Cryogenics 72 (2015) 14–21

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

# Visualization study of nucleate pool boiling of liquid nitrogen with quasi-steady heat input

Xiaobin Zhang [a,b], Jianye Chen [a,b], Wei Xiong [c], Tao Jin [a,b,*]

[a] Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, China
[b] Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, China
[c] 704th Research Institute of China, Shipbuilding Industry Corporation, Shanghai 200031, China

ARTICLE INFO

*Article history:*
Received 6 May 2015
Received in revised form 23 June 2015
Accepted 16 July 2015
Available online 29 July 2015

*Keywords:*
Nucleate pool boiling
Liquid nitrogen
Visualization
Cryogenic fluids

ABSTRACT

A visualization experimental device has been built to investigate the bubble behaviors in the nucleate pool boiling of cryogenic fluids at atmospheric pressure. The general morphologies of the bubbles are analyzed based on the captured films using a high-speed camera. The bubble behaviors leaving the wall at different heat flux can be divided into three regimes (low heat flux regime, fully developed nucleate boiling regime and intermediate regime) according to the availability of bubble parameters. In the low heat flux regime, the bubble is discrete and the interactive effects are ignorable. In the fully developed nucleate boiling regime close to CHF, the bubbles depart in the form of bubble cluster with a neck. In the intermediate regime, the interactive effect between the bubbles is significant and the bubbles follow a random pattern neither discretely nor as cluster neck. The information about the bubble departure diameter, the detachment frequency and the number density of activated sites are specially investigated. These data are used to evaluate the existing semi-empirical correlations widely applied to either the room-temperature or cryogenic fluids. It is found that the Kim's correlation for the departure diameter predicts a satisfactory agreement with the experimental results in the isolated bubble regime. For the predictions of the detachment frequency, the correlation by Katto and Yokoya is recommended after comparison. The relation between the diameter and frequency can also be well determined by the correlation proposed by Mcfadden et al. The number density of active sites for liquid nitrogen still can be considered to be linearly proportional to $\Delta T^m$ as it is for water, except that the exponent absolute $m$ is much smaller.



## 1. Introduction

The performance of an evaporator/condenser has a great influence on the power consumption and separation efficiency of the column in a cryogenic air separation system, where the liquid oxygen ($LO_2$) pool boils at the evaporator side and vapor nitrogen ($VN_2$) at relative high pressure condenses at the condenser side. In order to reduce the pressure of $VN_2$, a smaller temperature difference of the condensation and evaporation should be pursued. Therefore, it is of great significance to accurately predict the boiling heat transfer efficiency of the cryogenic fluids in the evaporation process.

The empirical and semi-empirical correlations for calculating the heat transfer rate during nucleate pool boiling process have made satisfactory success by present for both room-temperature fluids [1,2] and cryogenic fluids [3]. Recently, the statistical thermodynamic heat transfer theory has been applied to illustrate the kinetics of phase transition mechanisms, successfully predicting the relation between superheat and heat flux [4]. However, the mechanism and modeling of the transport process still remains incompletely understood. The modeling difficulty exists in the invariable knowledge of the dependence of the bubble departure diameter, frequency and active site density on the wall superheat [5]. It was reported that the correlations for the bubble departure diameter, at best, fit available experimental data for the room-temperature fluids to an average absolute deviation of over 20% [6]. The predicted detachment frequency also suffers the similar level uncertainty because they are often linked. Similar difficulties arise in predicting the active site density due to its complicated dependences on the surface morphology, the thermophysical properties of the fluids, the imposed pressure and the wetting characteristics of the liquid-surface combination. These uncertainties

* Corresponding author at: Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, China. Tel.: +86 571 87953233.

*E-mail address:* jintao@zju.edu.cn (T. Jin).

http://dx.doi.org/10.1016/j.cryogenics.2015.07.002
0011-2275/

undoubtedly contribute much to the disagreement in model predictions with the experimental data [7,8]. A general review and comment about these efforts can be found in the literatures [4,7,8].

Recently, the authors [5] demonstrated that the widely used closure correlations of heat and mass transfer on the heating surface during subcooled boiling flow of water are invalid to the boiling flow of liquid nitrogen ($LN_2$) due to the evident differences in physical properties of the liquids. In fact, many investigations have demonstrated that the physical properties of the liquids have significant effects on the characteristics of bubble generation [7]. However, most investigations concerned the experiments for both $LN_2$ and LHe I on the heat transfer rates, the transient transition of the boiling modes, and the burnout conditions for pool or forced boiling convection with various degrees of subcooling under quasi-steady or unsteady heating conditions [9–15]. The information about the bubble behaviors of cryogenic fluids is few. Kirichenko et al. [16] suggested that the bubble departure diameter $D_d$ for a heating tube was calculated as:

$$D_{\mathrm{d}} = 1.11\sqrt[3]{\frac{R_{\mathrm{c}}\sigma}{g(\rho_l - \rho_{\mathrm{v}})}} \tag{1}$$

where the critical radius of the bubble nucleus $R_c$ is used to calculate the radius of the active cavity mouth: $R_c = 2\sigma T_{sat}/h_{lv}\ \rho_v \Delta T$, $h_{lv}$ is the latent heat, $\Delta T = T_w - T_{sat}(P)$ is the superheat, $T_w$ is the wall temperature, $T_{sat}(P)$ is the saturated temperature at pressure $P$, and $\sigma$ is the surface tension. Eq. (1) agrees well with the experimental data at saturated pressures for $P/P_{cr} > 0.5$, $P_{cr}$ is the critical pressure. The detachment frequency $f$ is usually related to $D_d$. Mcfadden and Grassmann [17] found that the Zuber's relationship [9]

