CALCULATION OF THE LIMITING HEAT FLUX FOR A LIQUID BOILING IN A TWO-PHASE THERMAL SYPHON

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Theoretical formulas from various sources are examined, which give the limiting heat flux for a liquid boiling in a two-phase thermal syphon.

There has recently been increased interest not only in heat pipes but also in closed two-phase thermal syphons [1]. The latter have certain advantages over wick heat tubes: simple manufacture and higher limiting heat fluxes [2], and are widely used in industry [3-5]. The best use of a syphon requires a knowledge of the processes and the heat-transfer characteristics.

A major characteristic is the limiting heat transfer, since incorrect calculation of this can lead to the body failing [6], and under current conditions, a heat exchanger can operate efficiently only at heat fluxes close to the limiting value.

Although there are numerous papers [2, 6-24] on the limiting capacity of a syphon, there has been no agreed view on the effects of various parameters on it; the fullest information on this can be derived from similarity equations and general formulas (Table 1).

It has been found [13, 14, 18, 20] that the forms taken by the crisis differ with the syphon filling, which is defined by the ratio of the volume of the liquid phase under normal conditions to the internal volume ε or to the volume of the heating zone ε_h. Two basic states exist in general for vertical tubes: 1) the entire inner surface is covered with liquid film; 2) there is a certain liquid level in the evaporator, while the rest of the surface is covered with a liquid film.

In the first (film) state, the limiting flux is [18] somewhat higher for short syphons ($L_h \leqslant 0.5$ m) than in the second, but there is difficulty in maintaining that state in a real heat exchanger, so the second condition is usually employed.

In the first state, the liquid films tends to dry up in the lower part of the evaporator at the critical load because of inadequate supply [2, 9, 16, 17, 20]. In the second, dry spots on the evaporator wall may occur at any point along it [17, 21].

Opinions differ on the causes of the crisis. Some researchers consider that the reason is that the vapor flow disrupts the condensate film [9, 15, 20], while others [2, 22] use the analogy with the boiling crisis in a large volume to argue that a limiting vapor content is attained in the wall layer.

The formulas in Table 1 form two groups on the basis of our approach to the physical essence of the crisis. The first group consists of (1)-(7) and (9), which are based on blocking theory. The second consists of (8) and (10)-(12), which are based on a similarity equation for the critical flux for boiling in a large volume.

In spite of the different approaches, most researchers agree [2, 9, 10, 17, 19] that the syphon filling (ε_h = 25-100%) has no effect on the limiting flux, nor do the dimensions of the condenser; so, introducing ε and L_c into the general formula (8) distorts the picture and increases the error. In [16], where (11) is given, it was shown that q^{li} is in fact dependent on ε_h, but only at low levels (ε_h = 2.3-18%).

Visual observations on special sections [23] have shown that all the surplus coolant is transported by the vapor into the upper part of the condenser near the critical loading, where the liquid column oscillates up and down, i.e., all the coolant not participating directly in the heat and mass transfer. There is thus self-regulation of the amount of coolant partici-

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TABLE 1. Formulas for Defining the Limiting Heat Flux for a Liquid Boiling in a Two-Phase Thermal Syphon

Source	Formula		Coefficient values	Application range	Notes
[7]	$q_F^{li} = C_1 \dfrac{rd^{1,5}(g\rho_V(\rho-\rho_V))^{0,5}}{L_h(1+(\rho_V/\rho)^{0,25})^2}$	(1)	$C_1 = 0.25$ for a tube with edges rounded towards the top, and $C_1 = 0.125$ for a tube with sharp edges	—	—
[8]	$q_S^{li} = 0{,}526 \dfrac{rd^{0.5}(g\rho_V(\rho-\rho_V))^{0,5}}{(1+(\rho_V/\rho)^{0,25})^2}$	(2)	—	—	—
[9]	$K_S^{li} = C_1 \mathrm{We}^{-0,17}(K_p\rho_V/\rho)^m$	(3)		$L_h \leqslant 0{,}5$	Recommended for the range $0.004 \leq d/L_h \leq 0.2$
			$C_1 = 0{,}318, \quad m = -0{,}14$	$K_p\rho_V/\rho = 0{,}015 - 50$	
			$C_1 = 0{,}185, \quad m = 0$	$K_p\rho_V/\rho = 50 - 6\cdot10^3$	
	$K_S^{li} = C_2 K_p^n$			$L_h \geqslant 0{,}5$	
			$C_2 = 7{,}6, \quad n = -0{,}16$	$K_p = 160 - 5\cdot10^4$	
			$C_2 = 1{,}35, \quad n = 0$	$K_p = 5\cdot10^4 - 2\cdot10^5$	
[10]	$q_S^{li} = C_1 p^{0,25}\varphi^{0,54}L_h^{0,44}$	(4)	—	$p = 0{,}3 - 3$ MPa $\varphi = 5 - 30$, $L_h = 0{,}2 - 1$ $d = (12 - 38)\cdot10^{-3}$, coolant water	—
[11]	$q_S^{li} = 3{,}2r\,(\mathrm{th}\,(0{,}5d^{0,25}(g(\rho-\rho_V))^{0,125}\sigma^{-0,125}))^2 \times$ $\times \dfrac{(\rho\rho_V)^{0,5}(\sigma g(\rho-\rho_V))^{0,25}}{(\rho^{0,25}+\rho_V^{0,25})^2}$	(5)	—	—	—
[12]	$K_S^{li} = C_1 \mathrm{Ar}^{0,125} K_p^m$	(6)		$\mathrm{Ar} \leqslant 2\cdot10^{13}$	—
			$C_1 = 0{,}185, \quad m =$ [illegible]	$K_p \leqslant 2\cdot10^4$	
			$C_1 = 3{,}5\cdot10^{-2}, \quad m = 0$	$K_p \geqslant 2\cdot10^4$	

