

# A correlation for the limiting dryout steam quality in forced convection in uniformly heated vertical round tubes

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**Abstract**—The paper considers the thermal crisis which is associated with the wall liquid film dryout under the conditions of forced convection. On the assumption of heat transfer deterioration due to the break of film integrity, a dimensionless relation for these conditions is obtained which is used to derive a relation for the limiting steam quality. A comparison with 1115 experimental points for water, R-12, R-21, R-113, carbon dioxide, nitrogen, helium, parahydrogen, potassium, and sodium from 23 literature sources has shown that the mean deviation does not exceed 15%, while 91% of test data coincide within  $\pm 25\%$ .

## INTRODUCTION

RECENT investigations of the burnout heat transfer in the boiling of diverse liquids show that the main laws, that govern the heat transfer crisis in water, hold for these liquids too. Thus, at a particular combination of parameters these liquids have a more or less clearly defined, sloping (or vertical) segment of the function  $q_c = f(x)$  typical of the burnout which is associated with the wall liquid film dryout in annular-dispersed, two-phase flow called by Doroshchuk the second-kind crisis [1]. As a result, it is now possible, and there is already such a trend, to derive for the limiting steam quality corresponding to this kind of crisis, a single computational relation which would be applicable to different liquids.

At present at least three such relations have been suggested [2-4] in the hope of their universality, i.e. that with the same empirical coefficients they would predict the limiting steam quality of heat transfer deterioration for working bodies of different physical nature. The analysis of these relations (see, e.g. refs. [5, 6]) shows that they turn out to be quite inadequate for liquid metals.

However, investigations of the thermohydrodynamic characteristics of two-phase liquid metal flows made it possible to find out that:

- (1) the distribution of phases in a dispersed-annular potassium-vapour flow obeys the same laws that govern non-metal liquids [7];
- (2) the burnout heat transfer in boiling sodium [8] and potassium [9] occurs due to the liquid film dryout;
- (3) for boiling potassium there is a vertical [10] or sharply descending [11] portion in the function  $q_c = f(x)$ ;
- (4) in potassium vapour flow the crisis of hydraulic resistance [12] is observed characteristic for water [13] and other liquids.

These results indicate that, within the range of parameters corresponding to the dispersed-annular mode of flow, the thermohydrodynamic characteristics of two-phase flows of liquid metals do not differ in principle from those of other liquids. This allows one to hope for the existence of such a limiting steam quality correlation which would equally apply to liquid metals and non-metal liquids. Moreover, in the present author's opinion, the criterion for the universality of any relation of this kind is its applicability to liquid metals. Besides, this correlation could aid in developing an adequate physical model of the burnout associated with liquid film dryout. Following the above considerations, the task was set of obtaining a fairly exact, and as simple as possible, computational relation for the limiting steam quality of heat transfer deterioration in uniformly heated circular tubes which would be applicable to different working bodies, including liquid metals.

## BURNOUT MODEL

The physical model used in the present work is based on visual observations of this phenomenon reported by Hewitt *et al.* [14] who show that the liquid film dryout is a process which does not occur in a single section, and that first the film breaks up into rivulets the overall flow rate of liquid which approaches zero as these rivulets evaporate. This implies that the burnout is a process which occurs over a certain length of a steam generating channel. It starts with the 'deterioration of heat transfer', i.e. with the origination of the local dryout of a liquid film on the wall around the channel perimeter, and ends with the heat transfer 'crisis proper', i.e. the instant of local crisis spreading over the entire perimeter. It is therefore clear that, when referring to the thermal crisis, which owes its origin to the liquid film dryout,

## NOMENCLATURE

$Bo$	boiling number determined by equation (3) <sub>1</sub>	$\lambda$	latent heat of vaporization
$c_1, c_2, c_3, c_4$	constants	$\mu$	dynamic viscosity
$c_p$	heat capacity	$\nu$	kinematic viscosity
$D$	inner diameter of channel	$\rho$	density
$f$	function	$\sigma$	surface tension
$G$	mass velocity	$ d\sigma/dT $	absolute value of the surface tension gradient
$H$	liquid film thickness	$\psi_{DO}$	limiting steam quality simulation parameter determined by equation (13).
$k$	thermal conductivity; Prüger's constant		
$K$	dimensionless group		
$L$	length		
$Ma$	Marangoni number determined by equation (4)	<b>Subscripts</b>	
$N$	number of points	DO	dryout
$p$	absolute pressure	ex	experimental
$p_r$	relative pressure	G	vapour phase
$q$	heat flux	L	liquid phase
$q_c$	critical heat flux	lim	limiting
$Re$	Reynolds number determined by equation (2)	$q$	characterizes heat flux effect
$T$	temperature	$p$	characterizes pressure effect
$u$	velocity	pr	predicted
$We$	Weber number determined by equation (3) <sub>2</sub>	$s$	saturation
$x$	steam quality	T	corresponds to triple interface point
$x'_{lim}$	limiting steam quality.	$u$	characterizes effect of flow velocity
		w	value of parameter on the wall.
		<b>Superscripts</b>	
			mean value
		0	refers to the boundary between the first- and second-kind thermal crises.

