Int. J. Heat Mass Transfer. Vol. 24, No. 10, pp. 1657 1665, 1981
Printed in Great Britain

0017 9310/81/101657 09 $02.00/0
Pergamon Press Ltd.

A NEW CRITERION OF DRY-OUT IN TWO-PHASE FLOW

J. MADEJSKI
Aeronautical Institute, Ignacy Łukasiewicz Technical University, Rzeszów, Poland

(*Received* 12 *May* 1980)

Abstract—The criterion of dry-out is formulated as a limit of mist flow in upstream approach namely in this way, that at the place of dry-out the mass flux of droplets is so great that they cover occasionally the whole section of the wall. Based on such an assumption the theory is established, and the results compared with experimental data for water flowing in vertical round tubes.

NOMENCLATURE

- a, thermal diffusivity; also disc diameter;
- c, specific heat at constant pressure;
- d, tube diameter;
- D, droplet diameter;
- Δh, enthalpy of vaporization;
- l, path of flight;
- La, Laplace number, equation (3.13);
- m_d, mass of a droplet;
- Pr, Prandtl number;
- $\mathbf{q}$, heat flux;
- Q, heat;
- Re, Reynolds number;
- S, slip ratio;
- t_c, time of contact;
- t_f, time of flight;
- T_s, saturation temperature;
- T_w, wall temperature;
- U, a constant, equation (3.6);
- $\mathbf{w}$, velocity;
- We, Weber number;
- x, quality.

Greek symbols

- λ, heat conductivity;
- μ, dynamic viscosity;
- ν, kinematic viscosity;
- ρ, density;
- σ, surface tension;
- φ, void fraction.

Subscripts

- w, wall.

Superscripts

- $'$, liquid;
- $''$, vapour.

1. INTRODUCTION

IN VERTICAL boiling channels with upward flow the two-phase flow regime at higher qualities is usually drop–annular. The heated surface is then covered with liquid film, disturbed by impingement and entrainment of droplets flowing in the vapour core. All the heat has to be transferred through the film, and hence the wall superheat may be moderate. However, at certain critical conditions the film breaks off or vanishes so that the wall assumes direct contact with vapour; this is connected with violent deterioration of heat transfer and with conspicuous rise of the wall temperature. Sometimes at those places of "dry-out" the film may be re-established after a moment, and the wall temperature drops. If the phenomenon is repeated one has to do with temperature oscillations which may be even more dangerous than the high wall temperature.

There seems to be general agreement that the critical phenomenon occurs when the film dries out as a result of evaporation and liquid entrainment from its surface, these processes being offset by droplet deposition from the vapour core. This statement allows to write down the liquid film mass balance in which the liquid mass fluxes of deposition and entrainment normal to the film surface must be introduced. In a recent review Hewitt [1] discusses a number of models proposed for the solution of the liquid film mass balance equation, differing in the treatment of deposition and entrainment mass fluxes. Such analyses may be called "the downstream approach", as they try to predict the limits of the drop–annular flow from the features of the same.

In this report we present another method, namely that of the upstream approach, consisting in prediction of the dry-out conditions on the basis of what follows, i.e. on the basis of the mist flow features. Evidently, in post-dry-out conditions the liquid appears only as droplets. They evaporate due to contact with superheated vapour, but they can also strike against the wall and evaporate very quickly in the ping-pong described and analyzed in [2]. As the droplet concentration diminishes along the channel in the post-dry-out section, the mass flux of droplets normal to the wall is the greatest at the dry-out position. At that point the situation may be well illustrated by the sketch taken from the report of Doroshchuk, Lantsman and Lewitan [3], Fig. 1. The interpretation of

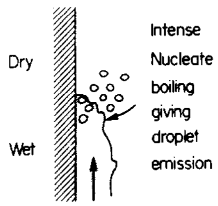

FIG. 1. Dry-out model according to Doroshchuk; figure taken from [1].

that phenomenon according to Doroshchuk *et al.* [3], is that intense nucleate boiling at the place of dry-out gives also intense droplet emission resulting in vanishing of the film. This explanation is typical for the downstream approach philosophy. In the "upstream approach" we would interpret the same Fig. 1 as follows: at the place of dry-out the mass flux of droplets is so great that they occasionally cover the whole field of view when looking in the direction normal to the surface.

An idealized model of such pattern of impinging and rejected droplets in mist flow is shown in Fig. 2. In post-dry-out conditions (Fig. 2a) the droplets strike against the wall (a process which corresponds to the deposition flux), flatten out on the surface to cover an area of a^2, a being the droplet diameter after flattening, and after a moment are rejected in the Leidenfrost phenomenon (which corresponds to the entrainment flux). The surface in this primitive model is divided into squares of side a, the droplets in contact with wall are denoted by circles, those flowing to the surface with smaller circles containing a letter c, and those flowing from the surface into the core are denoted by the same symbol reversed.

