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

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

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

1. NOTATION AND UNITS

		Units	
		SI	British
Bo	boiling number, defined by Equation (4.4)	—	—
c_p	specific heat capacity of a fluid at constant pressure	J/kg K	Btu/lb °F
D	internal diameter of tube	m	ft
h	enthalpy	J/kg	Btu/lb
K_D	correction factor for diameter, from Equations (5.8)	—	—
K_L	correction factor for length, from Equations (5.10)	—	—
L	heated length of tube	m	ft
$\tilde{M}$	relative molecular mass (molecular weight)	kg/kmole	lb/lbmole
$\dot{M}$	mass flow rate inside the tubes	kg/s	lb/h
$\dot{m}$	mass flux, from Equation (4.1) or (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
Re_{l0}	Reynolds number for flow of liquid at zero quality	—	—
T_C	temperature of cold stream	K	°F
T_H	temperature of hot stream	K	°F
T_W	temperature of inside surface of tube (and any dirt)	K	°F

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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 (mass flow rate of vapour/total mass flow rate); see also Equation (3.1)	—	—
z	distance from tube inlet	m	ft
α	heat transfer coefficient inside tube	W/m ² K	Btu/h ft ² °F
Δh_{in}	inlet subcooling, $(h_s - h_{in})$ or $c_{pl}(T_s - T_{in})$	J/kg	Btu/lb
Δh_v	latent heat of vaporisation	J/kg	Btu/lb
ε_g	volumetric quality, from Equation (5.9)	—	—
η	dynamic viscosity of fluid	kg/s m	lb/h ft
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
ψ	parameter defined by Equation (4.3)	—	—

Extra subscripts

cr	critical
$expt$	experimentally measured value
g	vapour
in	at inlet to tubes
l	liquid
out	at outlet from tubes
$pred$	predicted value
s	saturation
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

This is the second of a series of Data Items on heat transfer in boiling inside tubes. The first, ESDU 85041⁷, summarised the problems and gave a procedure for estimating heat transfer rates in saturated wet-wall boiling. It should be read before reading this Item. Here the emphasis is on determining the conditions when the boiling liquid ceases to wet the heated wall of the tube through which the liquid and vapour are flowing. This is known as “dryout” and has been discussed in Section 4.5 of ESDU 85041⁷.

ESDU 86032 is concerned with the estimation of the “critical heat flux” defined as the heat flux above which the wall would become dry, given the amounts of vapour and liquid flowing through the tube, the dimensions of the tube and the physical properties of the liquid and its vapour in equilibrium.

Many publications contain measured values of the critical heat flux for the upward flow of water and steam and of other single-component two-phase fluids in electrically heated vertical tubes. This Item is limited to flow up uniformly heated vertical tubes. Horizontal tubes will be dealt with in a future Data Item.

There are many vaporisers in the process industries, operating at a high heat flux, where it is desirable to be able to estimate the critical heat flux. The subject is of special interest in the design and operation of the large steam generators used in the generation of electricity, but these are highly specialised items and are outside the scope of this Data Item, which is mainly intended for dealing with the following types of equipment.

1) Vaporisers with recirculation, such as evaporators and vertical thermosyphon reboilers. Here the amount of liquid entering the tubes considerably exceeds the amount of vapour to be generated. After passing through the tubes, most of the liquid is returned to the inlet, after the vapour generated has been separated from it. It is desirable that the wall of the tubes should be wetted by the liquid at all points. It is therefore necessary to check that the heat flux is always significantly less than the critical. Dryout is most likely to occur at the outlet.

2) Once-through vaporisers. Here the intention is that all the liquid should be vaporised in the tubes, so dryout is inevitable, and the heat flux falls considerably in the post-dryout region. Hence it is desirable to be able to determine how much vapour has been generated at the level where dryout begins. The estimation of post-dryout heat transfer coefficients will be dealt with in a future Data Item.

2.1 Acknowledgement

ESDU is grateful to Dr D.C. Groeneveld of Atomic Energy of Canada Ltd for permission to include in this Data Item his tables for determining the critical heat flux of water and of non-aqueous liquids in boiling flow up vertical 8 mm bore tubes and to the Thermal Hydraulics Division of Harwell Laboratory for comparing correlations with their data bank.