Note:

$$\Delta_i = \left[ \frac{(x'_{lim})_{ex} - (x'_{lim})_{pr}}{(x'_{lim})_{pr}} \right]_i$$

is the relative deviation of the experimental value for the limiting steam quality from that predicted and

$$\sqrt{(\Sigma \Delta_i)^2 / N}$$

is the r.m.s. deviation.

one should bear in mind that there are two limiting steam qualities: at the start ( $x'_{lim}$ ) and at the end ( $x''_{lim}$ ) of the rivulet region.

The present author's analysis [15] of publications that deal with the heat transfer crisis that can, directly or indirectly, provide information about the extension of the liquid film dryout region  $\Delta x = x''_{lim} - x'_{lim}$ , has shown that the latter can be quite appreciable. For example, for boiling water  $\Delta x = 0.05-0.1$  [14, 16], and it is still larger for liquid metals,  $\Delta x = 0.2-0.4$  [17]. The influence of the technique of crisis detecting on the limiting steam quality in the case of the liquid film dryout with the formation of rivulets was analysed in ref. [18]. The results indicate that, depending on the technique, different phases of crisis development can be detected within the steam quality  $x'_{lim}$  and  $x''_{lim}$ . It is shown that a vast quantity of the available experi-

mental data on the burnout heat transfer present an objective testimony to the influence of the zone of rivulet drying of the liquid film on the experimental values of limiting steam quality, thus determining the character of segment II of the curve  $q_c = f(x)$  in Fig. 1.

The results indicate that this part of the curve in the coordinates  $q_c - x$  is not a line, but rather a band bounded by the qualities  $x'_{lim}$  and  $x''_{lim}$ . Based on this approach, it was found [18] that the sloping line  $x'_{lim}$  approximates most closely the condition for burnout heat transfer deterioration associated with the film dryout (Fig. 1).

In the present author's opinion, the above arguments make it possible to refine the model of this kind of crisis in the following fashion. The deterioration of heat transfer is a consequence of the disruption of

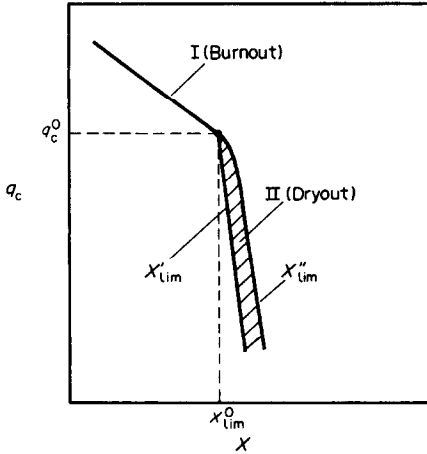


FIG. 1. The character of the function  $q_c = f(x)$  with regard for the zone of rivulet drying of a film.

liquid film continuity as a result of its rivulet-like drying out and is observed at the quality  $x'_{lim}$  which depends on  $p$ ,  $G$ ,  $D$  and  $q$ . Consequently, the means by which the limiting quality correlation can be obtained consists in the analysis of the conditions for the liquid film continuity disruption and of the effect of the above-mentioned parameters on it.

#### DEVELOPMENT OF THE CORRELATION

A qualitative analysis of the conditions for the liquid film continuity disruption as applied to the case of dispersed-annular flow in a steam generating channel has shown [19] that its break-up is determined by a set of the numbers

$$(Re_L)_{min} = f(Ma, Bo, We, x) \quad (1)$$

where

$$(Re_L)_{min} = \left( \frac{\bar{u}_L H_L}{\nu_L} \right)_{min} \quad (2)$$

is the limiting value of the film Reynolds number at which its continuity is broken

$$Bo = \frac{q}{\lambda \rho_G u_G}; \quad We = \frac{\rho_G u_G^2 D}{\sigma} \quad (3)$$

$$Ma = \frac{H_L (T_w - T_s) \left| \frac{d\sigma}{dT} \right|_s}{\alpha_L \mu_L} \quad (4)$$

where  $Ma$  is the Marangoni number which determines the degree of the thermocapillary force effect along the film surface at the triple interface where the film contracts into rivulets.

