Pool-Boiling Heat Transfer in Liquid Nitrogen*

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An experimental study was conducted on pool-boiling heat transfer from an electrically heated horizontal wire to saturated liquid nitrogen at atmospheric pressure. Experimental results of heat transfer characteristics in both nucleate- and film-boiling regimes, critical heat flux and minimum heat flux were analyzed and compared with various correlations. In addition, photography was used to obtain information concerning the vapor-bubble and vapor-film behaviors around the heating wire. These data of microcharacteristics were utilized for evaluating theoretical models of nucleate-boiling mechanism proposed by other investigators. Transient conduction to the relatively cold (saturated) liquid, which came into the space vacated by the departing bubble and contacted with the heating surface, was found to be important for high heat transfer rates associated with nucleate boiling.

KEYWORDS: liquid nitrogen, heat transfer, pool boiling, nucleate boiling, film boiling, bubble size, bubble frequency, nucleation sites, critical heat flux, minimum heat flux

I. INTRODUCTION

In recent years the growth of technical fields making use of low temperature has been exceptionally rapid. Large superconducting magnets, for instance, are now being developed for a Tokamak-type fusion reactor. Several types of cooling (pool or forced convection) by liquid helium are proposed for such magnets. The cooling of surfaces by cryogens, usually liquid nitrogen, is used to produce very low pressures in high-vacuum systems, which are needed for fundamental nucleonics experiments.

In dealing and storage of these cryogenic liquids a knowledge of heat transfer, especially during boiling, is important since the extremely large temperature difference between a solid at room temperature and a cryogenic liquid often gives boiling. Extensive studies of cryogenic liquid boiling have, therefore, been carried out in the world(1). Most of the past studies have been conducted to investigate the macrocharacteristics of boiling heat transfer. There are only limited data on microcharacteristics of boiling, i.e. the size of departing bubbles and the frequency of bubble formation, which are important for understanding the heat transfer mechanism during boiling and are necessary for deriving some heat transfer formulations. To meet this need, the present experiments have been conducted to examine the pool-boiling heat transfer from an electrically heated horizontal wire to saturated liquid nitrogen at atmospheric pressure. This paper gives the experimental results obtained on heat transfer characteristics in both nucleate and film boiling, with particular emphasis on the bubble size, the number of nucleation sites and the frequency of bubble formation in nucleate boiling, and on the vapor flow pattern in film boiling.


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II. EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows a schematic diagram of the experimental apparatus which consisted of a double-walled glass chamber of 90 mm in inner diameter. A gap between the inner and the outer walls was evacuated to isolate the inner wall, which contained liquid nitrogen, from room temperature. A thermal insulator also was equipped to keep the outer wall in an adiabatic condition. Two glass windows* were provided on the side wall for obtaining photographic records of vapor-bubble and vapor-film behaviors in liquid nitrogen.

The heater element was a pure, smooth platinum wire of 60 mm in length. Wire diameters were varied from 0.1 to 1.0 mm. It was connected to electrical leads supported by an acrylic structure and was placed horizontally 150 mm under the free surface of liquid nitrogen. The wire was heated by direct current supplied from a specially designed transistorized power control system. The potential drop \( V \) was measured between the two electrical leads 60 mm apart, the effective heat transfer area thus being \( 60 \pi D \) mm\(^2\) where \( D \) is the wire diameter in mm. The current \( I \) was measured by means of a shunt resistor (0.125 mΩ).

Prior to each set of runs the wire was annealed at approximately 1,000 K and then cleaned with acetone. After the chamber was filled with liquid nitrogen, the wire was gradually heated up to the critical heat flux by the power control system, resulting in a film boiling condition, as shown in Fig. 2. After film boiling had set in, the input power was further increased up to a prescribed value. Upon attaining the prescribed condition, the wire was, in turn, cooled down by gradually decreasing the power to zero through a minimum heat flux. The potential drop \( V \) and the resistance \( R = V/I \) of

* For heat transfer experiments, however, another chamber without windows was used to minimize heat leakage into liquid nitrogen.
the wire were measured continuously. During the runs, the liquid nitrogen was maintained at the saturation temperature corresponding to the atmospheric pressure.

