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Boiling inside tubes: critical heat flux for flow in uniformly heated horizontal tubes

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(Continued on inside back cover)

BOILING INSIDE TUBES: critical heat flux for flow in uniformly heated horizontal tubes

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BOILING INSIDE TUBES: critical heat flux for flow in uniformly heated horizontal tubes

1. NOTATION AND UNITS

		Units	
		SI	British
A, B	correlation constants for Equations (4.9) and (4.10)	–	–
Bo	boiling number – see Item 86032 ⁵	–	–
c_p	specific heat capacity of fluid at constant pressure	J/kg K	Btu/lb °F
D	internal diameter of tube	m	ft
g	acceleration due to gravity	m/s ² (9.81)	ft/h ² (4.17×10 ⁸)
h	enthalpy	J/kg	Btu/lb
j_g^+	dimensionless volumetric flux of vapour, $\dot{m}x_g / \sqrt{\rho_g(\rho_l - \rho_g)gD}$	–	–
j_l^+	dimensionless volumetric flux of liquid, $\dot{m}(1 - x_g) / \sqrt{\rho_l(\rho_l - \rho_g)gD}$	–	–
K_D	correction factor for diameter, $(0.008/D)^{1/3}$	–	–
K_L	correlation factor for length, from Section 5.6 of Data Item 86032 ⁵	–	–
L	heated length of tube	m	ft
$\dot{M}$	mass flow rate inside tubes	kg/s	lb/h
$\dot{m}$	mass flux – Equation (5.1)	kg/s m ²	lb/h ft ²
N_T	number of tubes in parallel	–	–
p_c	critical pressure	N/m ² (Pa)	lbf/ft ²
p_s	saturation pressure	N/m ² (Pa)	lbf/ft ²
$\dot{Q}$	rate of heat transfer	W	Btu/h
$\dot{q}$	heat flux, $\dot{Q}/(\pi D L N_T)$	W/m ²	Btu/h ft ²

$\dot{q}_{cr}$	critical heat flux	W/m ²	Btu/h ft ²
$R_{\dot{m}}$	mass flux ratio – Equation (4.4)	–	–
$R_{\dot{q}}$	critical heat flux ratio – Equation (4.1)	–	–
Re_{l0}	Reynolds number of liquid at zero quality – Equation (5.2)	–	–
T_C	temperature of cold stream	K	°F
T_H	temperature of hot stream	K	°F
U	overall heat transfer coefficient, referred to internal surface area	W/m ² K	Btu/h ft ² °F
U'	combined heat transfer coefficient of heating fluid, wall and any fouling, referred to internal surface area	W/m ² K	Btu/h ft ² °F
x_g	quality defined by Equation (3.1)	–	–
Δh_v	latent heat of vaporisation	J/kg	Btu/lb
ε_g	ratio of volumetric flow of vapour to total volumetric flow	–	–
η	dynamic viscosity of fluid	kg/s m	lb/ft h
λ	thermal conductivity of fluid	W/m K	Btu/h ft °F
ρ	density of fluid	kg/m ³	lb/ft ³
σ	surface tension	N/m	lbf/ft
X_{ft}	Martinelli parameter simplified for fully turbulent flow, see Equation (4.5)	–	–
ψ	mass flux parameter, $\dot{m}(D/\sigma\rho_l)^{1/2}$	–	–

Extra subscripts

cr	critical
$expt$	experimentally measured value
g	vapour
h	horizontal
in	at inlet to heated length of tube
l	liquid
m	mean

<i>out</i>	at outlet from heated length of tube
<i>pred</i>	predicted value
<i>s</i>	under saturation conditions
<i>tr</i>	transition to stratified flow under adiabatic conditions
<i>v</i>	vapour
<i>v</i>	vertical
5	at 5% quality
0	at zero quality

Superscript

*	for a tube of 8 mm internal diameter, at the same mass flux
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2. PURPOSE AND SCOPE OF THIS DATA ITEM

This is the third of a series of Data Items on heat transfer in boiling of single component fluids inside tubes. The first, ESDU 85041⁴, discussed the problems and gave a procedure for estimating heat transfer rates in saturated wet-wall boiling. The second, ESDU 86032⁵, gave a procedure for estimating the critical heat flux (CHF – sometimes referred to as “dryout” – see next Section) in upward flow in uniformly heated vertical tubes. Here the procedure for vertical tubes is extended to uniformly heated horizontal tubes. The previous Data Items must be to hand before the procedures in this Item can be used.