The incorporation of this number into equation (1) is based on the following considerations. When a liquid film borders on its own saturated vapour, its surface temperature is close to the saturation temperature. This fact is self-evident as regards those portions of the film which are located far enough from

the place of its rupture, i.e. from a dry patch. However, the film thickness on the meniscus near the dry spot decreases to zero, while its surface temperature increases and becomes higher than  $T_s$  at the triple interface. This phenomenon was observed experimentally by McPherson and Murgatroyd [20] with the aid of resistance paper analogues and was analysed in detail by McPherson [21] in terms of Prüger's 'sinking velocity' [22]. This excess in the temperature was attributed to the excess of the local pressure on the meniscus in the vicinity of the triple interface  $p_T$  over the saturation pressure  $p_s$  by the value

$$\Delta p = \frac{q}{k \rho_L \lambda} \quad (5)$$

where  $k = 1.65 \text{ ft h}^{-1} \text{ lb}^{-1} \text{ in}^2$  is Prüger's constant

$$\frac{q}{\rho_L \lambda} = v_L$$

is Prüger's evaporation-related 'sinking velocity' at the interface, whereas the triple interface temperature is equal to the saturation temperature which corresponds to the pressure  $p_T$ .

In the present author's opinion, an alternative explanation of this excess is that the triple interface neighbourhood is surrounded by vapour which is heated on the side of the dry patch to the temperature exceeding  $T_s$  and this brings about the increase of the triple interface temperature to that of the superheated vapour.

Thus, the existence of the temperature gradient on the meniscus gives rise to the surface tension gradient and consequently to the appearance of a thermocapillary force [23]. Along with the other forces, it will depend on the magnitude of this force whether the dry patch will persist after the film rupture or the wall will be rewetted. It is precisely this fact which is taken into account by the Marangoni number.

Based on the results of corresponding experimental investigations into the phenomenon considered, equation (1) can be presented in a more specific form as [19]

$$(Re_L)_{min} = c_1 \frac{Ma^{0.5}}{Bo We x^2}. \quad (6)$$

As follows from the model considered, equation (6) basically determines the condition for the onset of heat transfer deterioration in the case of the second-kind crisis. The substitution of equations (2)–(4) into equation (6) and respective transformations which account for the fact that  $x$  is the unknown quantity  $x'_{lim}$  will yield

$$(x'_{lim})^2 = c_2 \left[ \frac{\nu_L^2 \left| \frac{d\sigma}{dT} \right|_s}{q k_L \alpha_L \mu_L} \right]^{0.5} \frac{\lambda \sigma \rho_G u_G}{\rho_G u_G^2 D \bar{u}_L}. \quad (7)$$

Noting that

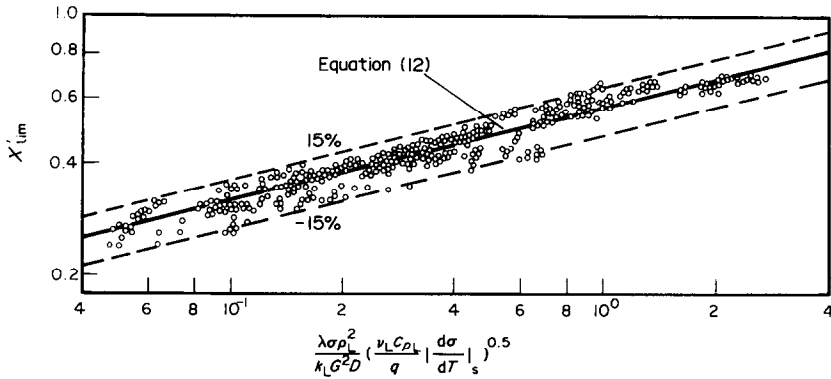


FIG. 2. Comparison between the predicted and experimental data on burnout heat transfer for water [24]:  $p = 29.4\text{--}127.5$  bar;  $G = 1000\text{--}5000$  kg m $^{-2}$  s $^{-1}$ ;  $D = 8$  mm.

