid particles are partly hanging on the boiling surface can be clearly observed; the medium-volume-fraction slush nitrogen is not transparent enough for observing the boiling surface; the solid nitrogen particles will be hanging on the visual window in the high-volume-fraction slush nitrogen.

Meanwhile, within the high-volume-fraction slush nitrogen, the boiling surface temperature of ONB increases and the natural convection heat transfer coefficient $\Delta T_{\text{onb}}$ increases due to the existence of subcooling, while the change of nucleate boiling heat transfer coefficient $h_{b}$ cannot offset the decrease of macroscopic heat transfer coefficient.

The decrease of macroscopic heat transfer coefficient is directly reflected by the increase of superheat $\Delta T$ under certain heat flux. As far as the practical application of slush nitrogen is concerned, the temperature of heating surface $T_w = 63.151 \, \text{K} + \Delta T$ needs to be lower than the critical transition temperature of high temperature superconductor. It is found that $T_w$ does not exceed 90 K (critical temperature of YBaCuO) under pressures of the research. In case of no quench for HTS cable, the slush nitrogen with pressure higher than TP can allow higher heat flux, and the safety will be improved in practical application. However, considering the quench-protection, the pressure definitely needs to be controlled since the superheat of heating surface increases with the pressure at a certain heat flux value.

The boiling curve of slush nitrogen also moves upward with pressure increasing, which means that the CHF increases. For further understanding the CHF characteristics, the following research was done and factor of solid volume fraction is taken into consideration.

### 4.2. Heat transfer coefficient of nucleate boiling

The macroscopic heat flux $q_{\text{nb}}$ in nucleate boiling region is composed of natural convection heat flux $q_{\text{nc}}$ and nucleate boiling heat flux $q_{b}$ [12]:

$$q_{\text{nb}} = q_{\text{nc}} + q_{b}$$

which can be converted to the form of macroscopic heat transfer coefficient:

$$h_{\text{nb}} = h_{\text{nc}} + h_{b}$$

As shown in figure 5, the boiling curve of slush nitrogen moves rightward with the increasing pressure, meanwhile, the macroscopic heat transfer coefficient $h_{\text{nb}}$ decreases. The main reason is that the superheat of ONB increases and the natural convection heat transfer coefficient $h_{\text{nc}}$ decreases due to the existence of subcooling, while the change of nucleate boiling heat transfer coefficient $h_{b}$ cannot offset the decrease of macroscopic heat transfer coefficient.

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The boiling curve of slush nitrogen also moves upward with pressure increasing, which means that the CHF increases. For further understanding the CHF characteristics, the following research was done and factor of solid volume fraction is taken into consideration.

### 4.3. Critical heat flux (CHF)

Combining the measurement of densimeter and the observation through the visual window, the solid volume fraction ranges of slush nitrogen are divided as followed: low (0%-5%), medium (5%-18%) and high (18%-30%). The division is based on the follows: through the low-volume-fraction slush nitrogen, the boiling surface can be clearly observed; the medium-volume-fraction slush nitrogen is not transparent enough for observing the boiling surface; the solid nitrogen particles will be hanging on the visual window in the high-volume-fraction slush nitrogen.

The results of CHF for different ranges of solid volume fraction are shown in figure 6(a), the CHF slightly decreases with the increase of solid volume fraction. The reason is that the solid particles are more likely to impact on the boiling surface with higher volume fraction of slush nitrogen. Within the near boiling field, the process of heat transfer will be partially influenced by solid particles. Meanwhile, the thermal conductivity of solid nitrogen is much lower than the convection heat transfer coefficient of liquid nitrogen. Therefore, the heat transfer performance of slush nitrogen becomes worse and the CHF is lower with the higher solid volume fraction of slush nitrogen.

The CHF ratios of slush nitrogen at different pressures to slush nitrogen at TP can be calculated by the following formula:

$$\left(\frac{q_{\text{ns}}}{q_{\text{ns}}^{\star}}\right)_P = \left(\frac{q_{\text{sat}}}{q_{\text{sat}}^{\star}}\right)_P \left(\frac{q_{\text{sub}}}{q_{\text{sub}}^{\star}}\right)_P \left(\frac{q_{\text{sl}}}{q_{\text{sl}}^{\star}}\right)_P \left(\frac{q_{\text{nb}}}{q_{\text{nb}}^{\star}}\right)_P$$

