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CONDENSATION ON A NONCOLLAPSING VAPOR BUBBLE IN A SUBCOOLED LIQUID

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IN A SUBCOOLED LIQUID

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SUMMARY

An experimental procedure is presented by which an estimate can be made of the condensation coefficient on a noncollapsing stationary vapor bubble in subcooled liquid nitrogen. The present experimental study utilizes film boiling from a thin wire to generate vapor bubbles which remain fixed to the wire at their base. A balance was established between the evaporation in the thin annular region along the wire and the condensation in the vapor bubbles.

INTRODUCTION

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Condensation of saturated vapor on cold surfaces has been studied extensively, as reported in the summary paper of reference 1. Because of recent interest in direct contact heat transfer, condensation has also been studied in relation to the decay of small vapor bubbles.

In reference 2, Florschuetz and Chao presented both a theoretical and experimental study of vapor bubble collapse in subcooled water and ethyl alcohol at atmospheric pressure. For a step increase in system pressure along with its associated increase in subcooling, their analysis indicated that the collapse rate might be controlled either by inertia force, heat transfer, or both, although in all their experiments the heat transfer mechanism dominated. Brucker and Sparrow (ref. 3) experimentally investigated direct contact condensation of saturated steam bubbles over a wide range of subcooling, system pressure, and bubble rise velocities. Most recently, Lee and Chan (ref. 4) presented a detailed mathematical analysis of how the various initial conditions affect bubble collapse in a subcooled liquid. Their analysis compares favorably with the previously published data of references 3 and 5 and predicts under what conditions bubble oscillations can be expected. If desired, these papers can be consulted for additional references concerning condensation of vapor bubbles.

In this study on bulk condensation, the collapse of vapor bubbles in a subcooled liquid as measured in reference 2 will be of particular interest. Florschuetz and

Chao measured the mean radius of a vapor bubble as a function of time. In using this indirect transient technique, the rate of change of the mean bubble radius with time is used to determine the heat flux and the condensation coefficient. Florschuetz and Chao also attempted to minimize the translatory motion of the bubbles by taking their measurements under a 6 foot free fall condition. However, they pointed out that small bubble velocities existed and could account for some of the deviation between experiment and theory.

In contrast to the indirect transient approach, an experimental procedure is now presented where the heat flux and condensation coefficient can be measured directly. The condensation coefficient is measured at a stationary interface in which the bubble does not collapse. In addition, this procedure eliminates the translatory motion of the bubble as well as the oscillations of the liquid vapor interface.

The present experimental study involves an extension of an earlier study of film boiling from a thin wire in a pressure vessel containing subcooled liquid nitrogen (ref. 6). In reviewing the previous film boiling data and movie sequencies, a set of system parameters (wire size, system pressure, subcooling, wire temperature, etc.) was found where a balance was established between evaporation and condensation of the film boiling vapor domes. The purpose of the present paper is to document the experimental method with the photographic results and to estimate the condensation coefficient from the photographic results and the measured system heating and bulk parameters.

LIST OF SYMBOLS

A_B	surface area of bubble, cm^2
C_v	specific heat of vapor at constant volume, J/g K
D	diameter of vapor dome, cm
D_A	diameter of vapor annulus, cm
D_W	diameter of wire, cm
g	local coefficient of gravity, m/sec^2
g_c	Newton's law conversion factor, 1 kg $m/N\ sec^2$
H'_{fg}	modified latent heat of vaporization, $h_{fg}(1 + 0.34\ C_v\ \Delta T/h_{fg})$
h_c	condensation heat transfer coefficient, W/cm^2 K
h_{fg}	latent heat of vaporization, J/g
k_v	thermal conductivity of vapor, cal/cm K
L	length of heating wire, cm
ℓ	characteristic length, eq. (A3)