	$K_S^{li} = C_2 K_p^n$		$C_2 = 8{,}2,\quad n = -0{,}17$ $C_2 = 1{,}35,\quad n = 0$	$Ar \geqslant 2\cdot 10^{13}$ $K_p \leqslant 4\cdot 10^4$ $K_p \geqslant 4\cdot 10^4$	
[13]	$q^{li} = \frac{0{,}36}{\zeta} r\rho_v^{0,5}\sigma^{0,45}(g(\rho-\rho_v))^{0,05}d^{-0,4}$	(7)	ζ is local-resistance coefficient	$p = 0{,}002 - 2$ MPa $d = (6 - 50)\cdot 10^{-3}$	—
[14]	$q^{li} = q_{cr} C_1^2 (0{,}4 + 0{,}012d\,(g(\rho-\rho_v)/\sigma)^{0,5})^2 \times$ $\times d^{0,22}\varepsilon^{2n} L_c^{0,88} L_h^{1,1}$	(8)	$C_1 = 0{,}538,$ $n = 0{,}13 - \varepsilon \leqslant 35\%$ $C_1 = 3{,}54,$ $n = -0{,}37 - \varepsilon \geqslant 35\%$	$2{,}9\% \leqslant \varepsilon \leqslant 60\%$ $2 \leqslant d\,(g(\rho-\rho_v)/\sigma)^{0,5} \leqslant 60$ $d = (5 - 22)\cdot 10^{-3}$ $\varphi = 4 - 90$ $d/L_h = 0{,}04 - 0{,}22$	—
[15]	$q_S^{li} = \frac{r\rho^{0,42}\rho_v^{0,58}\sigma^{0,08}g^{0,84}(\rho-\rho_v)^{0,84}d^{0,34}}{(\rho^{0,25}+\rho_v^{0,25})^2}$	(9)	—	$p = 0{,}5 - 8$ MPa $L_h = 1 - 2{,}4$ $d = (9{,}3 - 23)\cdot 10^{-3}$	—
[2]	$K_2^{li} = 0{,}16\,(1 - \exp(-(d/L_h)(\rho/\rho_v)^{0,13}))$	(10)	—	—	Recommended for the range $0{,}004 \leqslant d/L_h$
[16]	$Q^{li} = 0{,}00737\,(r\rho_v^{0,5}(\sigma(\rho-\rho_v))^{0,25})^{0,817} \times$ $\times (\sin\varphi)^{0,206}\varepsilon_h^{0,334}$	(11)		$\varphi = 1{,}5 - 20$ $\varepsilon = 2{,}3 - 18$	—
	$K_1^{li} = 7\,Fo^{0,5}(\rho/\rho_v)^{0,5}(1 - \exp(-(d/L_h) \times$ $\times (\rho/\rho_v)^{0,13}\cos^{1,8}(\varphi - 55)))^{0,8}$ $q_F^{li} = 7r\,(\lambda f \rho_v/C_p)^{0,5}(1 - \exp(-(d/L_h) \times$ $\times (\rho/\rho_v)^{0,13}\cos^{1,8}(\varphi - 55)))^{0,8}$	(12)	f — see Fig. 2		Recommended for the range $0{,}004 \leqslant d/L_h,\ 3° \leqslant$ $\leqslant \varphi \leqslant 90°$