In the upstream approach to the place of dry-out the number of occupied sites in the square "lattice" in Fig. 2 grows, and finally (Fig. 2c) all the sites are occupied. The picture resembles then an unstable film, being broken at several places and differing only in geometry from a liquid film saturated with bubbles. In reality such a regular distribution of sites as in Fig. 2 is of course impossible. The droplets may contact the wall in the most irregular way, therefore as a sign of dry-out we can take that all the surface is in contact with droplets either resting, leaving or coming. Note that if such a situation should be preserved the number of impinging droplets must be equal to that of the rejected ones. If the former is greater then the destroyed liquid film will be re-established. This idea has been utilized in application of helical-flow inserts in flow boiling (cf. e.g. [4], [5]).

Thus it can be seen that the upstream approach must base on the dynamics of droplets, as well in flow with vapour core as in the encounter with the wall. The knowledge of the average diameter D of droplets is of particular importance.

2. CRITICAL HEAT FLUX

Suppose a droplet of saturated liquid of diameter D strikes a hot wall of temperature T_w with a velocity $\mathbf{w}_i$ normal to the surface. This droplet flattens to form a round disc of diameter $a = \xi_m D$, and thus covers the area

$$A_d = \frac{\pi}{4} a^2 = \frac{\pi}{4} \xi_m^2 D^2. \tag{2.1}$$

If such a layer of saturation temperature T_s is brought to sudden contact with a hot wall of temperature T_w then on the boundary the temperature

$$T_b = T_s + \Delta T = T_s + \frac{T_w - T_s}{1+\kappa}, \quad \kappa = \left(\frac{\lambda' c' \rho'}{\lambda_w c_w \rho_w}\right)^{1/2} \tag{2.2}$$

is established instantaneously. In this formula λ, c, ρ denote the heat conductivity, specific heat at constant pressure, and density; subscript w refers to the wall material, and primes to the saturated liquid.

Thus T_b is the maximum temperature of liquid, and it is clear that the heat removed from the wall to the droplet in a single encounter cannot exceed the value

$$Q = m_d c' \Delta T, \quad \Delta T = T_b - T_s, \tag{2.3}$$

where

$$m_d = \frac{\pi}{6} \rho' D^3 \tag{2.4}$$

is the mass.

Suppose now that the time between two subsequent encounters on the same site is t_d; it consists of the time of contact, t_c, and the time of flight, t_f; thus

$$t_d = t_c + t_f. \tag{2.5}$$

Denoting by l the path of flight with velocity $\mathbf{w}_i$ we have $t_f = l/\mathbf{w}_i$, and

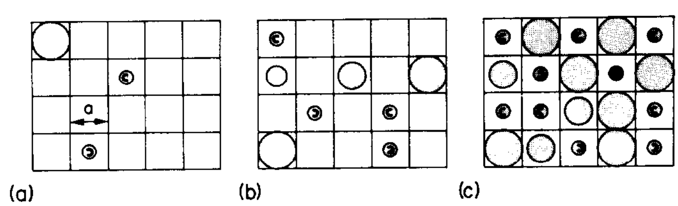

FIG. 2. Idealised model of droplet pattern in the vicinity of the wall; flattened droplets in contact with the wall shown thus ○, impinging droplets thus ©. rejected droplets thus Ⓢ ; the direction of flow is from the right to the left.

$$t_d = \frac{l}{\mathbf{w}_i}\left(1 + \frac{t_c \mathbf{w}_i}{l}\right). \tag{2.6}$$

The average heat flux on the site covered by the droplet is given by

$$\mathbf{q}_d = \frac{Q}{A_d t_d}, \tag{2.7}$$

or with use of equations (2.3) and (2.6) by

$$\mathbf{q}_d = \frac{m_d c' \Delta T \mathbf{w}_i}{A_d l\left(1 + \frac{t_c \mathbf{w}_i}{l}\right)}. \tag{2.8}$$

If only a portion of sites is occupied, as in the mist flow (Figs. 2a, b) then the average heat flux due to the contact of droplets with the wall is smaller in proportion. By addition of the heat flux removed directly by vapour convection the total average heat flux can be obtained.

Under the conditions of dry-out (see Fig. 2c) all the sites are occupied; therefore it must be

$$\mathbf{q}_d = \mathbf{q}, \tag{2.9}$$

where $\mathbf{q}$ is the total average heat flux in dry-out conditions, or the critical heat flux.

3. LEIDENFROST PHENOMENON

The dynamics of droplets in an encounter with the wall will be studied with help of a model demonstrated in Fig. 3. A droplet of diameter D approaches the wall with a velocity $\mathbf{w}_i$ normal to the surface (Fig. 3a). During the contact with the wall the droplet first flattens to form a round disc of diameter $\xi_m D$ (Fig. 3b). It is assumed that the process of flattening is very rapid and is not affected by vapour production at the boundary. It is assumed furthermore that this vapour production will take place immediately after the end of the flattening process in which liquid assumes the temperature $T_b = T_s + \Delta T$.

With the start of evaporation the droplet behaves like a rocket. In the initial phase of flight (Fig. 3c) the droplet has still a flattened form, and afterwards the surface tension forces re-establish the spherical shape of the droplet (Fig. 3d). The droplet is rejected from the wall with the velocity $\mathbf{w}_0$.