3. DISCUSSION OF THE NATURE OF CRITICAL HEAT FLUX

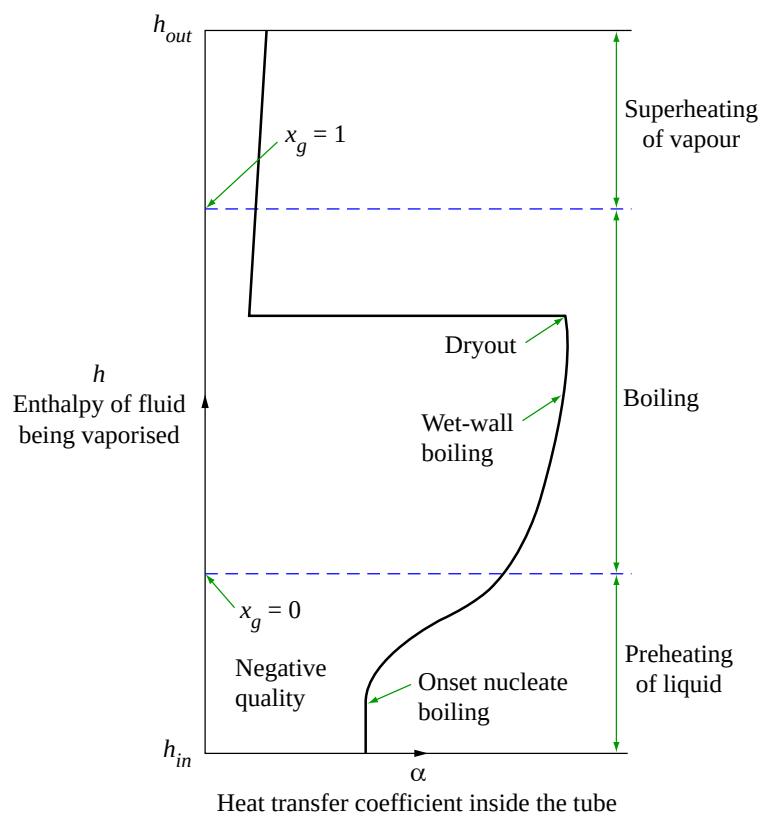
When vaporisation is taking place, the heat transfer coefficient changes considerably with increasing quality (mass flow rate of vapour/total mass flow rate, denoted by x_g). Sketch 3.1 shows the general shape of the curve of the heat transfer coefficient of the fluid to be vaporised, α , for upward flow in vertical tubes, for the full range of preheating, boiling and superheating. For convenience in covering the full range of enthalpy values, the quality is re-defined 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 is sometimes referred to as the “thermodynamic quality”. Hence the quality is negative in the preheating region ($h \leq h_l$), ranges from 0 to 1 in the boiling region, and is greater than unity in the superheating region.

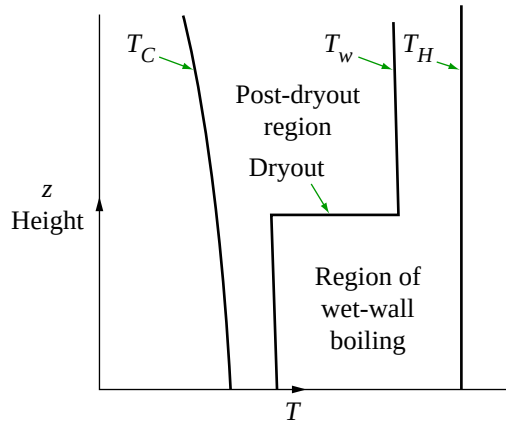
The distinctive feature of critical heat flux in uniformly heated vertical tubes is that the change to dry-wall heating is sudden. It may occur at any quality, depending on the conditions.

In a steam-heated vaporiser there is a considerable increase in T_w , the temperature of the wall, above the point where dryout occurs, as shown in Sketch 3.2. This is accompanied by a serious reduction in $\dot{q}$, the heat flux.



Sketch 3.1 Changes in heat transfer coefficient in a complete vaporiser

With a fired boiler T_H is very much higher than T_C but the heat transfer coefficient of the heating fluid is low, so there is only a slight fall in $\dot{q}$ at dryout but a considerable increase in T_w ; this is known as “burnout” and may lead to a failure of the tube.



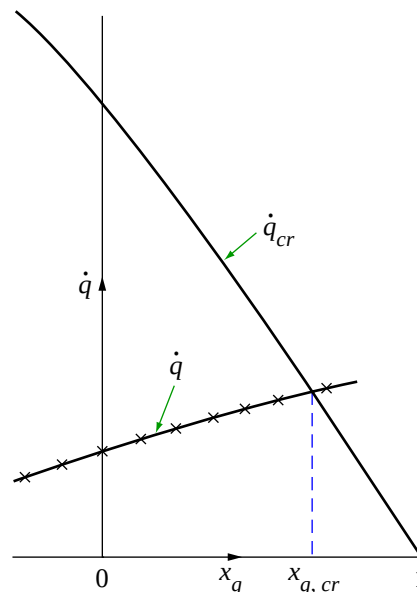
Sketch 3.2 Typical change in wall temperature at dryout with upward flow in a vertical tube heated by condensing steam

Research on critical heat flux is always carried out in an electrically heated tube, and so the heat flux is virtually uniform. In industrial vaporisers there are often considerable variations in $\dot{q}$ around the circumference and along the length of each tube.

Variations around the circumference of a vertical tube have been studied experimentally with high pressure water; the results have been published in papers listed in Section 4.5.1 of ESDU 85041⁷. Circumferential variations are neglected in this Data Item. It is assumed that the longitudinal variation has been determined by following the procedure detailed in Section 6 of ESDU 85041⁷.