P	system pressure, N/m^2
P_c	critical pressure, N/m^2
Q_c	total heat flow per cell, W
q	heat flux, W/cm^2
T_B	bulk temperature, K
T_S	saturation temperature, K
T_w	wire temperature, K
ΔT	temperature difference, K
ΔT_{sub}	subcooling temperature difference, $(T_S - T_B)$, K
X_{base}	length of bubble's base, see figure 2, cm
Y_D	height of vapor dome, cm
λ	cell wave length, cm
λ_N	cell wave length for liquid nitrogen, cm, eq. (A4)
μ_v	vapor viscosity, g/cm sec
ρ_L	density of liquid, g/cm^3
ρ_v	density of vapor, g/cm^3
σ	surface tension, N/m

PHYSICAL PHENOMENA

Film boiling from a horizontal wire is shown in figure 1 for a liquid at its saturation temperature ($\Delta T_{sub} = 0$) and for various levels of bulk subcooling ($\Delta T_{sub} > 0$). In film boiling, a layer of hot vapor supports a column of dense fluid. Thus, in a gravitational field this situation is inherently unstable. Figure 1 illustrates the form of these instabilities. At regularly spaced intervals along the wire, the vapor will break from the wire and escape under the influence of gravity into the bulk liquid, as shown by the rising bubbles in figure 1. In the saturated liquid ($\Delta T_{sub} = 0$), the bubbles rise with a constant volume, while in the subcooled liquid ($\Delta T_{sub} > 0$) the vapor condenses and the bubble quickly decreases in size.

As illustrated in figure 2, film boiling from a wire is characterized by the thin annular vapor blanket covering the wire and by spatially periodic vapor domes. The distance between domes is nearly constant with time. The growth and departure of a vapor dome has a temporal periodicity which represent some average cycle time. The cell wavelength as well as the average radius of the departing bubbles is proportional (ref. 7) to the critical wavelength of hydrodynamic stability theory (ref. 8). Predictions of λ are discussed in Appendix A.

Using the photographic evidence, the idealized geometry based on figure 2 was successfully used (ref. 9) to determine the heat-transfer characteristics of film boiling from thin horizontal wires. This model consists of a thin tubular vapor film between the wire and the liquid, with vapor escape points indicated by the dome-shaped areas.

The major portion of the heat transport occurs across the thin vapor film of the tubular portion between the vapor domes. In saturated film boiling the domes are considered to be so thick that essentially no heat is conducted through them. Physically, the domes act as hydrodynamic sinks into which the vapor generated in the annular region is released.

If the bulk liquid is subcooled, the growth rate of the bubble will be slowed by the process of condensation on the vapor dome. Eventually, when the bubbles break from the wire, they rise through the subcooled fluid and begin to condense and disappear, as shown in figure 1. The larger the subcooling the quicker the bubbles disappear. In the limit of very large subcoolings, there are situations where a vapor film cannot grow (ref. 10). In an intermediate case, it is possible for a vapor bubble to grow to a certain size at which time its volume will remain fixed.

In a review of earlier subcooled film boiling data and motion picture studies (ref. 6), a condition was found where the rate of condensation at the dome of figure 2 was just sufficient to balance the incoming vapor. In this case, the boiling process was no longer periodic in nature but attained a steady condition with well defined stationary vapor domes. Therefore, this experimental approach could be used to study condensation on a steady noncollapsing vapor bubble-liquid interface.

DESCRIPTION OF EXPERIMENT

The experiment was conducted in a double walled pressure vessel as shown in figure 3. The inner vessel was a 16.0 cm diameter by 32.0 cm high pressure vessel capable of operating up to 3.8 MPa (P_c of nitrogen is 3.417 MPa). The outer vessel was a vacuum insulating jacket. The assembly was equipped with quartz windows front and back for viewing. The system was pressurized on top with nitrogen gas. A 100 watt calrod heater was used to heat the pool to the desired bulk temperature following pressurization.