The power was readily calculated: \( W = VI \). The mean temperature \( T_w \) of the wire was obtained from the curve \( T(R)(9) \), which was previously confirmed by measuring \( R \) at some different temperatures using a current of very low intensity. Because of the relatively high thermal conductivity and the small diameter of the wire, there was no appreciable temperature gradient in the cross section; for instance, actual surface temperature being 0.19 K lower than the average temperature under a condition: heat flux of \( 2.4 \times 10^5 \) Wm\(^{-2} \) and wire diameter of 0.5 mm.

III. RESULTS AND DISCUSSIONS

1. Nucleate-boiling Heat Transfer

Figure 3 shows the present nucleate boiling data plotted on a log \( q \) vs. log \( \Delta T_s \) diagram; \( q \) is the heat flux and \( \Delta T_s \) the excess of the wall temperature \( T_w \) above the saturation temperature \( T_s \). The figure also contains other experimental results published to date\(^{(3)}\)~\(^{(11)}\). Complete agreement is lacking among the results since the nature of the surface has an important influence on nucleate boiling process, among other things. No theory, which explains the above-mentioned effects successfully, has yet been found. In addition to this, variations in system geometry, method of taking data, and uncertainties in measurement would cause the general scatter of data.

The solid line drawn in the figure indicates Kutateladze's correlation\(^{(12)}\), which was derived for nucleate boiling of water and various organic liquids and is represented by the form, after rearrangement,

\[
q = 3.046 \times 10^{-11} \left( \frac{\rho_l k_l P}{\rho_v \mu_l h_{fg}} \right)^{2/3} \left[ \frac{\sigma}{g(\rho_l - \rho_v)} \right]^{2/3} \frac{\mu_l C_p l}{k_l} \Delta T_s^{10/3},
\]

where \( \rho \) is the density, \( k \) the thermal conductivity, \( \mu \) the viscosity, \( C_p \) the specific heat, \( \sigma \) the surface tension, \( h_{fg} \) the latent heat of vaporization, \( P \) the pressure and \( g \) the acceleration due to gravity. The subscripts \( l \) and \( v \) signify values pertaining to liquid and vapor, respectively. Kutateladze's equation represents the present data fairly well although the data are scattered.

2. Critical Heat Flux

Figure 4 shows the effect of heater diameter \( D \) on the critical heat flux \( (CHF) q_{max} \). The plots reveal that the CHF increases with increasing diameter although the data are scattered slightly. This tendency is similar to the experimental results of ordinary liquid\(^{(13)}\)~\(^{(15)}\).
For comparison, Kutateladze's correlation\(^{12}\) is also indicated in the figure. Kutateladze was probably the first to point out that the critical heat flux condition was a matter of hydrodynamic stability on a flat horizontal surface. From the dimensional analysis, the final equation can be written in the form

\[ q_{\text{max}} = B h_{fg} \rho_0 \left[ \frac{g \sigma (\rho_f - \rho_v)}{\rho_v^2} \right]^{1/4}, \quad (2) \]

where \( B \) is a proportionality constant. Kutateladze found that this constant varied between 0.13 and 0.19, with 0.16 as average, for several sets of CHF data of both water and organics boiling on both flat plates and horizontal cylinders (wires). The solid line drawn in Fig. 4 was obtained by letting \( B = 0.16 \) in Eq. (2). The measured values, except for \( D = 0.1 \text{ mm} \), agree fairly well with the theoretical line in the data scattering range of \( \pm 20\% \). For \( D = 0.1 \text{ mm} \), however, the plots fall below the line. This suggests a dependency of CHF on the heater diameter.

Kutateladze et al.\(^{16}\) found that Eq. (2) could be used to correlate pool-boiling CHF data for horizontal cylinders if \( B \) could vary with the diameter of the cylinder (or wire) and the physical properties of the liquid. This dependency is expressed by the relation

\[ B = f(D^*), \quad (3) \]

where \( D^* \), the dimensionless diameter of the heater, is obtained by dividing the heater diameter by the Laplace characteristic length, or

\[ D^* = \frac{D}{\left[ \frac{g \sigma (\rho_f - \rho_v)}{\sigma} \right]^{1/2}}. \quad (4) \]

Figure 5 is a plot of Eq. (3) for the present experimental results. Correlations predicted by Kutateladze et al.\(^{16}\) and Rao & Andrews\(^{17}\) are also indicated in this figure. Kutateladze et al. proposed the best fitted curve for 14 sets of data of water and 6 organics, which were obtained over wide ranges of diameter and pressure, and with different kinds of smooth metallic heater surfaces. The broken lines drawn in the figure represent the band of the spread in these data.