Groeneveld⁶ suggested that the CHF for a horizontal tube is equal to that for a vertical tube under otherwise identical conditions multiplied by a flow factor and this is accepted as the basis for this Item. This factor depends on the flow pattern (see Section 4.1 of ESDU 85041) and the ratio of the actual mass flux to the maximum mass flux to avoid stratification, as defined by Taitel and Dukler³. In Section 5 the data bank described in Section 4 is used to derive an approximate procedure for estimating the CHF ratio from the mass flux ratio and a function of the quality, defined in Equation (3.1), the CHF ratio being defined as the ratio of CHF for a horizontal to that for a vertical tube under otherwise identical conditions.

This Data Item applies to tubes of internal diameter 5 to 25 mm. It should not be applied to larger tubes, where the predicted CHF is likely to be much higher than that experienced, especially when the boiling liquid enters a heated tube through a 180° bend in a vertical plane with upward flow – see Section 4.6. For tubes in the region 5 to 25 mm diameter, no effect of bends has been found.

The procedure in this Item will be of use in the design of two types of vaporiser found in the process industries.

1) Vaporisers with recirculation, such as evaporators and reboilers, where the mass flow rate of liquid entering the tubes considerably exceeds the mass flow rate of vapour generated. After passing through the tubes, most of the liquid is returned to the inlet, the vapour generated having been separated from it. It is desirable to check that the CHF is not exceeded, *i.e.* that the tubes are wetted by the liquid at all points. Serious trouble has been experienced as a result of dryout in steam generators due to corrosion of the top of the horizontal tubes and, also, dryout may cause a loss in the performance of evaporators with horizontal tubes. Small concentrations of contaminant in the liquid may accumulate in regions of dryout.

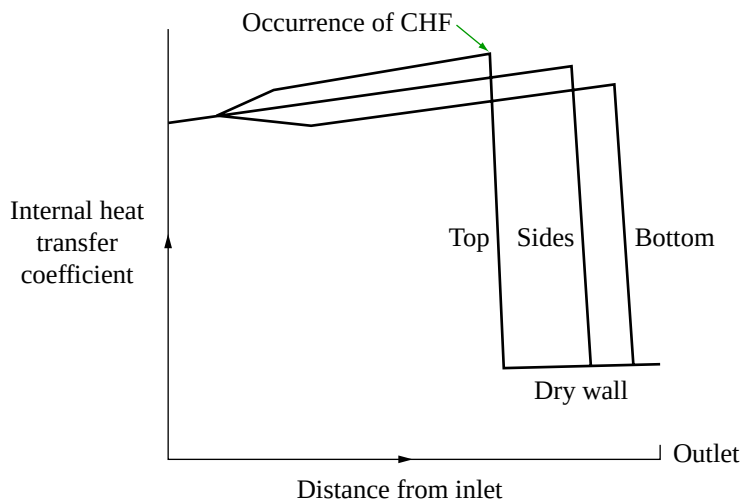
2) Once-through vaporisers, where all or most of the liquid is vaporised in the tubes and it is necessary to determine the quality at which dryout occurs and there is consequently a fall in heat flux.

In an industrial vaporiser it is likely that there are appreciable changes in heat flux, both along the length of each tube and around its circumference. However the data analysed were obtained from experiments in which the tube was heated electrically, and so the heat flux was the same at all points. No precise procedure currently exists for calculating the effect of changes in heat flux, which result from changes in the temperature difference and in internal and external heat transfer coefficients. However, some suggestions are made in Section 5.4 for coping with this problem.

3. DISCUSSION OF THE NATURE OF CRITICAL HEAT FLUX (CHF) IN HORIZONTAL TUBES

The onset of dryout in uniformly heated vertical tubes (the arrangement most frequently used in research) has been fully discussed in Section 3 of ESDU 86032⁵. Dryout occurs very suddenly at a certain height up the tube. Below that height the tube is fully wetted but above it the wall of the tube is dry. The term “critical heat flux” is used to define the heat flux at which this transition occurs. It is accompanied by a marked fall in heat transfer coefficient, as shown in Sketch 3.1 of ESDU 86032, the resulting rise in the wall temperature being shown in Sketch 3.2 of that Item.