The test wires were mounted horizontally under spring tension to an assembly which was in turn mounted to an access door as shown in figure 4. All the instruments and lead wires were also mounted to the door. Two 0.250 mm diameter platinum wires 5.44 and 5.48 cm long and one 0.040 mm diameter wire 4.58 cm long were used as test heaters. Two pins 0.800 mm diameter were inserted in the mounting assembly below the wire at distances apart of 5.43 mm for the 0.250 mm wire and 5.60 mm for the 0.040 mm wire. These provide a dimensional reference for the visual observations. It was on the 0.040 mm diameter wire that the present data was obtained.

Pressure was measured with a bourdon tube gage accurate to 0.1 percent of full scale. Fluid temperature was measured with a platinum resistance thermometer rated accurate to within 0.1 K. The resistance of the platinum heater wire was calibrated and found to follow that of standard platinum. The average wire temperature was determined by measuring voltage drop across the wire and current through the wire. Heat was generated using a d.c. power supply with rms ripple of less than 0.05 percent of test voltage. A precision digital voltmeter was used for voltage measurements. Current was measured using the same instrument and a calibrated shunt. All measurements were backed up by redundant instruments. The system had a tendency to drift slightly while acquiring data. This coupled with reproducibility results limit claims on data accuracy to the following values: ±1.0%: fluid temperature, ±0.2 K; wire temperature, ±5%; and heat flux, ±5%.

The photographs were taken with a 16 mm high speed movie camera operating at 400 frames per second. Lighting was provided from the back by a 1000 watt lamp diffused through a frosted glass for better shadowgraph.

RESULTS

Experimental Data

Data taken in the manner described above for conventional film boiling of liquid nitrogen on 0.250 mm and 0.040 mm diameter horizontal platinum wires were reported in reference 6 for the following range of conditions.

$$0.03 \leq P/P_c \leq 0.99$$

$$78 \leq T_B \leq 126 \text{ K}$$

$$250 \leq T_w < 900 \text{ K}$$

$$0 \leq \Delta T_{sub} \leq 45 \text{ K}$$

$$8 \leq q \leq 70 \text{ W/cm}^2$$

In reviewing this data set only one case was found where an equilibrium condition existed with the vapor bubbles remaining stationary and film boiling evaporation just balancing condensation on the vapor dome.

A high speed movie photograph corresponding to this condition where evaporation and condensation are in balance is shown in figure 5. Notice that this balanced condition results in a clear fluid above the vapor domes, which indicates the lack of vapor domes breaking off and rising from the wire. In viewing the motion picture from which figure 5 was selected, occasionally a bubble would rise from the wire or collapse. Thus, figure 5 depicts a metastable condition in which any change of system parameters would destroy the pattern shown in figure 5.

The photograph of figure 5 was scaled to determine the diameter, height, and base of the vapor dome as well as the distance between domes. The distance of 5.60 mm between the pins in figure 5 was used in the scaling. Seven measurements on different domes were taken for the dome diameter and spacing as sketched in figure 2. The data for this metastable boiling/condensation condition are summarized in table I.

Condensation Coefficient

Evaporation occurs on the small annular area while condensation occurs on the much larger vapor dome. The large differences in area can be accommodated at equilibrium because condensation heat transfer has a much smaller driving temperature difference.

Condensation is assumed to take place on the outer area of the vapor dome. The area of the vapor dome can be approximated by the area of a truncated sphere of diameter D and height Y as shown in figure 2. Since Y and D are about equal (fig. 2) calculations show that the area of the missing spherical cap near the wire is negligible compared to the total area of the sphere; consequently, the area of the whole sphere is used to compute the condensation area. For a 0.693 mm sphere (see table I) the surface area is

$$A_B = \pi D^2 = 0.0151 \text{ cm}^2 \tag{1}$$

For future experiments, it would be useful to predict the cell size that would develop under different experimental conditions such as increased pressure or a different fluid. Appendix A presents a prediction scheme.