Applying a hydrodynamic stability model for horizontal cylinders, Rao & Andrews derived the follow-
ing correlation

$$\frac{q_{\text{max}}}{q_{\text{max,F}}} = 0.805/D^* (D^* + 2)^{3/4}, \quad (5)$$

where $D^*$ is the dimensionless diameter of vapor-liquid interface. $q_{\text{max,F}}$ is the well-known CHF recommended by Zuber\(^{(18)}\) for infinite flat plates and is given by the following equation:

$$q_{\text{max,F}} = 0.131 h_f \rho_v \left[ \frac{g \sigma (\rho_i - \rho_v)}{\rho_v^2} \right]^{1/4}, \quad (6)$$

which, except for the coefficient, is identical to Eq. (2) derived by Kutateladze. A dot-and-dashed line drawn in the figure was obtained by letting $D^* = D^*$ in Eq. (5).

The proportional constant $B$ increases generally with increasing heater diameter in the range of the present heater diameter. Fairly good agreement is observed between the present data and both correlations within the spread range of data.

3. Film-boiling Heat Transfer

Film boiling as a cooling process has not had wide commercial applications because of the high surface temperatures. In cryogenic systems, however, a knowledge of film boiling is particularly important since the extremely large temperature difference between a equipment surface and a cryogenic liquid often causes film boiling during cooling down from the room temperature.

Figure 6 shows the experimental results of film-boiling heat transfer for various heater diameters. The abscissa is $\Delta T_s$, the excess of the wall temperature above the saturation temperature and the ordinate $h$, the heat transfer coefficient given by $q/\Delta T_s$. As $\Delta T_s$ increases, $h$ first decreases sharply. In this lower $\Delta T_s$ region, nucleate- and film-boiling regimes exist simultaneously along the heating wire, as clarified later by Photo. 1 (c). Film boiling becomes more dominant with increasing $\Delta T_s$, and extremely degrades the heat transfer characteristics. In the higher $\Delta T_s$ region where stable film boiling is established and no nucleate boiling exists, however, $h$ increases slightly with increasing $\Delta T_s$. For a given $\Delta T_s$, $h$ decreases with increasing diameter. The broken and the solid lines drawn in the figure are the correlations obtained by Bromley\(^{(19)}\) and Breen & Westwater\(^{(20)}\), respectively.

For film boiling, as compared with nucleate boiling, a reasonably well-known physical model is given, that vapor is generated at the liquid-vapor interface by conduction and radiation from the heating surface through the vapor film. By balancing the buoyant and frictional forces on the vapor film flowing on the outside of a horizontal tube, Bromley arrived at the following equation representing the convective heat transfer coefficient $h_c$ based on molecular conduction alone:
\[ h_c = 0.62 \left[ \frac{k_c \rho_c (\rho_i - \rho_v) g (h_f \rho_v + 0.5 C_{pv} \Delta T_s)}{D \mu_v \Delta T_s} \right]^{1/4}, \]  
\hspace{1cm} (7)

where all physical properties of the vapor are evaluated at the average temperature of the film.

Bromley also suggested an expression which included the radiative contribution to heat transfer
\[ h = h_c + 0.75 h_r, \]  
\hspace{1cm} (8)

for \( h_c > h_r \). He estimated the magnitude of \( h_r \) from the relation
\[ h_r = \frac{\kappa}{1/\varepsilon + 1/\alpha - 1} \frac{T_w - T_i}{\Delta T_s}, \]  
\hspace{1cm} (9)

which is the equation for net heat transfer by radiation between infinite parallel plates. In Eq. (9) \( \varepsilon \) is the emissivity of heating surface, \( \alpha \) the absorptivity of liquid and \( \kappa \) Stefan-Boltzmann constant.

Equation (7) can be rearranged into the dimensionless generalized form
\[ \text{Nu}_D = 0.62 (Ra_D \theta')^{1/4}, \]  
\hspace{1cm} (10)

where
\[ \text{Nu}_D = h D / k_v, \]  
\hspace{1cm} (11)

\[ Ra_D = D^3 \rho_c (\rho_i - \rho_v) g C_{pv} / (k_v \mu_v), \]  
\hspace{1cm} (12)

\[ \theta' = h f_g / (C_{pv} \Delta T_s) + 0.4. \]  
\hspace{1cm} (13)

Here the subscript \( D \) means that the Nusselt and modified Rayleigh numbers are based on the diameter of cylindrical heater.