If the tube is heated non-uniformly, or if it is horizontal or inclined, the symmetry is destroyed and the change in heat transfer coefficient takes place over a finite length of tube. The worst case is a large horizontal tube with intensive heating along the top. Sketch 3.1 shows the changes in heat transfer coefficient along the top, bottom, and sides of a uniformly heated horizontal tube, with complete vaporisation from inlet to outlet. At low quality the coefficient is uniform around the tube. When the flow becomes annular, the liquid film is thinner at the top of the tube (due to gravity), so the coefficient there is higher than at the sides; the converse applies to the bottom of the tube. The critical heat flux is defined as the flux when the top of the tube is no longer wetted and the heat transfer coefficient there falls. The region of dry-wall heat transfer then gradually spreads to the sides and ultimately to the bottom of the tube, when the heat transfer coefficient is again uniform around the tube, but at the value for single-phase heating of the vapour.



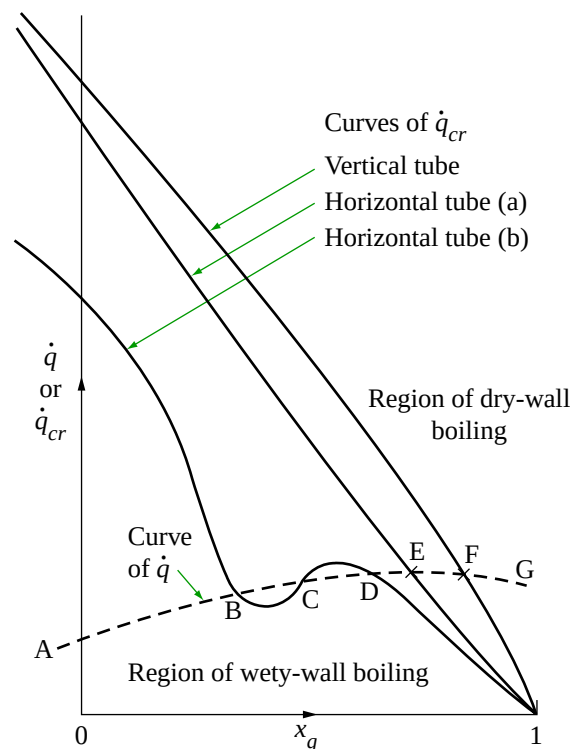
Sketch 3.1 Typical changes in heat transfer coefficient along a once-through vaporiser

The critical heat flux depends on the quality, which is here defined for a pure component as

$$x_g = \frac{h - h_l}{\Delta h_v} \quad (3.1)$$

where h is the local value of the enthalpy, h_l is the enthalpy of saturated liquid and Δh_v is the latent heat of vaporisation. This definition gives what is sometimes referred to as the “thermodynamic quality”. The quality is negative in the preheating region, where $h \leq h_l$; it ranges from 0 to 1 in the two-phase region and is greater than unity in the superheating region. In the two-phase region, assuming equilibrium between liquid and vapour, Equation (3.1) simplifies to the more usual definition of quality as the ratio of the mass flow rate of vapour to the total mass flow rate.

The upper curves in Sketch 3.2 show typical plots of $\dot{q}_{cr}$, the critical heat flux, against x_g , the quality, for a vertical tube and for two horizontal tubes under different conditions. Curve (a) is for a small horizontal tube at high velocity. In contrast, curve (b) is for a larger tube or a lower velocity or a combination of the two. It is seen that the CHF at high qualities is similar in all three curves. Curve (a) shows a small fall in CHF, relative to the curve for a vertical tube, in the middle of the range of quality. However with curve (b) the deterioration from the situation for a vertical tube is great at low and medium qualities; the curve falls steeply, reaches a minimum, rises to a maximum and then falls again. The serious reduction in CHF at low quality with tube (b) is attributed to thermal stratification – see Petukhov *et al.*²



Sketch 3.2 Heat flux, $\dot{q}$, against quality, x_g

The curve AG gives a typical relationship in an industrial vaporiser between heat flux ($\dot{q}$) and quality (x_g) calculated on the assumption that the wall is fully wetted at all points, as described in Section 6 of ESDU 85041⁴. The critical heat flux ($\dot{q}_{cr}$) and the critical quality ($x_{g,cr}$) in the vaporiser are given by the point of intersection of AG with the appropriate curve for CHF. Thus with the vertical tube and the horizontal tube with curve (a) there is a unique point of intersection, marked with a cross, which gives the required values of $\dot{q}_{cr}$ and $x_{g,cr}$. However, on curve (b) there are three points of intersection, B, C and D. Point B gives the low quality CHF, which occurs in a region of bubble or unsteady flow. Point C is the point of transition to annular flow, where the top of the tube becomes wetted again. Point D is the high quality CHF, where the supply of liquid to the top of the tube is not sufficient to replace that which evaporates, so dryout occurs for a second time.