Assuming all heat from the wire goes into vaporizing the liquid, and that condensation is uniform around the sphere, the condensation heat transfer coefficient can be defined as follows:

$$h_c = \frac{Q_c}{A_B(T_S - T_B)} \tag{2}$$

In this case

$$Q_c = (\pi D_W \lambda) q = 0.102 \text{ W} \tag{3}$$

Therefore

$$h_c = 0.506 \text{ W/cm}^2 \text{ K} \tag{4}$$

In the previous section, all the heat leaving the wire was assumed to vaporize the liquid. This neglects superheating the vapor, and direct convection and radiation of heat into the bulk liquid. For a cryogenic fluid, the wire temperature (487 K) is too low to give significant amounts of radiation. The convection losses into the bulk liquid surrounding the thin annulus in figure 2 were also estimated to be small (ref. 10 - Appendix D). Neglecting superheating of the vapor probably is the only significant source of error in the above assumption. Estimates from reference 10 indicate that as much as 27 percent of the heat could be transferred into superheating the vapor. Thus, in the present experiment, the actual condensation heat transfer coefficient is probably within the range of 0.4 to 0.5 W/cm^2 K.

CONCLUDING REMARKS

An experimental technique is shown by which condensation can be studied on a noncollapsing bubble in a subcooled liquid. This experimental technique could be used to establish a data base for condensation on stationary bubbles over a range of pressures and subcooling.

APPENDIX A

CELL WAVE LENGTH AND BUBBLE DIAMETER

As mentioned in the body of the report, for future experiments it is desirable to predict the cell length (distance between domes as defined in fig. 2) that would develop in film boiling under different experimental conditions. References 11 to 13 have established a formula for the cell length λ in film boiling which depends primarily on the wire size and the liquid and vapor properties.

The latest and most general correlation which accounts for the cell length is given in reference 13 as

$$\lambda = \frac{2\sqrt{3}\,\pi\ell}{\sqrt{1 + 2(\ell/D_A)^2}} \tag{A1}$$

where the diameter of the vapor annulus D_A is given in reference 12 as

$$D_A = D_w \exp\left\{4.35\left[\frac{k_v \mu_v (T_w - T_S)}{H'_{fg} D_w \rho_v \sigma g_c}\right]^{1/4}\right\} \tag{A2}$$

and

$$\ell = \left[\frac{g_c \sigma}{g(\rho_L - \rho_v)}\right]^{1/2} \tag{A3}$$

In reference 13, equation (A1) has been compared to methanol, isopropanol, acetone, and benzene with generally good agreement between the data and experiments.

Figure 6 shows the photographs of film boiling from a wire in saturated liquid nitrogen. For $\ell/D = 3.5$, λ is calculated to be 0.27 cm from equation (A2) while the measured value is 0.44 cm. For $\ell/D = 22.1$, λ is calculated to be 0.0614 which is about half the measured value of 0.12 cm. Apparently, the correlation that predicts the cell wavelength weight the diameter of the wire too strongly for liquid nitrogen. Therefore, for the purpose of this paper, a simple empirical modification based on the data is applied to equation (A2) to yield

$$\lambda_N = \frac{2\sqrt{3}\,\pi\ell}{\sqrt{1 + 0.75(\ell/D_A)^2}} \tag{A4}$$

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TABLE I. - DATA FOR METASTABLE BOILING/CONDENSATION BALANCE IN SUBCOOLED LIQUID NITROGEN

(a) Geometry

D_w	= 0.040 mm
L	= 4.580 cm
D	= 0.693 mm
X_{base}	= 0.654 mm
Y_D	= 0.687 mm
λ	= 1.15 mm