The first step in the analysis is the calculation of the quantity $\xi_m = a/D$. This has been done in the present author's report [6], concerning the solidification of droplets on cold walls with the application to plasma spraying and aircraft icing. The same theory applied for the case when droplets do not solidify on the surface leads to the following approximate formula

$$\frac{3\xi_m^2}{We} + \frac{1}{Re_i}\left(\frac{\xi_m}{1.2941}\right)^5 = \varepsilon = 1, \tag{3.1}$$

which was also given in [6]. Table 1 contains the results of accurate numerical calculations for the case in function of the Reynolds and Weber numbers

$$Re_i = \mathbf{w}_i D/\nu', \quad We = \rho' \mathbf{w}_i^2 D/\sigma, \tag{3.2}$$

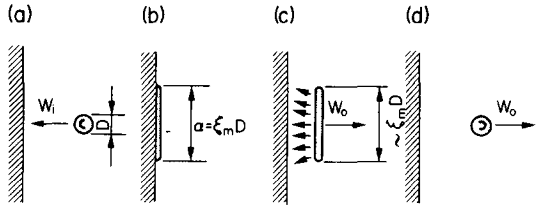

FIG. 3. Model of the Leidenfrost phenomenon for a droplet in flow normal to the hot wall.

where $\mathbf{w}_i$ is the impact velocity (as in Fig. 3a), ν' the kinematic viscosity of liquid, and σ the surface tension. Upper figures in Table 1 denote ξ_m, middle figures denote ε [which according to the approximate formula (3.1) should be equal to unity], lower figures denote the dimensionless time in which the dimension a of the disc is assumed, namely $t_m = 2\mathbf{w}_i t/D$. According to preceding assumptions this time t is identical with the time of contact t_c, so that

$$t_c = t_m D/2\mathbf{w}_i. \tag{3.3}$$

It is seen that the approximate formula introduces errors of a few percent. Furthermore from the numerical data contained in Table 1 it follows that

$$t_m \approx 1.17\,\xi_m \tag{3.4}$$

with mean-square error of 5%.

Let us study now the droplet in the role of a rocket, Fig. 3c. Its propulsion is due to evaporation, a process which may be studied with help of the model of evaporating superheated halfspace. Since the theory of the latter is known one may use the results according to which the mass evaporated in the moment t is equal to

$$\Delta m = A_d \rho' U \sqrt{(a't)}, \quad a' = \lambda'/c'\rho', \tag{3.5}$$

where the constant U fulfils the following transcedent equation

$$\sqrt{\pi}\frac{U}{2}\operatorname{erfc}\frac{U}{2}\exp\left(\frac{U}{2}\right)^2 = \frac{c'\Delta T}{\Delta h} = f\left(\frac{U}{2}\right), \tag{3.6}$$

where Δh is the enthalpy of vaporization. Values of the function $f(U/2)$ are given in Table 2.

During evaporation (Fig. 3c) vapour moves relatively to the droplet with a velocity

$$\mathbf{w}_p = \frac{\rho'}{\rho''}\frac{\mathrm{d}}{\mathrm{d}t}(U\sqrt{[a't]}) = \frac{\rho'}{\rho''}\cdot\frac{U}{2}\sqrt{\frac{a'}{t}}, \tag{3.7}$$

and this causes the droplet to move perpendicularly away from the wall with a velocity $\mathbf{w}_0$. Assuming constant momentum we obtain

$$(m_d - \Delta m)\,\mathbf{w}_0 = \Delta m\,(\mathbf{w}_p - \mathbf{w}_0), \tag{3.8}$$

whence

$$\mathbf{w}_0 = \frac{\Delta m}{m_d}\mathbf{w}_p = \frac{2A_d}{m_d}\cdot\frac{a'\rho'^2}{\rho''}\cdot\left(\frac{U}{2}\right)^2, \tag{3.9}$$

so that the Reynolds number, analogous to that of

Table 1. Results of the numerical solution of the equation of motion of flattening droplets

We \ Re_i	10^2	2×10^2	5×10^2	10^3	2×10^3	5×10^3	10^4	2×10^4	5×10^4	10^5
	3.077	3.462	4.008	4.433	4.845	5.320	5.594	5.785	5.930	5.986
100	1.044	1.045	1.052	1.061	1.072	1.084	1.090	1.093	1.095	1.096
	3.352	3.377	4.381	4.859	5.332	5.896	6.235	6.477	6.664	6.737
	3.156	3.584	4.222	4.756	5.325	6.103	6.686	7.204	7.742	8.016
200	1.012	1.007	1.007	1.010	1.015	1.025	1.039	1.046	1.052	1.055
	3.717	4.205	4.922	5.520	6.159	7.047	7.708	8.332	9.001	9.353
	3.211	3.668	4.366	4.973	5.651	6.658	7.505	8.399	9.617	10.507
500	1.002	0.995	0.989	0.986	0.986	0.987	0.994	0.999	1.008	1.015
	4.188	4.747	5.581	6.288	7.066	8.211	9.146	10.162	11.568	12.625

Upper figures denote ξ_m, middle figures ε, lower figures t_m.

equation (3.2), but for the rejected droplet, is equal to

$$Re_0 = w_0 D/v' = \frac{2A_d D}{m_d Pr'} \cdot \frac{\rho'^2}{\rho''} \cdot \left(\frac{U}{2}\right)^2, \quad (3.10)$$

where

$$Pr' = v'/a' \quad (3.11)$$

is the Prandtl number of liquid.