4. DATA BANK* OF CHF IN AN ELECTRICALLY HEATED HORIZONTAL TUBE

Memory and Laubscher²⁴ have prepared a data bank from the information given in Derivations 7 to 23. In each reported test, the pressure, inlet quality and flow rate were set at fixed values; the heat input was increased until there was a rise in wall temperature at the top of the tube. From a heat balance, see Equation (5.4), the experimenter calculated the quality at this point, known as “the critical quality” ($x_{g,cr}$) and the corresponding critical heat flux. In most cases there was just one critical quality and heat flux, occurring at the end of the tube. In some cases further increases in heat input were made; the point of dryout moved towards the inlet, then rewetting occurred and a second dryout was induced, so values were given for the quality at the first dryout, at rewetting and at second dryout. In a few cases heating was further increased until dryout occurred at the bottom of the tube, giving a fourth data point for the run.

In all cases the experimenter assumed that the heat input was distributed uniformly along the length and around the circumference of the tube. However changes of electrical resistance with temperature may have caused an uneven distribution of heat input, especially in a region of partial wetting or complete dryout at the top of the tube. This was not allowed for in the analysis of the results.

4.1 Scope of the Data Bank

The bank gives the internal diameter of the tube, the heated length and the unheated upstream and downstream lengths, the mass flux and pressure, the heat flux and the inlet and critical qualities. The unheated lengths were not always available, in which case they were set to zero. It is noted whether the critical conditions occurred at or before the outlet and if there was a bend before the test length. The physical properties given are the densities and viscosities of liquid and vapour at saturation temperature, the surface tension and the latent heat of vaporisation. The test fluids were water, nitrogen and refrigerants R12 and R113.

Table 10.1 summarises the scope of the data bank. There are 1402 values of the critical quality for dryout at the top of a uniformly heated horizontal tube, including 129 in the sub-cooled region. The bank contains 6 tests of Bagley⁹ where only the top of the tube was heated. Also there are 39 values of the critical quality for dryout at the bottom of the tube – 4 from Hein *et al.*²², 19 from Cumo *et al.*¹⁷, and 16 from Ricque and Roumy¹².

4.2 Derived Quantities

The most important of the derived quantities is the critical heat flux ratio, defined as

$$R_{\dot{q}} = \dot{q}_{cr,expt} / \dot{q}_{cr,v} \quad (4.1)$$

where $\dot{q}_{cr,expt}$ is the heat flux in the experiment and $\dot{q}_{cr,v}$ is the critical heat flux for an identical vertical tube calculated by the procedure given in ESDU 86032⁵ for the pressure, mass flux and critical quality in the experiment. This ratio should be less than one, but it was not always found to be so, either because of experimental error, or because of inaccuracies in the procedure for estimating the CHF in a vertical tube.

* For information on the availability of this data bank, contact ESDU International plc.

The dependence of the critical heat flux on the following quantities was studied.

- (i) Re_{l0} , the Reynolds number for the flow of liquid evaluated at zero quality (see Equation (5.2)). If this was found to be less than 4000, the result was rejected, as the flow was not fully turbulent.
- (ii) The density ratio, ρ_l/ρ_g , where ρ_l is the density of the liquid and ρ_g is the density of the vapour.
- (iii) j_{l0}^+ , the dimensionless volumetric flux of liquid evaluated at zero quality.

The dimensionless volumetric flux of liquid at quality x_g is

$$j_l^+ = \frac{\dot{m}(1 - x_g)}{\sqrt{\rho_l(\rho_l - \rho_g)gD}} \quad (4.2)$$

When $\rho_l \gg \rho_g$, putting $x_g = 0$, this tends to

$$j_{l0}^+ = \frac{\dot{m}}{\rho_l \sqrt{gD}} \quad (4.3)$$

where D is the internal diameter of the tube, g is the acceleration due to gravity, and $\dot{m}$ is the mass flux given by Equation (5.1). If j_{l0}^+ was found to be less than 0.2, the result was rejected, as the procedure in ESDU 85041⁴ is not valid.