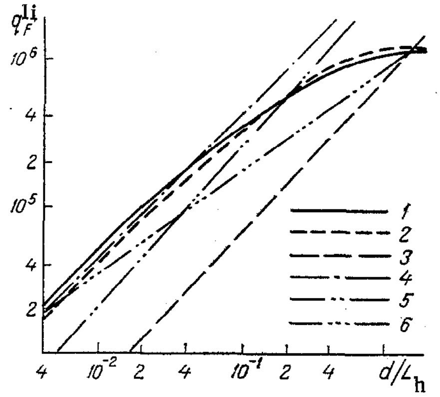

Fig. 1. Limiting heat flux density as a function of evaporator dimensions calculated from different formulas (Table 1); p = 0.1 MPa, φ = 90°, heat carrier water: 1) (12); 2) (10) [2]; 3) (5) [11]; 4) (3) [9]; 5) (2) [8]; 6) (6) [12]; q_F^{li} in W/m², d/L_h in mm.

pating in the transfer in a two-phase syphon. For ε_h < 25%, there may be insufficient coolant to cover all the inner surface, which causes the crisis to set in at lower fluxes.

The formulas in Table 1 show that there are considerable discrepancies over the effects of the dimensions on the limiting flux. Figure 1 shows that only the q_F^{li} derived from (10) and (12) virtually coincide throughout the range ($0.004 \leqslant d/L_h \leqslant 2$), while in the narrower range ($0.004 \leqslant d/L_h \leqslant 0.2$), one can add (3) to these. Formulas (2) and (5) incorporate the effects only from the syphon diameter, while (3) and (6) incorporate only the heating-zone length. The range in d is much narrower than that in L_h, so formulas that include the heating-zone length enable one to determine q_F^{li} with less error. The transition from large-volume boiling to the conditions of boiling in a syphon, i.e., hindered conditions, occurs for d/L_h = 1-2 at atmospheric pressure with water, which is important because this also defines the limit to the use of formulas for the critical fluxes in large volume, and it further demonstrates an essential relationship between the heat-transfer crisis in a syphon and that in a large volume.

Visual observations [23] show that bubble boiling in a metal syphon occurs throughout the range, so it is reasonable to construct general formulas from similarity equations for the critical fluxes on boiling in a large volume. However, the heating-surface dimensions for a large volume do not affect q_{cr} because the mean vapor content of the wall layer is the same throughout the surface, whereas in a two-phase syphon, the vapor content increases not only up the evaporator, where it attains a maximum at the exit, but also in the cross section towards the axis [23], so the liquid in the syphon boils under hindered conditions, and the degree of it is determined by the ratio of the heating-zone length to the diameter. The larger that ratio, the greater the effect of the dimensions on q_F^{li}. For example, q_F^{li} is independent of the dimensions for water at atmospheric pressure with L_h/d = 2, whereas $q_F^{li} \sim (L_h/d)^{-1}$ for L_h/d = 50. The difference in the effects of the dimensions occurs because some researchers [9, 10, 12] have incorporated the effects of the heating-zone length, while others [7, 8, 11, 13, 15] have incorporated the diameter.

According to Fig. 1, the limiting capacity for d/L_h < 2 begins to be affected by the evaporator dimensions. Firstly, as this ratio decreases, the mean vapor content along the evaporator alters, and secondly, the interaction of the vapor flow with the moving condensate increases, i.e., the conditions for the condensate to reach the heating surface deteriorate. For d/L_h < 0.1, the vapor almost attains its limiting speed, so the condensate tends to be blocked and has difficulty in covering the dry spots where vapor bubbles arise. In that case, the limiting flux will be attained at a much lower vapor content in the wall layer than is the case for boiling in a large volume.

We are therefore justified in introducing corrections into the similarity equations for boiling in a large volume to incorporate the features in a syphon (trapped volume, orientation in space, and so on). Our own studies and the results of [24] enable one to incorporate the spatial orientation of the syphon as regards the effects on the limiting flux.

If the syphon is inclined, there is a reduction in the hydrostatic head, which retards the entry of the condensate to the evaporator. Also, there is a component from the force of

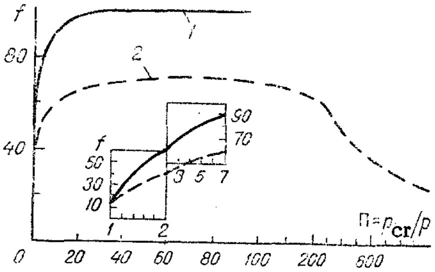

Fig. 2. Average relation of f to Π [25]: 1) organic and inorganic (cryogenic) liquids; 2) water; f in 1/sec.