By making use of equations (2.1) and (2.4) we obtain also

$$Re_0 = \frac{3\xi_m^2}{Pr'} \cdot \frac{\rho'}{\rho''} \cdot \left(\frac{U}{2}\right)^2. \quad (3.12)$$

It is thus seen that the velocity w_0 (or the Reynolds number Re_0) depends upon the superheat ΔT via $U/2$ and equation (3.6), and also upon Re_i and We via ξ_m [equation (3.1)].

Now we will argue that in the Leidenfrost phenomenon it must be $w_i = w_0$, or $Re_i = Re_0$. Suppose first that the process shown in Fig. 3 takes place on a horizontal plate in the gravity field. In such a case if $w_0 < w_i$ then at assumed small rates of evaporation the droplet will land on the plate after several encounters; if $w_0 > w_i$ it will escape. In the case of a vertical hot surface, the inequality $w_0 < w_i$ leads finally to the establishing of a liquid film. By this argument the equation (3.12) represents a relationship between ΔT (or $U/2$) and $Re_i = Re_0$ and We for a given pressure. Since the Weber number contains also the velocity it is useful to express it by means of the Reynolds number thus

$$We = \frac{Re_i^2}{La}, \quad (3.13)$$

$$La = \sigma D/\rho' v'^2 \quad (3.14)$$

is the Laplace number; its reciprocal is sometimes called the stability number.

In Fig. 4 the graph ΔT vs. Re_i is given for water at 7 MPa. It is seen that each curve La = constant exhibits a minimum, ΔT_{min} at a value of $Re_i = Re$ equal to

$$Re = 3.0014\, La^{5/8}. \quad (3.15)$$

The corresponding value U_{min} equals

$$\frac{U_{min}}{2} = 0.7452\left(Pr' \frac{\rho''}{\rho'}\right)^{1/2} . La^{3/16}. \quad (3.16)$$

Substituting (3.15) and (3.13) in (3.1) and solving for ξ_m we obtain for the above condition

$$\xi_m = 1.3423\, La^{1/8}. \quad (3.17)$$

Turning to the interpretation of the Fig. 4 we have at $\Delta T > \Delta T_{min}$ two values of $Re_i = Re_0$, namely Re_i^+ and $Re_i^- < Re_i^+$. For all values of $Re_i < Re_i^-$ and $Re_i > Re_i^+$ there is $Re_0 < Re_i$, a fact which has been observed (cf. [7]), leading to the formation of the film at small rates of evaporation. For $Re_i^- < Re_i < Re_i^+$ it is on the other hand $Re_0 > Re_i$, a condition never observed experimentally. We thus may conclude that

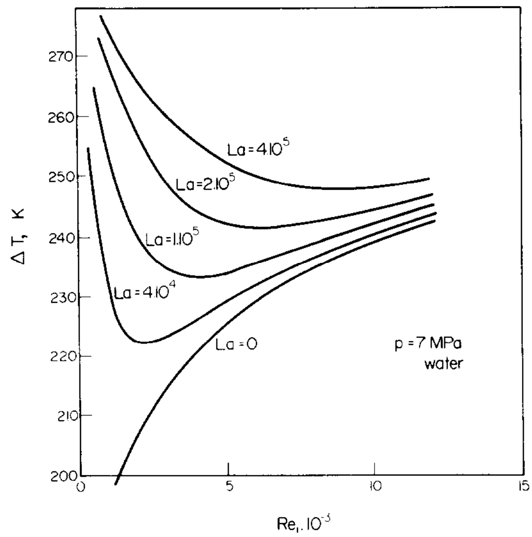

FIG. 4.

in the analyzed process the superheat ΔT attains its minimum value at a given droplet diameter D (or Laplace number La) and at a given pressure. Therefore in making use of the formula (2.8) the quantities (3.15–3.17) must be used. Thus utilizing equations (2.9), (3.3), (3.4) and (3.9) at $w_0 = w_i$, and quantities (3.15–3.17) we obtain the following formula for the critical heat flux

$$q = 1.11\frac{\rho' v' \Delta h}{l} \cdot \frac{La^{3/8}}{1+0.79\dfrac{\rho' v'^2}{\sigma l} La^{9/8}} \cdot f, \quad (3.18)$$

where $f = f(U_{min}/2)$, i.e. it also depends upon the Laplace number.

In this formula the length l of flight is not determined as yet. In the case of a round tube of diameter d it is natural to assume the proportionality $l \propto d$ so that the ratio l/d should be independent of other working conditions for a given tube diameter. This assumption must be verified experimentally.

