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FILM BOILING NEAR THE CRITICAL STATE

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Abstract—The transition from column boiling to sheet boiling during film boiling in CO_2 in the two-phase region below the critical point is studied. It is found that this transition is due to the effect of the buoyancy forces acting upon the film formed around small horizontal wires.

NOMENCLATURE

B,	Bond number defined by equation (4);
R,	wire radius;
T,	temperature;
U,	speed of rise of the vapor;
Wb,	Weber number defined by equation (3);
a,	transverse vapor film thickness;
g,	gravitational constant;
h,	enthalpy per unit mass;
h_{vl},	heat of evaporation per unit mass;
k,	thermal conductivity;
p,	pressure;
q,	heat flux.

Greek symbols

α,	constant defined by equation (6);
β,	constant defined by equation (10);
γ,	defined by equation (9);
δ,	height of the vapor film;
λ,	vapor column spacing;
μ,	dynamic viscosity;
ρ,	density;
σ,	surface tension.

Subscripts

A, B, C, D,	refer to the points A, B, C, D;
a,	average;
l, v,	refer to the liquid, respectively the vapor phase;
m,	maximum;
w,	refers to the conditions at the heater wall.

INTRODUCTION

IT HAS been observed [1–3] that during film boiling from small horizontal wires in CO_2 close to the critical conditions, the following modes of vapor removal occur. At low heat fluxes nucleate boiling occurs in which vapor bubbles grow on the surface of the heater and detach when their diameter reaches a certain value. Increasing the heat flux gives rise to film boiling in which a layer of vapor completely covers the wire. Bubbles detach from the vapor–liquid interface (see Fig. 1a). Further increase of the heat flux results in the formation of vapor columns (see Fig. 1b) through which the vapor created in the film is transported. The same may be obtained at low heat fluxes by increasing the pressure close to the critical pressure of CO_2. Further increasing of the heat flux gives rise to increased instability of the vapor columns. Finally a point is reached at which the vapor columns cease to exist and the vapor moves away from the wire in a large vapor sheet (see Fig. 1c). It is this transition from vapor columns to a vapor sheet which will be studied here for the case of film boiling in CO_2 in the neighbourhood of the critical point and from small horizontal cylinders.

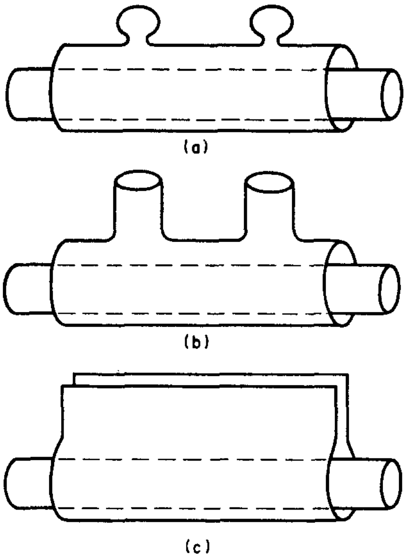

FIG. 1. The modes of vapor removal from a horizontal cylindrical heater at increasing heat flux: (a) bubble formation; (b) column formation; (c) sheet formation.

MAXIMUM COLUMN SPEED

During film boiling vapor is created by evaporation of the vapor–liquid interface. This vapor leaves the heated surface in the form of bubbles or columns which are formed at regular distances along the interface. It has been shown by Lienhard and Wong [4] that the spacing of these bubbles is equal to the wavelength of the most unstable displacement of the vapor–liquid interface. Grigull and Abadzic [1] and Abadzic and Goldstein [2] observed the same thing for the spacing of the vapor columns which occur at high heat fluxes and when the film boiling in CO_2 takes place at conditions close to the critical state.