$$f \cdot D_{\mathrm{d}} = 0.59 \cdot (\sigma g \Delta\rho/\rho_l^2)^{1/4} \tag{2}$$

always over-predicts the experimental value for $LN_2$. Then, following the Zuber's idea, they made the dimensional analysis and proposed the following relation:

$$f \cdot D_{\mathrm{d}}^{1/2} \sim 0.56 \cdot (g\Delta\rho/\rho_l)^{1/2} \tag{3}$$

for cryogenic liquids, which fits the experimental data better in a wider frequency range. Another requisite parameter for modeling the boiling heat transfer is the active site density $n_a$, a recognized semi-empirical formula for the room-temperature fluids was given as

$$n_{\mathrm{a}} = C_{\mathrm{n}}[h_{\mathrm{lv}}\rho_{\mathrm{v}}\Delta T/\sigma T_{\mathrm{sat}}(P)]^{\mathrm{m}} \tag{4}$$

It is shown that $n_a$ varies proportionally to $\Delta T^m$ if the properties are constant, thus Eq. (4) can be reduced into

$$n_{\mathrm{a}} = C'_{\mathrm{n}}\Delta T^{\mathrm{m}} \tag{5}$$

The combination of Eqs. (1), (2) and (4) was adopted by Li [5] in modeling the $LN_2$ boiling flow and the results satisfactorily agreed with the experimental data. Nevertheless, above correlations on bubble behaviors are virtually only applicable to the isolated bubble regime. Jin et al. [18] reported that the detachment frequency is about 13.47 Hz by observing the coalesced bubbles behavior in $LN_2$ pool boiling over a heating metal surface. They verified that the Kunada's correlation developed for room-temperature fluids [19,20] are still in good agreement with the $LN_2$ data at this boiling regime.

On the visualization experiments of pool boiling of cryogenic fluids, Bland et al. [21] found that the formed spherical bubble of $VN_2$ was connected to the heated wall by a neck with the diameter approximately same as that of the artificial cavity mouth. The growth rate profiles of the bubble were drawn and the departure diameter was calculated by assuming the balance among the buoyancy force, the excess pressure and the surface tension force. Okuyama and Iida [22] presented three typical unsteady boiling patterns of bubble behavior at different heat flux for the case of a 0.1 mm diameter platinum wire immersed in $LN_2$ pool. Similarly, by visualizing the boiling transition on a 1.2 mm diameter horizontal cylinder in $LN_2$ under the condition of increasing heat inputs, Sakurai et al. [23] indicated that the direct transition mechanism from non-boiling regime to film boing is principally attributed to the explosive heterogeneous spontaneous nucleation (HSN) due to the absence of the active cavities, which is the result of contact angle of $LN_2$-wall approaching to $0^0$. However, after studying the transient bubble behaviors of $LN_2$ pool boiling for a brass wire with diameter of 25 μm subjected to stepwise heating, Duluc et al. [13] considered that the statement of premature transition due to the HSN needs at least to be further discussed, since the recognized rate of formation of embryos $10^6\ cm^{-2}\ s^{-2}$ requires the static contact angle between the fluid and the smooth solid wall to be far larger than the actual value of $LN_2$. They insisted that the boiling onset is more likely to result from the activation of pre-existing vapor embryos entrapped in the cavities. The opinion seems to be strongly enforced by the theoretical works of You and Tong [24], who pointed out that the vapor embryos can be activated since the advancing contact angle will be large enough to entrap vapor during the boiling process for a highly wetting liquid. It is known that the advancing contact angle is larger than the static one, and its magnitude increases with the interfacial velocity. Deev and Kharitonov [25] calculated the accumulated energy inside the thermal boundary layer as well as the energy necessary for forming vapor film on the heated surface under stepwise heat flux input, and stated that the premature transition to film boiling regime at $q_{cr2} < q < q_{cr1}$ will occur if the former is larger than the latter. $LN_2$ meets this condition, while, LHe does not, therefore, the premature will not happen for LHe at the same condition. The predictions were well proved by the experimental data.

In spite of many excellent studies, the correlations of bubble departure diameter, frequency and nucleation density in pool boiling of cryogenic fluids are only partially or indirectly validated. Experimental studies are still essential to further evaluate these correlations. With regards to this, we built a visualization device for the pool boiling on a copper disk in $LN_2$ at atmospheric pressure. A high-speed camera was used to capture the transient bubble behavior. The photos of typical bubble behaviors at different moments from the boiling onset to boiling crisis of critical heat flux (CHF) are presented. Based on the visualization observation, the whole nucleate boiling process is divided into three regimes: the discrete bubble regime at low heat flux, the coalesced bubble regime at high heat flux and the intermediate regime, according to the availability of the parameters. The bubble departure diameter, frequency and active nucleate density are especially concerned. These parameters are used as a database to evaluate the available corresponding correlations outside the intermediate regime, in which the bubble bundle appears the degree of randomness and uncertainty and it is difficult to define the exact values.

## 2. Experimental setup

The visualization experimental rig mainly consists of a visual $LN_2$ vessel with the double wall vacuum insulation, a test piece assembly and a high-speed image acquisition system, as shown in Fig. 1. The detailed introduction to the device can be found in our previous papers [18]. Here a short introduction is presented for completeness. Two glass windows at opposite directions of the diameter are arranged for observations. The piece assembly comprises a side shell, a top Teflon plate and an inner conic copper base with the top surface flushing with the Teflon plate as well as the glass window center. Fig. 2 is a 200-fold amplified photo of the