$$\alpha_L = \frac{k_L}{\rho_L c_{pL}}, \quad \mu_L = v_L \rho_L, \quad \rho_G u_G = x'_{\text{lim}} G \quad (8)$$

it is possible to reduce equation (7) to the form

$$(x'_{\text{lim}})^4 = c_3 \frac{\lambda \sigma \rho_G^2}{k_L G^2 D} \left( \frac{v_L c_{pL}}{q} \left| \frac{d\sigma}{dT} \right|_s \right)^{0.5} \frac{u_G}{\bar{u}_L}. \quad (9)$$

Here, the quantity  $u_G/\bar{u}_L$  remains to be determined. Following Doroshchuk [1], it is possible to assume that this quantity is independent of the mass velocity, but is a function of pressure

$$\frac{u_G}{\bar{u}_L} = K_p \quad (10)$$

and depends on the relationship between the densities of the liquid and vapour phases.

The analysis shows that the best agreement with the experimental data is obtained when it is assumed that

$$K_p \sim (\rho_L/\rho_G)^2. \quad (11)$$

Then, with this equation taken into account, the final expression for  $x'_{\text{lim}}$  will take the form

$$x'_{\text{lim}} = c_4 \left[ \frac{\lambda \sigma \rho_L^2}{k_L G^2 D} \left( \frac{v_L c_{pL}}{q} \left| \frac{d\sigma}{dT} \right|_s \right)^{0.5} \right]^{0.25}. \quad (12)$$

The constant in this equation was determined from experimental data on burnout heat transfer for water as the most thoroughly studied working body. For this purpose, the results of Smolin [24] were used as being systematic, obtained for a wide range of parameters and most reliably corresponding to the model considered. As a result, it has been found that  $c_4 = 0.568$ .

Figure 2 presents the experimental data of ref. [24] in the coordinates of equation (12). The results show that all the points group near the line given by the relation obtained with the standard deviation of 7.2%; 90.1% of the data coincide within  $\pm 12\%$ , and 95.1% within  $\pm 15\%$ . This agreement with the prediction for  $G = 1000\text{--}5000$  kg m $^{-2}$  s $^{-1}$  and  $p = 29.4\text{--}127.5$  bar indicates that equation (12) accounts correctly for the effect of operational parameters on the conditions of heat transfer deterioration.

It follows from equation (12) that  $x'_{\text{lim}} \sim D^{-0.25}$ . This is in accord with the findings of ref. [25] regarding the effect of the channel diameter on the limiting quality. To verify the range of the applicability of equation (12) with respect to  $D$ , the predicted results were compared with experimental data on the burnout heat transfer in tubes of 'small' ( $D = 0.004$  m [25]) and 'large' ( $D = 0.02$  m [26],  $D = 0.04$  m [27]) diameters. A perfect satisfactory agreement between the prediction and experiment has been found for these diameters.

Consequently, a conclusion can be drawn that equation (12) is suitable for determining the conditions of heat transfer deterioration for water boiling in straight tubes with the diameters of  $D = 0.004\text{--}0.04$  m and uniform distribution of  $q$  within the ranges of the parameters  $G = 300\text{--}5000$  kg m $^{-2}$  s $^{-1}$  and  $p = 30\text{--}150$  bar.

#### COMPARISON OF THE PROPOSED RELATION WITH EXPERIMENTAL DATA FOR DIFFERENT FLUIDS

Equation (12) has a dimensionless form, it has been derived from equation (6), which accounts in dimensionless terms for the heat transfer deterioration in a steam generating channel. It was therefore presumed that this equation could be good for various fluids. To verify this assumption, all the available reported experimental data on burnout heat transfer in boiling of various liquids under the conditions of forced flow and uniform distribution of  $q$  were compared with the prediction. Selected for the analysis were the data that pertained to the crisis originating because of the liquid film dryout, i.e. those data which: (a) either relate to the vertical or sharply descending segment II of the curve  $q_c = f(x)$  (Fig. 1) (these are the data for water [24–28], R-12 [29, 30, 32–34], helium [35–38]), (b) or, when the number of points is insufficient and it is difficult to identify their location, were surely obtained in the ranges of the parameters  $p$ ,  $G$ ,  $q$ ,  $x$  that corresponded to the conditions of film dryout in a dispersed-annular mode of flow. These are the data for