Using the ratio l/d the formula (3.18) may be rewritten thus

$$\frac{qd}{\rho' v' \Delta h} = 1.11\frac{d}{l} \cdot \frac{La^{3/8}}{1+0.79\dfrac{\rho' v'^2}{\sigma d} \cdot \dfrac{d}{l} \cdot La^{9/8}} \cdot f . \quad (3.19)$$

4. AVERAGE DROPLET DIAMETER

The results of the foregoing theory express the local heat flux as a function of the local average droplet diameter. They are valid therefore for an arbitrary vertical channel with arbitrary cross-section under the condition that the dimension l is suitably chosen. Note that the working conditions as the mass velocity **G** and

Table 2. Values of the function $c'\Delta T/\Delta h = f(U/2)$

$U/2$	f	$U/2$	f	$U/2$	f
0.1	0.1590	1.0	0.7579	1.9	0.8976
0.2	0.2868	1.1	0.7832	2.0	0.9054
0.3	0.3906	1.2	0.8050	2.1	0.9123
0.4	0.4755	1.3	0.8240	2.2	0.9187
0.5	0.5457	1.4	0.8405	2.3	0.9242
0.6	0.6039	1.5	0.8550	2.4	0.9295
0.7	0.6549	1.6	0.8678	2.5	0.9341
0.8	0.6936	1.7	0.8790	2.6	0.9383
0.9	0.7283	1.8	0.8889	2.7	0.9422

vapour quality x do not appear in the formula (3.19); however, these quantities determine the average droplet diameter as it will be seen from the following argument.

The liquid mass flow rate, i.e. the mass flow rate of droplets in mist flow can be figuratively treated as a vector the lateral component of which was utilized in the analysis of the Leidenfrost phenomenon. In theories of drop–annular flow that lateral component is of vital importance since it determines the mass fluxes of entrainment and of deposition. In the presented theory the value of the lateral mass flux is of no importance, although its existence is the basis of the analysis.

In order to determine the average droplet diameter the longitudinal component of liquid mass flow rate will be utilized. One-dimensional slip flow is assumed with $\mathbf{w}'$ as the velocity of droplets, and $\mathbf{w}''$ that of vapour. In vertical upward flow and stationary conditions the friction force, calculated from the Stokes law, namely $3\pi\mu''(\mathbf{w}''-\mathbf{w}')$, where μ'' is the dynamic viscosity of vapour, is balanced by the gravity force $g\rho'\pi D^3/6$. Hence in equilibrium

$$\mathbf{w}''-\mathbf{w}' = \frac{g\rho' D^2}{18\mu''}, \tag{4.1}$$

so that the slip ratio is given by

$$S = \frac{\mathbf{w}''}{\mathbf{w}'} = \frac{1}{1-\dfrac{g\rho' D^2}{18\mu''\mathbf{w}''}}. \tag{4.2}$$

In the general case of 1-D two-phase flow it is

$$S = \frac{\rho'}{\rho''}\cdot\frac{x}{1-x}\cdot\frac{1-\varphi}{\varphi}, \tag{4.3}$$

where φ denotes the average void fraction, and

$$\mathbf{w}'' = \frac{x\mathbf{G}}{\varphi\rho''}. \tag{4.4}$$

Eliminating S and $\mathbf{w}''$ we obtain a quadratic equation

$$(1-\varphi)\left(1-\frac{g\rho' D^2}{18\nu'' x\mathbf{G}}\cdot\varphi\right) = \frac{\rho''}{\rho'}\cdot\frac{1-x}{x}\cdot\varphi, \tag{4.5}$$

from which φ can be found, and the result inserted in formula (4.4) to determine the vapour velocity as a function of the following groups:

$$\frac{x\mathbf{G}}{\rho''},\quad \frac{g\rho' D^2}{18\nu'' x\mathbf{G}},\quad \frac{\rho''}{\rho'}\cdot\frac{1-x}{x}.$$

As to the droplet diameter one must have in view that in developed mist flow, i.e. far from the place of dry-out, there must be a variety of droplet diameters of statistical nature. The reason for this statement is in particular the evaporation of droplets in contact with superheated vapour. At the dry-out position, however, the droplets are "fresh", i.e. they are created by entrainment due to disintegration of the film. In the latter process the droplet diameters may be comparatively great, but if it is so they must disintegrate due to their own instability. The greatest diameter of the droplet is determined by the critical Weber number

$$We_{crit} = \rho''\mathbf{w}''^2 D/\sigma = 12. \tag{4.6}$$

Note that this Weber number is defined in a different way to the one used previously, equation (3.2).