### Table 1. Degrees of subcooling and superheat under pressures of the research

| Pressure $p$ (kPa) | Saturation temperature $T_{\text{sat}}$ (K) | Subcooled temperature $\Delta T_{\text{sub}}$ (K) | Superheat temperature of ONB $\Delta T_{\text{onb}}$ (K) |
|-------------------|-------------------|-------------------|-------------------|
| 12.5              | 63.151            | 0                 | 1.258             |
| 25                | 67.177            | 4.023             | 4.698             |
| 50                | 71.826            | 8.666             | 8.410             |
| 75                | 74.891            | 11.726            | 10.906            |
| 101               | 77.244            | 14.073            | 13.136            |

| Subcooled temperature $\Delta T_{\text{sub}}$ (K) | Superheat temperature of ONB $\Delta T_{\text{onb}}$ (K) |
|-------------------|-------------------|
| 0                 | 1.258             |
| 4.023             | 4.698             |
| 8.666             | 8.410             |
| 11.726            | 10.906            |
| 14.073            | 13.136            |
In the certain range of solid volume fraction, $(\frac{q^*_{sat}}{q_{sat}})_{TP}$ can be simplified into 1, then equation (5) can be written to the following formula:

$$\frac{(q^*_s)_{P}}{(q^*_s)_{TP}} = \frac{(q^*_{sat})_{P}}{(q^*_{sat})_{TP}} \frac{(q^*_{sub})_{P}}{(q^*_{sub})_{TP}}$$

(6)

Substituting equation (1) and equation (2) into equation (6) to get the fitting formula, and the correlation can be further simplified because $\rho_v$ is far less than $\rho_l$:

$$\frac{(q^*_s)_{P}}{(q^*_s)_{TP}} = \left(\frac{\rho_v}{\rho_v_{TP}}\right)^{\frac{1}{2}} \left[\frac{(\rho_l)_{P}}{(\rho_l)_{TP}}\frac{(\sigma)_{P}}{(\sigma)_{TP}}\right]^{\frac{1}{4}} \left\{1 + A \left(\frac{\rho_l}{\rho_v}\right)_P m \left[\frac{(c_p)_{P}}{h_{lv}} (\Delta T_{sub})_{P}\right]\right\}$$

(7)

Due to the different experimental conditions (surface material, roughness, area, orientation and liquid flow condition, etc.), there will be obvious deviations among the results of different experimental systems. The form of correlation fitting as the CHF ratios of slush nitrogen under different pressures to slush nitrogen at TP can reduce the interference of experimental conditions on the results. Fitting the measured CHF ratios by equation (7), the constants are obtained as $A=0.50$ and $m=0.44$:

$$\frac{(q^*_s)_{P}}{(q^*_s)_{TP}} = \left(\frac{\rho_v}{\rho_v_{TP}}\right)^{\frac{1}{2}} \left[\frac{(\rho_l)_{P}}{(\rho_l)_{TP}}\frac{(\sigma)_{P}}{(\sigma)_{TP}}\right]^{\frac{1}{4}} \left\{1 + 0.50 \left(\frac{\rho_l}{\rho_v}\right)_P^{0.44} \left[\frac{(c_p)_{P}}{h_{lv}} (\Delta T_{sub})_{P}\right]\right\}$$

(8)

which is compared with that of Kutateladze and that of Ivey and Morris, as shown in figure 6(b). It is indicated that $A=0.50$ and $m=0.44$ have better applicability for slush nitrogen. Additionally, figure 7
shows the comparison of $q_p/q_{FP}$ between the measured value and the calculated value. It can be clearly seen that the accuracy of fitting correlation is within a band of ±10%.

5. Conclusion
The nucleate boiling heat transfer characteristics of slush nitrogen under various pressures were experimentally studied. The nucleate boiling curves of slush nitrogen at 12.5 kPa (triple point), 25 kPa, 50 kPa, 75 kPa and 101 kPa (atmospheric pressure) with solid volume fraction of 5-15% and the critical heat fluxes of slush nitrogen with low (0%-5%), medium (5%-18%) and high (18%-30%) solid volume fraction were obtained. The main conclusions can be made as follows:

1. The degrees of superheat of onset of nucleate boiling are almost equal to the degrees of subcooling of slush nitrogen at the corresponding pressure, because the boundary layer near the wall should be heated to saturation temperature before vaporization.

2. The macroscopic heat transfer coefficient of nucleate boiling section decreases with pressure increasing, mainly due to the decrease of natural convection heat transfer coefficient with the degrees of superheat of onset of nucleate boiling increasing.

3. By comparing saturated liquid nitrogen, subcooled liquid nitrogen and slush nitrogen at different pressures, the critical heat flux of slush nitrogen increases with pressure increasing from triple point to atmospheric pressure. The critical heat flux of higher-volume-fraction slush nitrogen is slightly smaller, due to the larger proportion of solid particles with poor heat transfer performance near the wall.

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