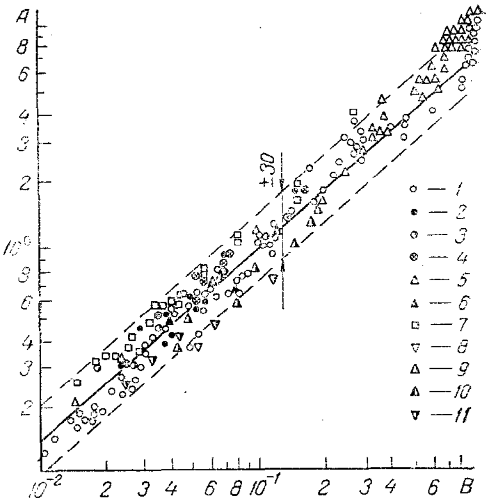

Fig. 3. Collected measurements on q_F^{li} for water (1), water [24] (2), water [9] (3), ethylene glycol (4), freon-113 (5), freon-113 [9] (6), isooctane (7), freon-30 (8), freon-11 [9] (9), freon-12 [9] (10), and methanol [9] (11); the solid line is the calculated one from (12) (see Table 1); A) $q_F^{li}/(r\sqrt{\lambda\rho_v/C_p})$; B) $1 - \exp(-(d/L_h)(\rho/\rho_v)^{0.13}\cos^{1.8}(\varphi - 55))$.

gravity displacing the liquid from the upper generator to the lower one. On the one hand, this thins the condensate film on the upper generator, and this with the reduction in the hydrostatic head reduces the limiting flux, while on the other, the liquid transfer to the lower generator reduces the interaction surface between the vapor and the condensate, which improves the conditions for the condensate to enter the evaporator and thus increases the limiting flux. The joint action of these factors produces a maximum in the limiting transfer in the range of inclination angles with respect to the horizontal of 50-60°, so the effects of orientation on q_F^{li} can be incorporated via the dimensionless quantity $\cos^{1.8}(\varphi - 55)$.

Our measurements and the results of [2] indicate that there are interactions between the volume constriction, the syphon orientation, the thermophysical properties of the coolant, and the pressure, so the general relationship is (Fig. 3):

$$q_F^{li} = q_{cr}\,(1 - \exp[-(d/L_h)(\rho/\rho_v)^{0,13}\cos^{1,8}(\varphi - 55)])^{0,8}.$$

Here q_{cr} has been calculated from Tolubinskii's formula [22, 25].

Figure 4 shows that q_F^{li} as calculated from (10) and (12) differ only slightly over a wide range in the relative pressure.

Table 1 then shows that only the general relationship of (10) enables one to determine the limiting flux throughout the ranges in dimensions and working parameters, as it incorporates the joint effects of the dimensions, the pressure, and the properties of the coolant on q_F^{li}, while (12), which further incorporates the spatial orientation, can be used to calculate the flux for an inclined syphon.

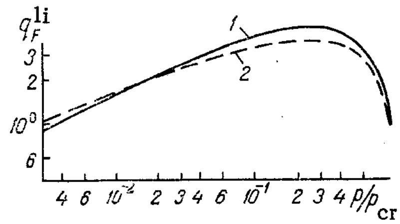

Fig. 4. Dependence of limiting heat flux density on relative pressure ($d/L_h = 1$, coolant water): 1) formula (12); 2) formula (10), table [2].

NOTATION

a, thermal diffusivity, m²/sec; C_p, specific heat, J/kg•K; d, evaporator internal diameter, m; d_0, vapor bubble detachment diameter; F, area of inner surface of heating zone, m²; f, bubble detachment frequency, sec⁻¹; g, acceleration due to gravity, m/sec²; L_c, condensation zone length, m; L_h, heating zone length, m; m and n, exponents; p, pressure, Pa; Q, heat flux, W; q, heat flux density, W/m²; r, latent heat of evaporation, J/kg; S, cross-sectional area of heating zone, m²; ρ, liquid density, kg/m³; ρ_v, vapor density, kg/m³; σ, surface tension, N/m; ν, kinematic viscosity, m²/sec; φ, inclination to horizontal, deg; ε, degree of filling, %. Subscripts: cr, critical; h, heating zone; hc, heat carrier. Similarity numbers: $Ar = gL^3_h/\nu^2\ \rho - \rho_v/\rho$, Archimedes number; $Fo = a/(d_0^2 f)$, Fourier number; $We = \sigma/(g(\rho - \rho_v)L_h^2)$, Weber number. $K_1^{li} = q_F^{li}/(r\rho_v d_0 f)$; $K_2^{li} = q_F^{li}/(r\rho_v^{0.5}(g\sigma(\rho - \rho_v))^{0.25})$; $K_p = p/(g\sigma(\rho - \rho_v))^{0.5}$; $K_s^{li} = q_s^{li}/(r\rho_v^{0.5}(g\sigma(\rho - \rho_v))^{0.25})$.

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