Breen & Westwater analyzed the results of several investigators, including their own, for isopropanol and Freon-113, that were obtained on horizontal cylinders ranging from fine wires to large tubes, and concluded that the critical wavelength \( \lambda_c \) was sometimes preferred rather than the diameter as the characteristic length in the Nusselt and modified Rayleigh numbers, where
\[ \lambda_c = 2 \pi \left[ \frac{\sigma}{g (\rho_i - \rho_v)} \right]^{1/2}. \]  
\hspace{1cm} (14)

They also found that, depending on the value of the dimensionless ratio \( \lambda_c / D \), the boiling characteristics for a horizontal heater fell into three different regimes. However, they succeeded in correlating the data in all three by the equation
\[ Nu_{\lambda_c} = (0.59 + 0.069 \lambda_c / D) (Ra_{\lambda_c} \theta^*)^{1/4}, \]  
\hspace{1cm} (15)

where
\[ \theta^* = (h f_g / (C_{pv} \Delta T_s) + 0.34)^{1/2}. \]  
\hspace{1cm} (16)

This correlating expression is obviously a modified form of Eq. (10).

All the measured values are higher than the calculated results of Bromley's equation and agree better with the empirical correlation of Breen & Westwater, except for \( D = 0.1 \) mm. Similar tendency was observed with small diameter wires for water and common liquids. For such cases the vapor film thickness is comparable to the wire diameter, as *In the present experiments the radiative contribution was estimated to be less than 20% of the total heat transfer.*
suggested by Bromley. The Bromley's model is not applicable for this physical situation. In the higher $dT_s$ region wave motion or turbulent flow is further observed, especially due to the intermittent release of bubbles from the vapor film, which is not considered in Bromley's model where the vapor-liquid interface is assumed to be completely smooth, i.e. no capillary nor standing waves existing.

**Figure 7** shows the generalized plots of film-boiling heat transfer data in the dimensionless form. The abscissa is $\lambda_c/D$ and the ordinate $Nu_{\lambda_c}/(Ra\ast\theta^*)^{1/4}$. The figure contains other experimental results\(^{(19)}\)\(^{(20)}\)\(^{(28)}\)\(^{(31)}\) of water, organics and cryogenic liquids. The height of the bar indicated on the data does not mean the uncertainty range of the measured values, but the spread of each measurements.

Correlations predicted by Bromley and Breen & Westwater are also indicated in this figure. In the region $\lambda_c/D \leq 8$, fairly good agreement is observed between the experimental results and both correlations. For $\lambda_c/D \geq 8$, however, the measured values are higher than the Bromley's prediction (broken line) and lower than the empirical correlation of Breen & Westwater (solid line). The plots diverge increasingly from the theoretical curves with increasing $\lambda_c/D$, i.e. with decreasing wire diameter.

A dot-and-dashed line then gives a best fit for the data and is represented by the following equation:

$$Nu_{\lambda_c} = (0.75 + 0.032 \lambda_c/D)(Ra\ast\theta^*)^{1/4}. \quad (17)$$

### 4. Minimum Heat Flux

The transition from film boiling to nucleate boiling occurs at a heat flux known as the minimum heat flux $q_{\text{min}}$ (see Fig. 2). The minimum heat flux is normally of lesser im-
importance than the critical heat flux in fluid with high boiling point since the transition to nucleate boiling generally produces a marked reduction in surface temperature and then lessens the thermal loading on the system. In cryogenic fluids, however, one encounters a need to predict the minimum heat flux since the transition to nucleate boiling occurs at operating temperatures. The large changes in the heat transfer coefficient during the boiling transition must be considered for design of many applications.

Figure 8 shows the effect of heater diameter on the minimum heat flux data. In the present experiments the data of minimum heat flux were taken at the moment immediately before the transition from partial film boiling to nucleate boiling, i.e. no vapor film existing on the surface of heating wire. The minimum heat flux $q_{\text{min}}$ decreases with increasing diameter. In this figure are also shown the theoretical correlations predicted by Lienhard & Wong (21) for horizontal cylinders and by Berenson (22) for horizontal flat plates.