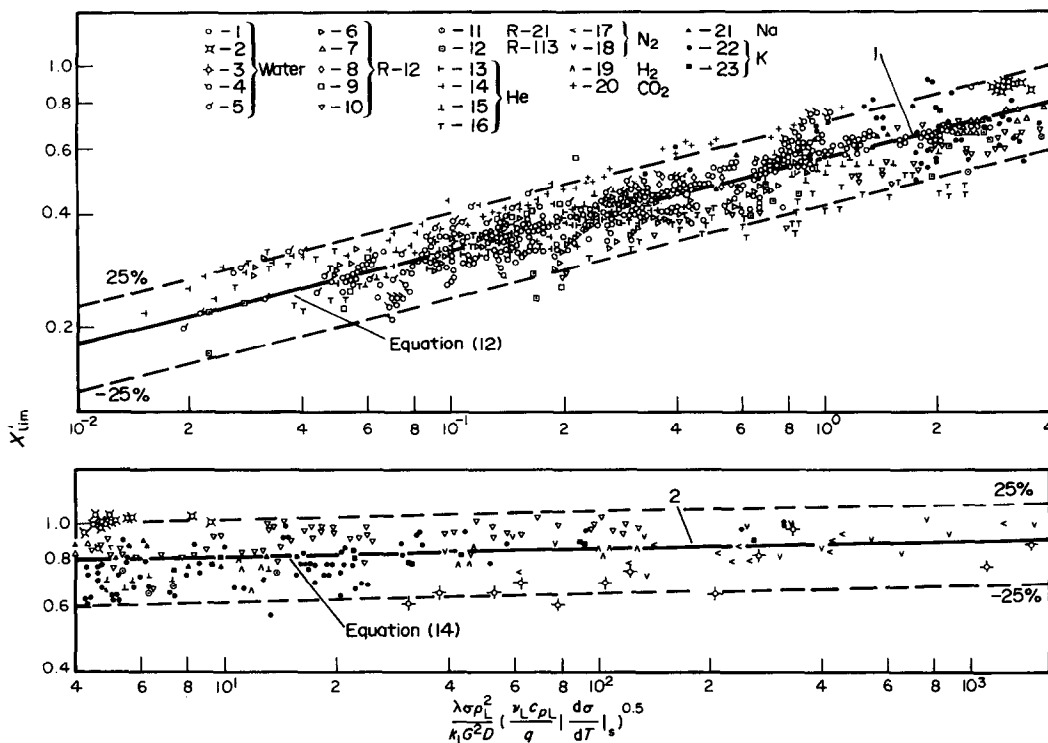


FIG. 3. Master plot of the generalization of experimental data on burnout heat transfer for various liquids.

water [39] (in the region of small mass velocities and pressures), R-21 [40, 41], R-113 [42], parahydrogen [43], nitrogen [43, 44], and carbon dioxide [45].

As regards the data on liquid metals (potassium [47] and sodium [8]), then, based on the ideas advanced in the Introduction, it was assumed that all of these pertain to dryout. This assertion is also based on the analysis made by Katto who found [48] that the data on potassium burnout heat transfer related to the so-called L-regime when the crisis, in his opinion, was due to the liquid film dryout.

The ranges of parameters investigated in the above-mentioned works are summarized in Table 1. It also contains the present author's data on the burnout heat transfer for potassium boiling in a straight 0.008 m diameter vertical tube.

The thermophysical properties were taken as given: in ref. [49] for water, in refs. [49, 50] for R-12, R-21, R-113, in refs. [49, 51] for nitrogen, helium, parahydrogen, in ref. [49] for carbon dioxide and in ref. [52] for potassium and sodium. All the properties were taken at the saturation temperature.

Figure 3 presents these data which have been processed in the coordinates of equation (12).

It is seen that the group

$$\frac{\lambda \sigma \rho_L^2}{k_L G^2 D} \left( \frac{v_L c_{pL}}{q} \left| \frac{d\sigma}{dT} \right|_s \right)^{0.5} = \psi_{DO} \quad (13)$$

allows one to rather closely bring together the values of  $x'_{lim}$  for different liquids and it can be treated as the parameter for limiting steam quality simulation.

### FINAL RELATION

The analysis of the results obtained shows (Fig. 3) that there are two distinct regions in the relation  $x'_{lim} = f(\psi_{DO})$ . In the first region ( $\psi_{DO} < 4$ ) the values of  $x'_{lim}$  are described well by equation (12); the results lie along correlation line 1. In the second region ( $\psi_{DO} > 4$ ), the experimental points start to deviate from line 1 and group along line 2 approaching the value  $x = 1$ .