It is thus assumed that the significant (or average) droplet diameter is given by equation (4.6). To calculate it one must solve the set of equations (4.4), (4.5) and (4.6). This is possible by various iteration schemes applied to the equation

$$\frac{g\rho'\rho''^2\sigma^2}{18\nu''}\cdot We_{crit}^2\cdot z^2 = \frac{1}{\sqrt{z}} - \frac{\dfrac{\rho''}{\rho'}\cdot\dfrac{1-x}{x}}{\dfrac{1}{x\mathbf{G}}-\sqrt{z}}, \tag{4.7}$$

in which

$$z = \frac{\rho'}{\rho''}\cdot\left(\frac{\nu'}{\sigma}\right)^2\cdot\frac{La}{We_{crit}} = \frac{D}{\sigma\rho'' We_{crit}}. \tag{4.8}$$

Thus, if the working parameters as pressure, mass velocity $\mathbf{G}$, and vapour quality x are given one can compute the Laplace number $La = \sigma D/\rho'\nu'^2$ from equations (4.7 and 4.8). The latter substituted in equation (3.19) gives the value of the critical heat flux.

5. EXPERIMENTAL VERIFICATION

Fortunately there are very reliable data for the boiling crisis of water in vertical round tube of 8 mm bore, produced by the USSR Academy of Sciences [8]. The mean-square error of the recommended figures is 10%.

Sample results of calculations for the lowest pressure in the tables [8], i.e. 2.95 MPa, are given in Table 3. For this pressure it is T_s = 232.3°C, ρ' = 819.8 kg/m^3, ρ'' = 14.77 kg/m^3, Pr' = 0.87, ν' = 0.144 · 10^{-6} m^2/s, σ = 3.16 · 10^{-2} kg/s^2, Δh = 1.8014 MJ/kg, ν'' = 1.187 · 10^{-6} m^2/s. Figure 5 shows the relationship $\mathbf{q}d/\rho'\nu'\Delta h$ vs. Laplace number for all 74 data recommended [8] at 2.95 MPa. In 45 cases, denoted in Fig. 5 by black points, the dry-out occurs in drop–annular flow beyond doubt. The rest of data, shown by circles in Fig. 5, was recognized as slug flow by the method

Table 3. Sample results for water at 2.95 MPa flowing in tube of 8 mm bore with mass velocity 750 kg/m^{2}s

No.	x	$\mathbf{q}_{exp}$ (MW/m^2)	$La \cdot 10^{-5}$	$U/2$	f	$\frac{\mathbf{q}_{exp}\, d}{\rho' v' \Delta h}$	$\mathbf{q}_{exp}/\mathbf{q}$	l/d
1	0.05	7.95	8.866	1.217	0.808	299.1	1.05	0.2602
2	0.1	7.50	8.217	1.199	0.805	282.1	1.00	0.2939
3	0.15	7.10	6.126	1.134	0.791	267.1	0.99	0.3198
4	0.2	6.75	3.907	1.043	0.769	253.9	1.00	0.3168
5	0.25	6.45	2.616	0.967	0.748	242.6	1.02	0.2999
6	0.3	6.15	1.867	0.908	0.731	231.4	1.02	0.2833
7	0.35	5.80	1.394	0.859	0.714	218.2	1.01	0.2720
8	0.4	5.50	1.081	0.819	0.700	206.9	0.99	0.2612
9	0.45	5.25	0.833	0.780	0.686	197.5	0.98	0.2472
10	0.5	5.0	0.704	0.756	0.677	188.1	0.98	0.2429

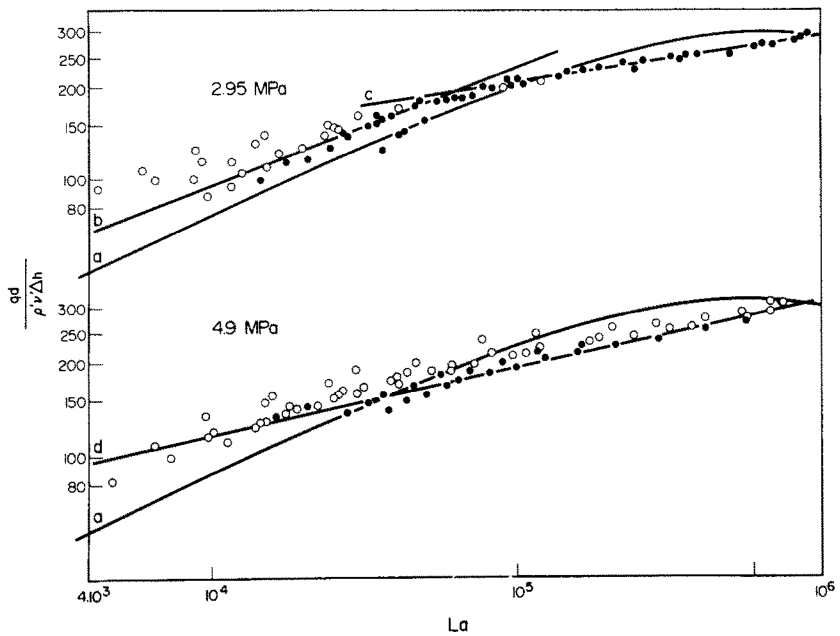

FIG. 5. Upper data: water 2.95 MPa, 8 mm bore, a—theoretical curve, b, c—empirical curves equation (5.1). Lower data: water, 4.9 MPa, 8 mm bore, a—theoretical curve, d—possible empirical correlation. Drop–annular flow shown by black points, slug flow by circles.