The formation of these columns can be explained by means of the following argument. It has been observed that the diameter of the detaching bubbles is about half their spacing [4]. However, the latter is independent of the heat flux, such that the diameter of the bubbles is independent of the heat flux. The speed of rise of a gas bubble rising in a liquid on account of its own buoyancy depends upon its diameter and the properties (viscosity and density) of the gas–liquid system. So this speed of rise is also independent of the heat flux. Yet increasing the heat flux amounts to an increased vapor production rate which means an increased bubble production rate since size and spacing of the bubbles are independent of the heat flux. The distance covered by a bubble between its moment of detachment from the film and the moment when the next bubble detaches from the same spot thus decreases when the heat flux increases. If this distance becomes smaller than a bubble diameter then the separate bubbles will merge into a vapor column. This explains the vapor columns which are formed during film boiling at high heat fluxes.

Assuming the surrounding liquid to be stagnant, application of Bernoulli's equation to two points A and B located at the bottom and the top of the interface, but in the liquid, yields (see Fig. 2):

$$p_A - p_B = \rho_l\, g(2R+\delta).$$

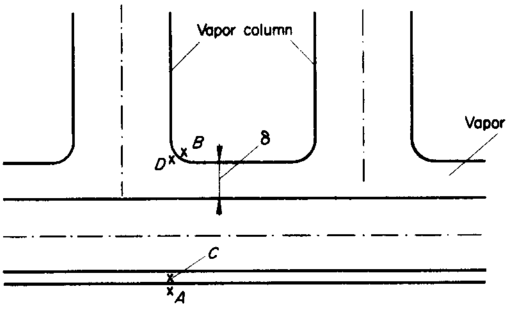

FIG. 2. Vapor columns detaching from the vapor film.

Because of this pressure difference, a vapor flow exists inside the film. The average vapor speed at the bottom D of the column is found by applying Bernoulli's equation to the points C and D in the vapor region, which gives:

$$p_C - p_D = \rho_v g(2R+\delta) + \tfrac{1}{2}\rho_v U^2.$$

Assuming that the vapor column has about the same radius as the vapor film $(R+a)$, then the pressure differences $p_A - p_C$ and $p_B - p_D$, which are due to surface tension, are equal, such that subtraction of the two equations gives:

$$\tfrac{1}{2}\rho_v U^2 = (\rho_l - \rho_v)g\,(2R+\delta).$$

Since vapor is generated all along the vapor–liquid interface, the average speed in the vapor column corresponds approximately to the speed due to gravitational acceleration over the distance $(2R+\delta)/2$. Furthermore, in a cross-section of the vapor film the vapor speed is not uniform: it is certainly zero at the wire and smaller than the maximum value at the vapor–liquid interface. Assuming the average velocity in a cross-section to be half the maximum value in this cross-section, the average vapor speed in the vapor column is found to be:

$$\rho_v U_a^2 = (\rho_l - \rho_v)g\left(R + \frac{\delta}{2}\right). \qquad (1)$$

In dimensionless form this last expression may be written as:

$$Wb^2 = B^2 \frac{R + \frac{\delta}{2}}{R} \qquad (2)$$

in which the dimensionless groups Weber number (Wb) and Bond number (B) are defined by:

$$Wb^2 = \frac{\rho_v U_a^2 R}{\sigma} \qquad (3)$$

$$B^2 = \frac{(\rho_l - \rho_v)gR^2}{\sigma}. \qquad (4)$$

Thus the Weber number is the ratio of the inertia forces to the surface tension forces, while the Bond number represents the ratio of the gravity forces to the surface tension forces.

In order to be able to estimate the height δ of the vapor film it will be assumed that the diameter of the vapor columns at the contact with the vapor film is approximately equal to the diameter of this film $2(R+a)$, in which a is the transverse vapor film thickness. Furthermore considering that the major contribution to the total heat flux, for the experiments under consideration, consists of the heat of evaporation carried away in the columns, it is possible to write the energy balance:

$$q = \frac{\rho_v h_{vl} U_a \pi (R+a)^2}{2\pi R\lambda}. \qquad (5)$$

It has been observed experimentally [1,2] that the vapor column spacing λ corresponds to the spacing between bubbles detaching from a cylindrical interface. Lienhard and Wong [4] showed this spacing to depend upon the Bond number based upon the radius of the interface. For small Bond numbers λ is proportional to this radius:

$$\lambda = \alpha(R+a). \qquad (6)$$

The proportionality factor α thus depends upon $[(\rho_l - \rho_v)g]/\sigma$ only and not upon the heat flux.