The above can be explained as follows. It is known that there is a certain limiting vapour velocity below which the droplets do not shed from the liquid film. To this velocity there corresponds the limiting mass velocity  $G_{lim}$  [53] below which there is no entrainment of droplets in the entire range of qualities. This leads to the situation when with  $G < G_{lim}$  the film should dry out in a purely annular flow. However, in an actual steam-generating channel the entire range of qualities is present and, consequently, all of the structures of a two-phase flow are successively realized. Therefore, on the one hand, at  $x'_{lim}$ , even when  $G < G_{lim}$ , the flow core should contain droplets resulting from the destruction of liquid slugs in transition from the plug to a purely annular mode of flow. Moreover, under these conditions the flow core may contain liquid splashed by bubbles growing in the liquid film on the heating surface.

On the other hand, as follows from the model considered, at  $x'_{lim}$  a portion of the liquid should also be present in the channel corresponding to its flow rate in rivulets.

Table 1. The data analysed for developing and verifying the proposed relation

Labelling of points Fig. 3	Reference	Liquid	D (mm)	L/D	Pr
1	Smolin [24]	water	8	187-680	0.133-0.574
2	Levitan and Lantsman [28]	water	8	375	0.24-0.312
3	Sevastiyarov <i>et al.</i> [39]	water	8	50-150	0.00775
4	Levitan <i>et al.</i> [25]	water	4	375	0.222-0.619
5	Belyakov <i>et al.</i> [27]	water	40	125-200	0.687
6	Merilo and Ahmad [29]	R-12	5.3	575.5	0.254-0.368
7	Groenveld [30]†	R-12	7.8 and 11	177	0.266
8	Gorban <i>et al.</i> [32]	R-12	12	62.5-625	0.549
9	Groenveld [33]	R-12	7.8	177	0.259
10	Bertoni <i>et al.</i> [34]	R-12	7.8	256.4	0.257-0.603
11	Sedler and Mikielwicz [40, 41]	R-21	8	527.5	0.106-0.29
12	Koizumi <i>et al.</i> [42]	R-113	10	206.4	0.0891-0.0906
13	Deyev <i>et al.</i> [35]	He	1.63	110	0.458-0.463
14	Subbotin <i>et al.</i> [36]	He	1.63	110	0.454-0.769
15	Romanov <i>et al.</i> [37]	He	0.47	213	0.445-0.454
16	Petuchov <i>et al.</i> [38]	He	0.8	226	0.437
17	Lewis <i>et al.</i> [43]‡	N <sub>2</sub>	14.1	29	0.1
18	Grigoriev <i>et al.</i> [44]	N <sub>2</sub>	0.327-1.29	101-397	0.029
19	Lewis <i>et al.</i> [43]‡	H <sub>2</sub>	14.1	24.5-26.2	0.26
20	Rotem and Hauptmann [45]§	CO <sub>2</sub>	6	175	0.271
21	Kaiser <i>et al.</i> [8]	Na	9	23.6	0.00158-0.00379
22	Aladiev <i>et al.</i> [47]	K	4 and 6	30-100	0.0008-0.0254
23	Present work	K	8	170	0.000812-0.009
23 references		10 liquids	0.327-40	24-680	0.0008-0.769

† Reference [30] is cited from ref. [31].

‡ Reference [43] is cited from ref. [48].

§ Reference [45] is cited from ref. [46].

In the present author's opinion, the above arguments allow the following interpretation of these two regions:

(1)  $\psi_{DO} < 4$  is the region of the dispersed-annular flow in which the value of  $x'_{lim}$  is greatly determined by the processes of droplet mass transfer between the flow core and the liquid film and depends strongly on  $\psi_{DO}$ , as defined by equation (12);

(2)  $\psi_{DO} > 4$  is the region of predominantly annular flow in which the value of  $x'_{lim}$  ceases to depend on the flow hydrodynamics and is mainly determined by the limit of the existence of a continuous film flow. The processed results show that for  $\psi_{DO} > 4$  the experimental points group around line 2 (Fig. 3) which is described by

$$x'_{lim} = 0.779\psi_{DO}^{0.022}. \quad (14)$$

Thus, the final formula for the determination of the limiting quality takes the form

$$x'_{lim} = \begin{cases} 0.568\psi_{DO}^{0.25} & \text{for } \psi_{DO} < 4 \\ 0.779\psi_{DO}^{0.022} & \text{for } \psi_{DO} > 4. \end{cases} \quad (15)$$

Comparison of this relation with 1115 points from 23 sources indicated in Table 1 shows that the r.m.s. deviation for all the points does not exceed 15%, whereas 91% of the data coincide within  $\pm 25\%$ .