The film boiling regime is characterized by the steady formation and release of bubbles at the liquid-over-vapor interface over a heating element. Zuber (18) was the first to apply the Taylor instability theory to transition- and film-boiling heat transfer from a flat horizontal plate. Based on the analysis of Zuber, Berenson had determined the following relation for the minimum heat flux with film boiling on a horizontal flat plate,

$$ q_{\text{min}} = 0.09 \left( \frac{\rho_v}{\rho_l + \rho_v} \right)^{1/3} h_f g \frac{\rho_v \left[ \frac{\sigma g (\rho_v - \rho_l)}{\rho_v^2} \right]^{1/2}}{D \rho_l + \rho_v} $$

(18)

Accounting for the effect of surface tension in the traverse direction upon the Taylor instability of the interface for a horizontal cylinder, Lienhard & Wong derived the following correlation:

$$ q_{\text{min}} = 0.114 h_f \rho_v \frac{2 g (\rho_v - \rho_l)}{D \rho_l + \rho_v} \left[ \frac{\sigma g (\rho_v - \rho_l)}{\rho_v^2} \right]^{1/2} \left[ \frac{g (\rho_v - \rho_l)}{\sigma} + \frac{2 \gamma}{D^2} \right]^{3/4} $$

(19)

Although a partial film boiling, i.e. nucleate boiling coexisting with film boiling, is dominant at $q_{\text{min}}$ in the present experiments, the measured values agree well with the theoretical curve predicted from the correlation of Lienhard & Wong.

5. Microcharacteristics of Boiling

The knowledge of microcharacteristics of boiling, i.e. departure sizes of vapor bubbles, departure frequencies and growth rates, is important for understanding the heat transfer mechanism during boiling. For ordinary liquids that wet the heating surface, the departure size of bubbles has been studied by many investigators (23). There are, however, limited data for cryogenic liquids. This led the present authors to carry out a study on liquid nitrogen to examine the bubble size and frequency in saturated pool boiling.
Photograph 1 (a) shows a typical photograph of vapor bubble behavior on the heating wire ($D=0.5\,\text{mm}$) during nucleate boiling. Small bubbles of $0.43\,\text{mm}$ in average diameter stream forth from many nucleation sites on the wire. The number of nucleation sites is $9.55\times10^5\,\text{m}^{-2}$. The frequency of bubble formation is approximately $90\,\text{Hz}$ which was determined from the photographic records taken by the high-speed camera. In film boiling, however, a film of vapor is always formed on the heating wire, as shown in Photo. 1 (b). Waves are observed along the top of the wire, and the crest-to-crest average distance for the waves on the top of the wire is $7.2\,\text{mm}$, a value close to the critical wavelength $\lambda_c=6.6\,\text{mm}$. Larger bubbles of $3.6\,\text{mm}$ in average diameter are released from the top of the wire. A decrease of heat flux produces a partial film boiling where film boiling and nucleate boiling exist simultaneously along the heating wire, as shown in Photo. 1 (c).

From the above-mentioned observations, vapor bubbles or vapor films in liquid nitrogen are found to behave quite similarly to those in noncryogens.

Figure 9 shows the effect of changes in heat flux $q$ on the number of nucleation sites per unit area of the heating surface $n$, the frequency of bubble formation $f$ and the diameter of departing bubble $d_0$ for the wire diameter of $0.5$ and $1.0\,\text{mm}$. With the rise in heat flux the number of nucleation sites and the bubble diameter increase in the nucleate-boiling regime, and film boiling produces much larger bubbles. In this figure are also shown the theoretical values of Fritz$^{(24)}$ and the empirical correlation of Verkin & Kirichenko$^{(25)}$ in nucleate boiling.

Fritz considered a balance between buoyancy and surface tension forces to derive the expression for departure diameter

$$d_0=0.0208\,\beta\left[\frac{\sigma}{g(\rho_t-\rho_v)}\right]^{1/2},$$

(20)

where $\beta$ is the bubble contact angle. For most situations, the value of $\beta$ under dynamic conditions appears to be nearly constant at $45^\circ$. 

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Verkin & Kirichenko found that for 12 sets of data obtained on water, organics and 4 cryogenic liquids over the wide ranges of pressure and subcooling, both the diameter of departing bubbles and the frequency of bubble formation were correlated well with the reduced pressure \( P/P_c \), where \( P_c \) is the critical pressure. Applying their correlation to the present experimental condition \( (P/P_c = 3.0 \times 10^{-2}) \), \( d_0 = 0.46 \text{ mm} \) and \( f = 100 \text{ Hz} \) are obtained.