Substituting λ from (6) and U_a from (1) into (5), it is found that:

$$(R+a)^2\left(R + \frac{\delta}{2}\right) = \frac{4R^2\alpha^2 q^2}{\rho_v h_{vl}^2(\rho_l - \rho_v)g}.$$

Evidently a and δ are interrelated and are proportional to each other: a increases when δ increases. Therefore this last equality shows that for a certain experiment (fixed R and material properties) δ will increase with increasing heat flux. This has also been observed experimentally [1–3].

An increase in the film height gives rise to an increasing buoyancy force acting upon the film. This force can be held in equilibrium only by surface tension. The buoyancy force per unit length in the axial direction may be estimated to be

$$\pi\left(\frac{\delta}{2}\right)^2 (\rho_l-\rho_v)g,$$

as can be seen from Fig. 3 which shows a cross-section of the vapor film halfway between two vapor columns.

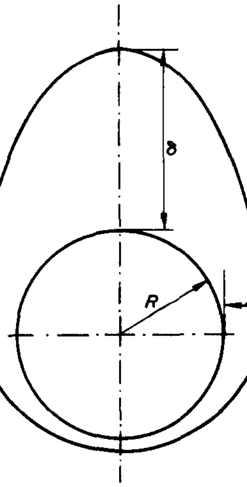

FIG. 3. Cross-section of the vapor film halfway between two vapor columns.

The retaining force is 2σ. Increasing q increases δ but leaves σ unchanged. Therefore it may be expected that at a certain heat flux the buoyancy force will become larger than the surface tension force, resulting in the destruction of the vapor film and giving rise to a vapor sheet. This maximum vapor thickness δ_m may be estimated by putting:

$$\pi\left(\frac{\delta_m}{R}\right)^2 (\rho_l-\rho_v)g = 2\sigma$$

or in dimensionless form:

$$\frac{\delta_m}{R} = \left(\frac{8}{\pi}\right)^{\frac{1}{2}}\frac{1}{B}. \quad (7)$$

To this maximum film thickness there corresponds a maximum Weber number found by putting $\delta = \delta_m$ into (2):

$$Wb_m = B\left[1+\left(\frac{2}{\pi}\right)^{\frac{1}{2}}\frac{1}{B}\right]^{\frac{1}{2}}. \quad (8)$$

Considering the simplifying assumptions made to obtain (8) it may be expected that this equality will not be satisfied exactly. Yet the above quantitative arguments show that the maximum Weber number is related to the Bond number by a relation of the form:

$$Wb_m = \gamma B\left[1+\left(\frac{2}{\pi}\right)^{\frac{1}{2}}\frac{1}{B}\right]^{\frac{1}{2}}. \quad (9)$$

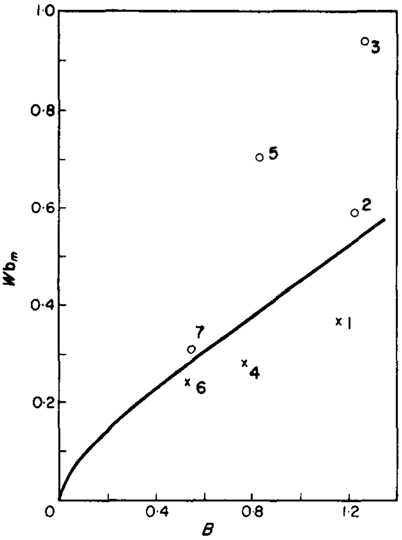

FIG. 4. The maximum Weber number as a function of Bond number: 1—Abadzic and Goldstein [2], q = 10 W/cm^2; 2—Abadzic and Goldstein [2], q = 18 W/cm^2; 3—Abadzic and Goldstein [2], q = 35 W/cm^2; 4—Nishikawa *et al.* [3], q = 3·14 W/cm^2; 5—Nishikawa *et al.* [3], q = 13·15 W/cm^2; 6—Grigull and Abadzic [1], q = 3·72 W/cm^2; 7—Grigull and Abadzic [1], q = 4·66 W/cm^2. Circled data points represent conditions under which sheet formation is observed.