[9]; these data were not taken into account in correlations.

For every point the ratio l/d was calculated by use of equation (3.19); these ratios are given in Table 3. The average was $\langle l/d \rangle = 0.2636$ and this value was used to draw the curves a in Fig. 5. The mean-square error in the correlation of equation (3.19) (curve a) was then 11.9%, i.e. something greater than the 10% guaranteed by the recommendation [8]. However, it was possible to make a more accurate correlation for the pressure 2.95 MPa, namely

$$\frac{\mathbf{q}d}{\rho' v' \Delta h} = 36.9\, La^{0.15} \quad \text{for} \quad La > 8.10^4, \qquad (5.1)$$

$$\frac{\mathbf{q}d}{\rho' v' \Delta h} = 2.75\, La^{0.38} \quad \text{for} \quad La < 8.10^4.$$

The mean-square error in the first formula (curve c in Fig. 5) is only 2.2% (correlation coefficient 0.98), that in the second relationship (curve b in Fig. 5) is 6.7% (correlation coefficient 0.93).

The same procedure was applied to 75 data for 4.9 MPa [8], from which only 24 were recognized as drop–annular flow. Curve a for 4.9 MPa represents equation (3.19) with the same ratio $l/d = 0.2636$ as it was taken for 2.95 MPa. As it is seen from Fig. 5 also in this case the agreement between theory and experiment is tolerably good.

According to the tables [8] the critical heat flux is approximately inversely proportional to the square root of the tube diameter. From this theory it follows that for smaller Laplace numbers, when the denominator in equation (3.19) is close to unity, the critical heat flux should be inversely proportional to

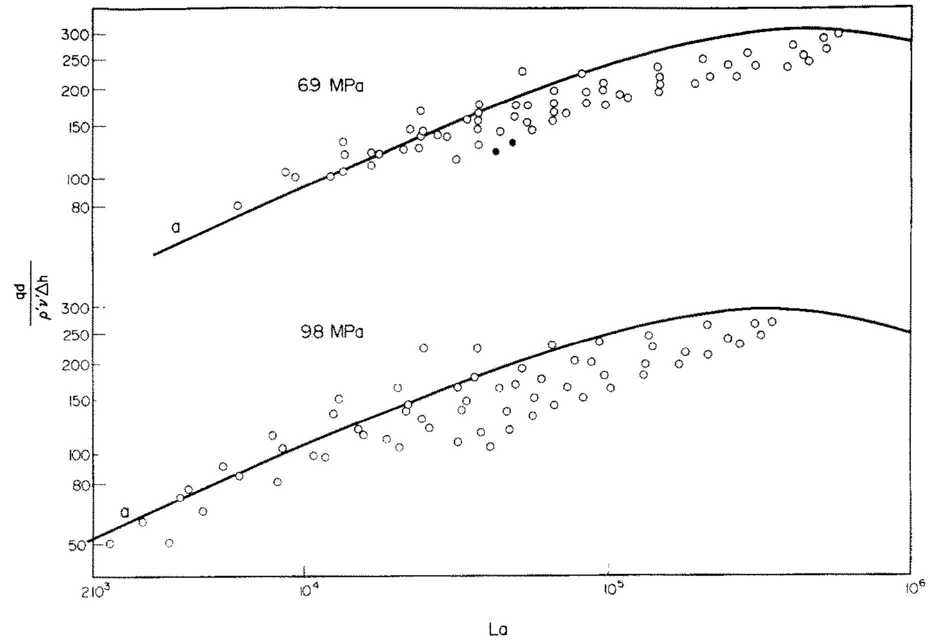

FIG. 6. Upper data: water 6.9 MPa, 8 mm bore, a—theoretical curve; only two points (marked black) were identified as drop–annular flow, other data represent slug flow (circles). Lower data: water 9.8 MPa, 8 mm bore, a—theoretical curve; all the experimental points refer to slug flow.

the tube diameter. For greater Laplace numbers the influence of the tube diameter is weaker. In Table 4 an example of $La = 8.10^5$ at 2.95 MPa is given. It is seen that the influence of diameter is similar to that in the recommended formula [8].

6. CONCLUSIONS

The present theory is based on a number of simplifying assumptions of which the more important will be briefly discussed here. First of all, it is assumed that in the case of dry-out all the surface is covered with flattened droplets of maximum diameter. Secondly, the time of contact of the droplet with the wall is assumed to be identical with the time of flattening. It is clear that such an assumption leaves much to be desired. Thirdly, the velocity of the droplet in the Leidenfrost phenomen is calculated without taking into account the resistance of flow in vapour. The next assumption refers to the heat absorption by the droplet in contact with the wall. It is assumed that the droplet is uniformly superheated to the temperature of contact T_b. Sure enough this superheat is attained mainly from the side of the wall, and this indeed causes the rocket effect by the rejection of the droplet. The last simplification to be criticised is the method of calculation of the average droplet diameter. It has been assumed that the flow is 1-D and with slip. It is known that in mist flow there are considerable differences between the average and the maximum velocity of vapour. Therefore using the critical Weber number the distribution of droplet diameters connected with the vapour velocity distribution might be found, and an average value established. It is obvious that this problem is connected with the question of average path of flight, l. It must be added that the slip is more important for greater droplets, or greater Laplace numbers; it would be better therefore to use in such cases more accurate formulae for the slip ratio.