It can be seen from the figure that the measured values of bubble diameter fall below the theoretical line derived from Fritz's equation, but agree fairly well with the correlation of Verkin & Kirichenko although the data are scattered.

The microcharacteristics have often been used in deriving heat transfer correlations for saturated nucleate boiling*. Several correlations are based on one or more (simultaneous) contributions of the following mechanisms:

1. Transient conduction to the relatively cold (saturated) liquid that comes into the space vacated by the departure of the bubble.
2. Evaporation of a liquid microlayer at the base of a growing bubble.
3. Circulation of liquid in vicinity of a growing bubble due to thermocapillarity effects on vapor-liquid interface.

The third mechanism was thought to cause the high heat transfer rates for many years, and on the analogy of heat transfer in single-phase turbulent flow, investigators have derived an equation of the following type for nucleate pool-boiling heat transfer

\[
N_{ub} = A(Re_b)^{m_1}(Pr_l)^{m_2},
\]

where \( N_{ub} \) is the boiling Nusselt number, \( Re_b \) the boiling Reynolds number and \( Pr_l \) the liquid Prandtl number; \( A, m_1 \) and \( m_2 \) are constants.

Rohsenow\(^{(26)}\) defined a bubble Reynolds number by the relation

\[
Re_b = G_b d_b / \mu_t,
\]

where \( G_b = (\pi/6) d_b^3 \rho_v f n \), the average mass velocity of vapor receding from the heating surface.

He also defined the Nusselt number in Eq. (21) by the equation

\[
N_{ub} = q \, d_b / (\Delta T, k_l).
\]

The heat flux was evaluated by the equation

\* In the present experiments liquid nitrogen was maintained at saturation temperature.
\[ q_{nb} = \frac{\pi}{6} h_{fg} d_0^2 n. \]  
\[ (24) \]

A different nucleate-boiling heat transfer correlation was derived by Mikic & Rohsenow\(^{(27)}\). Their analysis is based on the first mechanism that the significant mode of heat transfer from the heating surface is transient conduction to the liquid of \( T_s \), which comes into the space vacated by the departure of the bubble and the superheated layer, and then contacts with the heating surface at \( T_w \). After the formulation and integration of related terms, they obtained the final equation of the average nucleate-boiling heat flux over the whole heating surface,

\[ q_{nb} = 2\pi k_i \rho_i C_{pi} f^{1/2} d_0 n DT_s. \]  
\[ (25) \]

Figure 10 shows a comparison of measured total heat flux \( q \) with nucleate-boiling heat flux \( q_{nb} \) predicted by Eqs. (24) and (25). In the calculation of \( q_{nb} \) the measured values were applied to \( f \), \( d_0 \), \( n \) and \( DT_s \). The solid line indicates a relation \( q_{nb} = q \).

The measured values of \( q \) are much higher than the predicted values of \( q_{nb} \) by Rohsenow's correlation, but agree well with the correlation of Mikic & Rohsenow. This means that the transient conduction to the relatively cold (saturated) liquid, which comes into the space vacated by the departure of the bubble, is dominant in the high heat transfer rates associated with nucleate boiling.

IV. CONCLUSIONS

Saturated pool-boiling experiments were conducted with an electrically heated horizontal wire in liquid nitrogen at atmospheric pressure. The wire diameter ranged from 0.1 to 1.0 mm. In each run the heater power was gradually increased and decreased by a specially designed power control system. Changes in the potential drop and the resistance of the wire were measured during boiling. Bubble behaviors were also recorded on the photo-film.

Comparison of the experimental results with various correlations yielded the following conclusions:

1. Nucleate-boiling heat transfer characteristics can be represented fairly well by Kutateladze's correlation, although the data are scattered.
2. The critical heat flux tends to be higher with increasing wire diameter. The measured values agree fairly well with the theoretical values predicted by Kutateladze et al. and Rao & Andrews.
3. The diameter of departing bubble (0.3~0.9 mm) and the frequency of bubble formation (approximately 90 Hz) agree fairly well with the correlations of Verkin & Kirichenko for nucleate boiling. The present data suggest that the transient conduction to the cold (saturated) liquid is much more responsible for the high heat transfer rates
associated with nucleate boiling.