(b) Operating conditions

P	= 0.342 MPa
T_B	= 79.0 K
T_S	= 92.4 K
T_w	= 487 K
q	= 70.8 W/cm^2

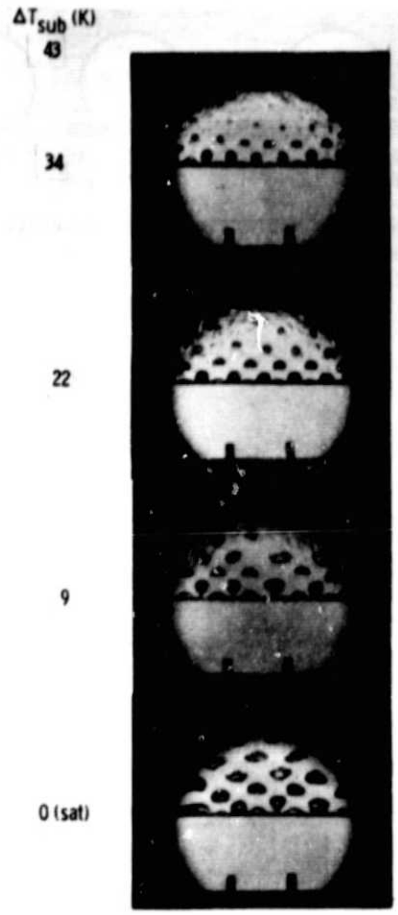


Figure 1. - Effect of subcooling on liquid vapor interface for 0.25 mm wire, (q ≈ 35 W/cm^2, and p/p_c = 0.54).

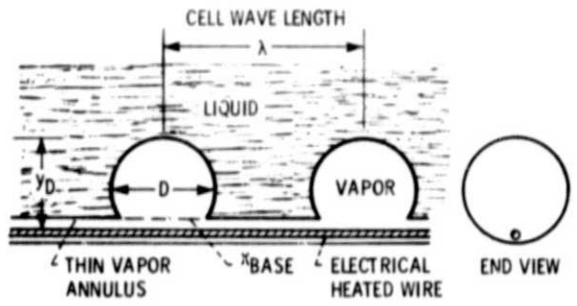


Figure 2. - Schematic representation of film boiling on an electrically heated horizontal wire.

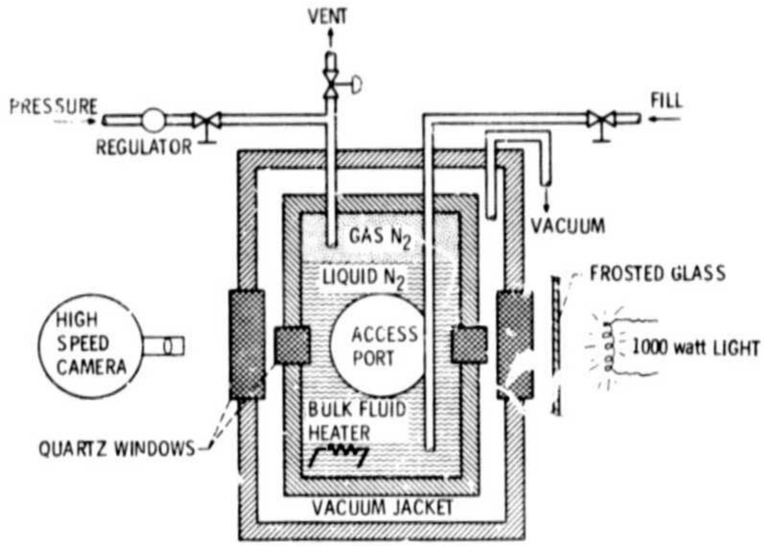


Figure 3. - Liquid nitrogen pool-schematic layout.