Some of the above assumptions might be easily improved, i.e. it was possible without much effort to make the theory more complicated. Nevertheless, the present theory in comparison with experimental data gives correct results in these cases when the boiling crisis takes place in actual drop–annular flow. However, at higher mass velocities and higher vapour density to liquid density ratios such a flow regime is less probable than the slug flow. Therefore all the theoretical considerations with respect to the mechanism of the boiling crisis must begin with the identification of the flow régime. In the present study the method [9] has been utilized.

If in experiments the drop–annular flow has been identified, then—as it follows from the present

Table 4. Influence of the tube diameter on the critical heat flux. Water, 2.95 MPa, $La = 8 \times 10^5$

d (mm)	q(MW/m^2) from equation (3.19)	q(MW/m^2) from the proportion $q \propto d^{-1/2}$ [8]
4	10.9	11.3
8	8.0	8.0
16	5.2	5.6

report—a fairly accurate empirical correlation for a given system pressure can be done using a relationship $\mathbf{q}d/\rho'v'\Delta h$ vs. the Laplace number. Such a correlation in case of slug flow is characterized by considerable scattering of data (see Fig. 6).

The presented theory can be used, under the above conditions, in establishing of the scaling law for the modelling of the boiling crisis in drop–annular flow.

REFERENCES

1. G. F. Hewitt, Critical heat flux in flow boiling, *6th Int. Heat Transfer Conf., Montreal* (1978).
2. J. Madejski, On the evaporation of droplets in mist flow, *Bull. Acad. pol. sci. Sér. Sci. techn.*, **24**, 12, 31–35 (1976).
3. V. E. Doroshchuk, F. P. Lantsman and L. L. Lewitan, A peculiar type of burnout in evaporative tubes, *4th Int. Heat Transfer Conf., Paris.* Vol. 6, Paper B 6.1, (1970).
4. W. R. Gambill, R. D. Bundy and R. W. Wansbrough, Heat transfer, burnout and pressure drop of water in swirl flow through tubes with internal twisted tapes, ORNL—2911 (1960).
5. J. R. Stone, On the effect of helical-flow inserts on boiling pressure drop, *4th Int. Heat Transfer Conf., Paris*, Vol. 5, Paper B 5.1 (1970).
6. J. Madejski, Solidification of droplets on a cold surface, *Int. J. Heat Mass Transfer*, **19**, 1009–1013 (1976).
7. M. Cumo, G. E. Farello, Heated wall–droplet interaction for two-phase flow heat transfer in liquid deficient region, *Proc. Symp. Two-Phase Flow Dynamics*, Euratom, 1967.
8. Tabular data for calculation of the boiling heat transfer crisis of water in uniformly heated round tubes (in Russian), *Teploenergetika*, **9**, 90–93 (1976).
9. J. Madejski, Analysis of the two-phase slug flow in vertical channels, *Archiwum Termodynamiki* (to be published).

UN NOUVEAU CRITERE D'ASSECHEMENT EN ECOULEMENT DIPHASIQUE

Résumé—Le critère d'assèchement est formulé comme une limite de l'écoulement en brouillard dans une approche telle qu'à la place de l'assèchement, le flux massique des gouttelettes est si grand que celles-ci couvrent occasionnellement toute la section de la paroi. A partir de cette hypothèse on établit une théorie et les résultats sont comparés avec les données expérimentales pour l'écoulement d'eau dans des tubes verticaux à section circulaire.

EIN NEUES KRITERIUM FÜR DAS AUSTROCKNEN IN DER ZWEIPHASENSTRÖMUNG

Zusammenfassung—Das Kriterium für das Austrocknen wird (gegen die Strömungsrichtung betrachtet) als Grenze der Spritzerströmung formuliert: stromaufwärts vom Ort des Austrocknens wird der Massenstrom der Tröpfchen so groß, daß sie gelegentlich die ganze Wand bedecken. Auf dieser Annahme wird die Theorie aufgebaut; die Ergebnisse werden mit experimentellen Daten für Wasser bei senkrechter Rohrströmung verglichen.

НОВЫЙ КРИТЕРИЙ КРИЗИСА КИПЕНИЯ В ДВУХФАЗНОМ ПОТОКЕ

Аннотация — Критерий кризиса кипения для течения при наличии взвешенных частиц жидкости определяется как предельная величина, соответствующая области, где капли заполняют все сечение канала. На основе принятого допущения предложена теория процесса. Дано сравнение теоретических результатов с экспериментальными данными для течения воды в вертикальных круглых трубах.