## CONCLUSION

A satisfactory agreement between the experimental and predicted data for both organic and non-organic fluids, including cryogenic liquids and liquid metals, can indicate that equation (15), and also the main concepts employed for its derivation, account correctly for the physical nature of heat transfer deterioration in the case of the crisis, originating due to the liquid film dryout, and the effect of the operational ( $p$ ,  $G$ ,  $q$ ) and geometric ( $D$ ) parameters on the development of the critical situation.

As follows from the comparison with experimental data, equation (15) can be applied within the following range of  $\psi_{DO}$ :

$$10^{-2} < \psi_{DO} < 10^5$$

which corresponds to a wide range of conditions of practical significance.

The limiting value of the specific heat flux  $q_c^0$  (Fig. 1), below which the burnout heat transfer region develops due to the liquid film dryout, can be estimated from the relation [6] which connects  $q_c^0$  and  $x'_{lim}$ .

Assuming segment II (Fig. 1) to be vertical and  $x'_{lim}$  to be independent of  $q$ , it was shown in refs. [3, 54] that the experimental data on the second-kind burnout heat transfer could be well correlated by the relation

Table 1 (continued)

$G$ ( $\text{kg m}^{-2} \text{s}^{-1}$ )	$q$ ( $\text{MW m}^{-2}$ )	$x_{\text{DO}}$	Number of points	r.m.s. deviation (%)	Number of points with deviation > 25%	Number of points with deviation > 30%
1000–5000	0.3–3.75	0.24–0.69	365	7.2	0	0
442–750	0.51–0.85	0.87–1.05	32	23.7	12	2
20–500	0.059–1.83	0.61–1.00	31	16.6	5	2
3000–5000	0.66–3.2	0.2–0.53	47	20.8	9	4
300–1000	0.21–0.63	0.18–0.76	48	19.1	10	6
1600–6800	0.05–0.145	0.27–0.56	66	16.9	9	7
550	0.055–0.1	0.66–0.78	14	4.4	0	0
750	0.045–0.14	0.4–0.52	11	8.3	0	0
2700 and 4050	0.078–0.15	0.22–0.41	9	12.1	0	0
125–1340	0.012–0.104	0.24–1.06	95	14.9	4	2
1000–7000	0.040–0.16	0.17–0.59	16	22.4	3	3
541–1154	0.0213–0.841	0.52–0.75	6	15.4	1	0
92 and 144	0.0003–0.0024	0.29–0.42	20	7.6	0	0
85–248	0.00018–0.0026	0.22–0.49	47	18.3	7	5
40–275	0.0003–0.0041	0.26–0.75	31	9.7	0	0
60–313	0.00017–0.0043	0.22–0.51	67	20.8	17	12
20–72	0.032–0.083	0.75–1.01	11	7.2	0	0
40–620	0.013–0.115	0.73–1.05	19	12.1	1	1
6.0–15.4	0.02–0.05	0.66–0.87	11	7.3	0	0
1130–4070	0.31–0.39	0.34–0.78	25	27.7	14	9
68.8–240	2.7–7.4	0.47–0.91	16	8.9	0	0
22.3–334.5	0.15–1.69	0.52–1.02	116	16.3	7	5
19.9–82.9	0.06–0.23	0.75–0.92	12	7.9	0	0
6.0–7000	0.00017–7.4	0.17–1.00	1115	14.7	99 (8.9%)	58 (5.2%)

$$x_{\text{lim}}^0 = f(G\sqrt{(D/\sigma\rho_L)}). \quad (16)$$

As the main simulation parameter for  $x_{\text{lim}}^0$ , Katto [2] also uses an analogous dimensionless group

$$\frac{\sigma\rho_L}{G^2D}. \quad (17)$$

It was assumed in the above-mentioned works that the limiting quality was independent of  $q$  and that it was determined only by the flow hydrodynamics.

As follows from equation (13), the parameter for simulating the limiting quality  $\psi_{\text{DO}}$  can be presented in the form

$$\psi_{\text{DO}} = \frac{K_q}{K_u} \quad (18)$$

where

$$K_u = \frac{G^2D}{\sigma\rho_L} \quad (19)$$

$$K_q = \frac{\lambda\rho_L}{k_L} \left( \frac{v_L c_{pL}}{q} \left| \frac{d\sigma}{dT} \right|_s \right)^{0.5}. \quad (20)$$

By assuming in the first approximation that the limiting quality is independent of  $q$ , i.e.  $K_q = \text{const.}$ , then  $\psi_{\text{DO}} = \sigma\rho_L/G^2D$  and equation (15) reduces to the form of equation (16).