(4) In film boiling the heat transfer coefficient decreases with increasing wire diameter. The measured values are higher than Bromley's correlation and agree fairly well with the correlation of Breen & Westwater. This is suggested by the photographic observations that the turbulent wave motion of vapor film is caused along the top of the wire.

(5) The minimum heat flux for film boiling decreases with the increase of the wire diameter. The measured values are in good agreement with the theoretical values predicted by Lienhard & Wong.

The foregoing observations in liquid nitrogen are similar to those in noncryogens, but much more studies are required experimentally and analytically in order to obtain the detailed knowledge about both nucleate and film boiling of cryogenic liquids, especially the microcharacteristics of boiling, including the size of departing bubbles, the frequency of bubble formation, the growth rate of bubble and the number of nucleation sites.

Transient boiling also occurs in an accident as well as during some normal operations, such as cooling down in many applications. Rapid temperature change during such transient boiling will significantly affect the strength of structures, which is important for safety. In order to fill this need transient boiling experiments are scheduled for coming years, based on the present steady-state boiling experiments.

[NOMENCLATURE]

\begin{itemize}
  \item \( A \): Proportionality constant in Eq. (21)
  \item \( B \): Proportionality constant in Eq. (2)
  \item \( C_p \): Specific heat
  \item \( D \): Diameter of cylindrical heater
  \item \( D_i \): Interfacial diameter of vapor film
  \item \( D^* \): Dimensionless diameter of cylindrical heater, defined by Eq. (4)
  \item \( D^*_i \): Same as \( D^* \), except that characteristic length is taken as \( D_i \)
  \item \( d_b \): Diameter of departing bubble
  \item \( f \): Frequency of bubble formation
  \item \( g \): Acceleration due to gravity
  \item \( h \): Total heat transfer coefficient
  \item \( h_c \): Convective (based on molecular conduction) heat transfer coefficient
  \item \( h_{fg} \): Latent heat of vaporization
  \item \( h_r \): Radiation heat transfer coefficient
  \item \( I \): Electric current flowing wire
  \item \( k \): Thermal conductivity
  \item \( m_1, m_2 \): Constant exponents in Eq. (21)
  \item \( n \): Number of nucleation sites per unit area of heating surface
  \item \( N_{u_b} \): Boiling Nusselt number, defined by Eq. (23)
  \item \( N_{u_D} \): Nusselt number based on diameter of cylindrical heater, defined by Eq. (11)
  \item \( N_{u_{\lambda_e}} \): Same as \( N_{u_D} \), except that characteristic length is taken as \( \lambda_e \)
  \item \( P \): Static pressure in liquid at boiling surface
  \item \( P_c \): Critical pressure
  \item \( Pr \): Prandtl number \((=C_p \mu/k)\)
  \item \( q \): Total heat flux
  \item \( q_{\text{max}} \): Critical heat flux
  \item \( q_{\text{maxf}} \): Critical heat flux for horizontal flat plate, defined by Eq. (6)
  \item \( q_{\text{min}} \): Minimum heat flux
  \item \( q_{\text{nb}} \): Nucleate-boiling heat flux
  \item \( R \): Electric resistance of wire
  \item \( Ra_D \): Modified Rayleigh number, defined by Eq. (12)
  \item \( Ra_{D,\lambda_e} \): Same as \( Ra_D \), except that characteristic length is taken as \( \lambda_e \)
  \item \( R_e \): Boiling Reynolds number, defined by Eq. (22)
  \item \( T \): Temperature \((\text{K})\)
  \item \( T_s \): Saturation temperature \((\text{K})\)
  \item \( T_w \): Temperature of heating surface \((\text{K})\)
  \item \( \Delta T_s \): Excess of temperature of heating surface above saturation temperature \((= T_w - T_s)\)
  \item \( V \): Potential drop of wire
  \item \( W \): Input power \((= VI)\)
  \item \( \alpha \): Thermal radiative absorptivity of liquid
  \item \( \beta \): Bubble contact angle
  \item \( \theta' \): Dimensionless heat parameter, defined by Eq. (13)
  \item \( \theta'' \): Dimensionless heat parameter, defined by Eq. (16)
  \item \( \kappa \): Stefan-Boltzmann constant, \(5.669 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}\)
  \item \( \lambda_e \): Critical wavelength, defined by Eq. (14)
\end{itemize}
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