On Fig. 4 this relation is represented for $\gamma = 0{\cdot}3$. Below the curve representing this relation, film boiling with vapor columns detaching from the film is possible. Above this line the upper part of the vapor film is destroyed and film boiling is only possible in the form of a vapor sheet leaving the wire. Also on Fig. 4 are represented the data points obtained from the experiments of Grigull and Abadzic [1], Abadzic and Goldstein [2] and Nishikawa *et al.* [3]. Only data points are represented for which these experimenters provide photographic pictures of the vapor formation on the wires. To calculate the Weber numbers, use is made of relation (5) to calculate U_a. In this relation the transverse film thickness is taken to be equal to the film thickness on a flat plate [5]:

$$a = \left[\frac{1{\cdot}09\beta\mu_v k_v(T_w-T_l)}{g\rho_v(\rho_l-\rho_v)(h_v-h_l)}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{\frac{1}{2}}\right]^{\frac{1}{4}} \quad (10)$$

in which β is a constant which is here taken to be equal to 7. In all the calculations use is made of the expression for surface tension established by Woljak [6] and mentioned by Grigull and Abadzic [1]. Furthermore use is made of the expressions for μ_v and k_v established by Kennedy and Thodos [7] and given in the paper of Abadzic and Goldstein [2]. The p, v, T diagram for CO_2 given by Martin [8], also reported by Abadzic and Goldstein [2] is used. The physical properties μ_v, k_v, ρ_v and h_v are all evaluated at the average temperature of the vapor film $T_w+(T_w-T_l)/2$. The sensible heat corresponding to this temperature is included in h_{vl}. The film widths thus obtained are about 20–40 per cent of the wire radius.

From Fig. 4 it can be seen that all the data points which correspond to sheet type film boiling are situated above the curve while the data points referring to column type film boiling are under it, as predicted by the theory above. Thus good agreement may be claimed between the present theory and the experimental observations.

The fact that the calculated maximum Weber numbers here are found by putting $\gamma = 0{\cdot}3$ in (9) may be due to the assumption that the vapor columns have a diameter of $2(R+a)$. If this overestimates the column diameter (as observations seem to indicate), then the real average vapor speed U_a obtained from (5) will be larger than the calculated one and the real Weber number will also be larger than the calculated one. The relation (9) will then be satisfied for a larger value of γ, thus agreeing better with (8).

CONCLUDING REMARKS

The present work provides an explanation for the transition from the vapor column mode of film boiling to the sheet mode. It is shown that at high heat fluxes the buoyancy forces in the vapor film will overtake the surface tension forces, thus destroying the upper part of the vapor film. This phenomenon is characterized by a maximum Weber number which depends upon the Bond number only. This relation obtained with the present theory is in good qualitative agreement with experimental observations on film boiling of CO_2 at conditions close to the critical state. A better quantitative result can be obtained by considering the whole flow problem inside the vapor film in detail.

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EBULLITION EN FILM AU VOISINAGE DE L'ETAT CRITIQUE

Résumé—On étudie la transition de l'ébullition en colonne à l'ébullition pelliculaire pendant l'ébullition en film dans du CO_2 dans la région biphasique en dessous du point critique. Il est trouvé que cette transition est dûe à l'effet des forces d'Archimède agissant sur le film formé autour de fils horizontaux.

FILMSIEDEN IN DER NÄHE DES KRITISCHEN PUNKTES

Zusammenfassung—Der Übergangsbereich zum vollständigen Filmsieden im unterkritischen Bereich wird bei CO_2 untersucht. Dieser Übergang beruht auf den Auftriebskräften, die auf den sich um dünne horizontale Drähte ausbildenden Film wirken.