The foregoing results allow the following refinement of the physical nature of the burnout heat transfer originating due to the liquid film dryout. This

kind of crisis is both a hydrodynamic and thermal phenomenon. Its hydrodynamic aspect consists in the limiting steam quality being determined by the amount of liquid left as droplets in the channel by the instant of the break of a continuous liquid film and being dependent on the conditions of mass transfer between the flow core and the film, and this is mainly associated with the hydrodynamic processes. This aspect is accounted for by the number  $K_u$ . The thermal aspect consists of the effect of  $q$  on the limiting liquid flow rate in the film, at which its continuity breaks, and is determined by the number  $K_q$ .

It is ultimately a simultaneous account for these two factors which made it possible to correlate, by a single relation, the experimental data on heat transfer deterioration in the boiling of working bodies of different physical nature, including liquid metals.

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UNE FORMULE POUR LA QUALITE DE LA VAPEUR A L'ASSECHEMENT  
PARIETAL EN CONVECTION FORCEE DANS DES TUBES CIRCULAIRES VERTICAUX,  
UNIFORMEMENT CHAUFFES

**Résumé**—On considère la crise thermique associée à l'assèchement du film liquide pariétal dans les conditions de convection forcée. Dans l'hypothèse d'une détérioration du transfert thermique par rupture de l'intégrité du film, une relation adimensionnelle de ces conditions est obtenue et elle conduit à une relation pour la qualité de la vapeur. Une comparaison avec 1115 points expérimentaux sur l'eau, R-12, R-21, R-113, gaz carbonique, azote, hélium, parahydrogène, potassium et sodium, tirés de 23 références, montre que l'écart moyen ne dépasse pas 15%, tandis que 91% des données coïncide à mieux que  $\pm 25\%$ .

EINE KORRELATION FÜR DEN BEGRENZENDEN DAMPFGEHALT IM DRYOUT  
BEI ERZWUNGENER KONVEKTION IN GLEICHFÖRMIG BEHEIZTEN VERTIKALEN  
ROHREN

**Zusammenfassung**—Es wird die Wärmeübergangskrise betrachtet, die mit dem Austrocknen des Flüssigkeitsfilms an der Wand bei erzwungener Konvektion verbunden ist. Unter der Annahme, daß die Wärmeübergangverschlechterung mit dem Aufreißen des zusammenhängenden Flüssigkeitsfilms zu tun hat, erhält man eine dimensionslose Beziehung, welche zur Ableitung eines begrenzenden Dampfgehaltes verwendet wird. Ein Vergleich mit 1115 experimentellen Werten für Wasser, R12, R21, R113, CO<sub>2</sub>, N<sub>2</sub>, He, Parawasserstoff, K und Na aus 23 Literaturstellen hat gezeigt, daß die mittlere Abweichung 15% nicht übersteigt, während 91% der Meßwerte innerhalb  $\pm 25\%$  übereinstimmen.

ОБОБЩЕННОЕ СООТНОШЕНИЕ ДЛЯ ГРАНИЧНОГО ПАРСОДЕРЖАНИЯ КРИЗИСА  
ТЕПЛОТДАЧИ, СВЯЗАННОГО С ВЫСЫХАНИЕМ ПЛЕНКИ ЖИДКОСТИ ПРИ  
ВЫНУЖДЕННОЙ КОНВЕКЦИИ В РАВНОМЕРНО ОБОГРЕВАЕМЫХ ВЕРТИКАЛЬНЫХ  
КРУГЛЫХ ТРУБАХ

**Аннотация**—Рассматривается кризис теплоотдачи, связанный с высыханием пристенной жидкой пленки в условиях вынужденной конвекции. В предположении о том, что ухудшение теплоотдачи является следствием нарушения сплошности пленки, получена в критериальном виде зависимость для этих условий, на базе которой разработано соотношение для граничного паросодержания. Проведенное сравнение соотношения с 1115 экспериментальными точками для воды, фреонов R-12, R-21, R-113, углекислоты, азота, гелия, параводорода, калия и натрия из 23 источников показано, что среднее отклонение не превышает 15%, а 91% опытных данных находится в пределах  $\pm 25\%$ .