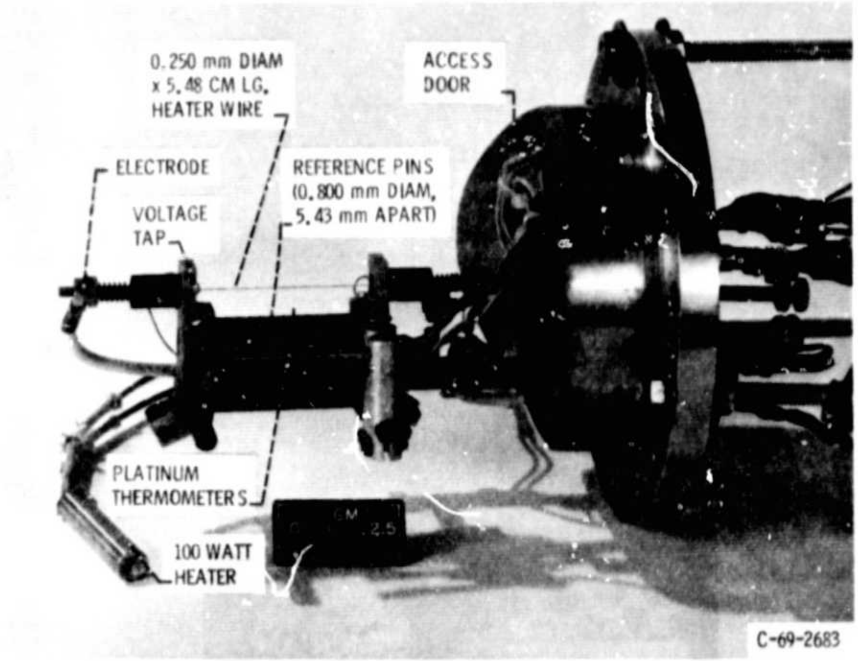


Figure 4. - Test heater wire and associated instruments.

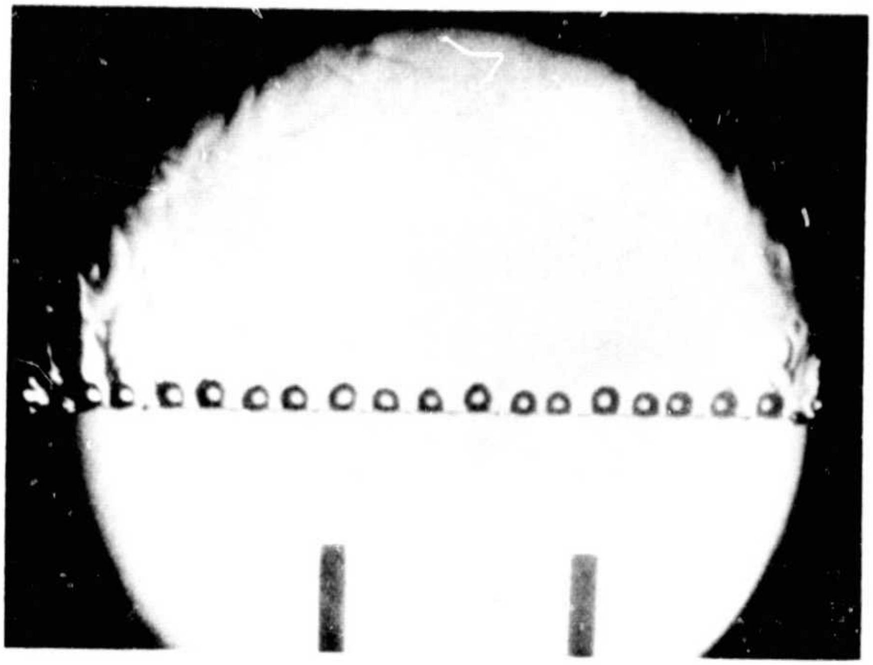
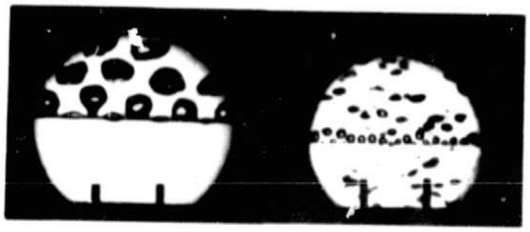


Figure 5. - Stationary subcooled film boiling.



$\ell/D_W = 3.5$
$D_W = 0.25$ mm

$\ell/D_W = 22.1$
$D_W = 0.04$ mm

Figure 6. - Effect of diameter on the saturated liquid-vapor interface. ($q \approx 35$ W/cm^2, $p/p_c = 0.13$).