- (iv) $R_{\dot{m}}$, the mass flux ratio, *i.e.* the ratio of the actual mass flux to the minimum mass flux necessary to avoid stratified flow under adiabatic conditions at the prevailing pressure and the critical quality in the two-phase region, *i.e.* when $0 < x_{g,cr} < 1$. This can be determined from the parameters defined in (vi) and (vii) as

$$R_{\dot{m}} = \frac{j_{g,cr}^+}{j_{g,tr}^+} \quad (4.4)$$

It was found that $R_{\dot{m}}$ was greater than 1 in almost all the results in the data bank. Results where $R_{\dot{m}} \leq 1$ have been rejected as being for stratified flow, which should be avoided in practice.

- (v) $X_{ft,cr}$, the Martinelli parameter simplified for fully turbulent flow at the critical quality to

$$X_{ft,cr} = \frac{1 - x_{g,cr}}{x_{g,cr}} \left(\frac{\rho_g}{\rho_l} \right)^{1/2} \quad (4.5)$$

- (vi) $j_{g,cr}^+$, the dimensionless volumetric flux of vapour at the critical quality, from

$$j_{g,cr}^+ = \frac{\dot{m}x_{g,cr}}{\sqrt{\rho_g(\rho_l - \rho_g)gD}} \quad (4.6)$$

- (vii) $j_{g,tr}^+$, the dimensionless volumetric flux of vapour at the transitional mass flux below which the flow would become stratified under adiabatic conditions. This can be obtained from the curve given

by Taitel and Dukler³, which has been fitted by the equation

$$j_{g, tr}^+ = \left(\frac{1}{0.77 + 0.85(X_{ft, cr})^{0.6}} \right)^3 \quad (4.7)$$

Of the 1402 points in the data bank for the CHF along the top of a uniformly heated tube, certain points were rejected as follows:

$Re < 4000$	20	points
$\dot{m}$ greater than that covered by ESDU 86032 ⁵	211	points
$D < 0.002$ (the lowest covered by ESDU 86032 ⁵)	11	points
$x_{g, cr} > 1.0$ (superheated at outlet)	6	points
$R_{\dot{q}} > 1.5$ (too high for result to be reliable)	126	points
$j_{l0}^+ < 0.2$	4	points
	total	378 points

Of the remaining 1024 points 14 were not used in the analysis because $R_{\dot{m}} > 100$ and $R_{\dot{q}}$ was always near to unity, as expected, so they would not be suitable for plotting on the graphs, Figures 1 – 7.

Next the results obtained with three pieces of equipment were rejected on account of the large amount of scatter. The criterion was that the standard deviation was more than four times that obtained with the accepted results, using an approximate form of the correlating equations developed in Section 4.4. The results rejected were those of Ricque and Roumy¹², Bonn *et al.*¹⁹, and the 12.5 mm tube of Hein *et al.*²².

A further 7 points were rejected as being very low. The criterion used was

$$R_{\dot{q}} < 1 - \exp[-(R_{\dot{m}} - 1)/80] \quad (4.8)$$

Of the remaining total of 900 points, 119 were in the subcooled boiling region ($x_{g, cr} \leq 0$), 18 were in the low quality region ($0 < x_{g, cr} < 0.05$) and 763 in the rest of the two-phase region ($0.05 \leq x_{g, cr} < 1.0$). The last three columns of Table 10.1 show the number of points in each quality range. Full details of derived quantities are given in Memory²⁵.

4.3 Graphical Presentation

The majority of the accepted points for critical heat flux in uniformly heated horizontal tubes are plotted in Figures 1 to 7, taken from Memory²⁵. In all cases the ordinate is $R_{\dot{q}}$, the CHF ratio, defined in Equation (4.1). It is plotted for the different qualities as follows.

- (a) Subcooled boiling: $x_{g, cr} \leq 0$

Here $R_{\dot{q}}$ is plotted against j_{l0}^+ , for all critical qualities, in Figure 1.

- (b) Low quality region: $0 < x_{g, cr} < 0.05$