Experimental studies have been made of longitudinally non-uniform fluxes^{1,4} where the heat flux in the centre of the tube was considerably greater than at inlet and outlet. It is not possible to apply the results to the various contours that may occur in an industrial vaporiser.

The upper curve in Sketch 3.3 shows a typical plot of $\dot{q}_{cr}$, the critical heat flux, against x_g , the quality, for upward flow in a vertical tube. The points marked "x" give the heat flux at several selected values of quality calculated as described in ESDU 85041⁷. As long as these points are below the curve of $\dot{q}_{cr}$, wet-wall boiling will occur and the heat flux will be as calculated.



Sketch 3.3 Heat flux/Quality

However the last point is above the line, so this point represents conditions that cannot be achieved. The intersection of the curve through the points of $\dot{q}$ with the curve for $\dot{q}_{cr}$ gives the conditions for dryout, known as "critical quality", denoted by $x_{g, cr}$. This is normally determined by interpolation between the last two points shown on the sketch. The procedure is illustrated in the example in Section 7.

At high qualities in the post-dryout region heat is transferred to superheated vapour containing suspended drops which evaporate as they are carried up the tube. Liquid will still be present when the thermodynamic quality reaches unity.

4. ASSESSMENT OF PUBLISHED CORRELATIONS FOR CRITICAL HEAT FLUX IN VERTICAL TUBES

Govan and Robinson¹⁰ have assessed five published correlations for critical heat flux against their extensive data bank of critical heat flux in flow up electrically heated vertical tubes. For each tube the flow rate ($\dot{M}$ kg/s) and inlet quality of the fluid ($x_{g, in}$) were set at known values and the heat input was increased until there was a sudden rise in the temperature of the tube at outlet. This critical heat flux ($\dot{q}_{cr}$ W/m²) was studied in relation to the following:

- D internal diameter of the tube,
- L heated length of tube,
- $\dot{m}$ mass flux (from Equation (4.1)),
- p_s saturation pressure of the boiling single-component liquid,
- $x_{g, cr}$ critical quality (at outlet),
- Δh_{in} inlet subcooling ($h_s - h_{in}$) or $c_{pl} (T_s - T_{in})$,

and thermodynamic and transport properties of liquid and vapour saturated at p_s .

The mass flux is given by

$$\dot{m} = \frac{4 \dot{M}}{\pi D^2} . \quad (4.1)$$

A heat balance gives the following relationship between the critical heat flux and the critical quality:

$$\dot{q}_{cr} = \frac{\dot{m} D}{4 L} (\Delta h_{in} + \Delta h_v x_{g, cr}) . \quad (4.2)$$

The liquids used in the experiments were water, nitrogen, methane, R.12, hydrogen and neon. The scope of the data bank is given in Table 10.1.

This data bank was tested against the following six methods of predicting CHF.

- (1) The Bowring correlation², which is for water only.

- (2) The Ahmad correlation³, where the CHF is determined from a modelling parameter dependent on the densities and viscosities of the liquid and vapour.
- (3) The Bowring correlation for water; for non-aqueous liquids CHF was predicted from Bowring allowing for differences in physical properties by using Ahmad's alternative modelling parameter, which also contains the surface tension.
- (4) The Katto and Ohno correlation⁶, where CHF is related to the densities of liquid and vapour (ρ_l and ρ_g) and to surface tension (σ).
- (5) The tabular method of Groeneveld, using for water the tables of CHF published in Reference 8 and reproduced here in Table 10.4. For non-aqueous liquids CHF was predicted from the boiling number, defined in Equation (4.4) and presented in Table 10.5, which was derived from Table 10.4 by following the procedure described in Reference 9, using Katto and Ohno's parameter in the form

$$\psi = \dot{m} \left(\frac{D}{\sigma \rho_l} \right)^{1/2} . \quad (4.3)$$

The boiling number is defined by

$$Bo = \frac{\dot{q}}{\dot{m} \Delta h_v} . \quad (4.4)$$

- (6) The improved method of Groeneveld, using the tabular procedure described in the previous paragraph, but with the improved correction factors for diameter and heated length given in Sections 5.5 and 5.6 of this Item.

Table 10.2 is taken from Derivations 10 and 11; it gives the mean value of

$$(\dot{q}_{cr,pred} - \dot{q}_{cr,expt}) / \dot{q}_{cr,expt}$$

and the standard deviation for all the experimental results compared with each of the six methods of prediction. It is seen that Groeneveld's method is the best of the published methods. Improving his correction factors for diameter and length gives a slight overall improvement and a considerable improvement in the industrially important diameter range of 20 to 45 mm. Method (6) is therefore recommended, and the procedure for predicting critical heat flux by this method is detailed in Section 5 and illustrated in the example in Section 7. The accuracy of the method is discussed in Section 6. Table 10.3 (from Derivation 11) compares the recommended correlation with the results obtained with each of the six fluids used in the tests.

The second best of the published methods for predicting CHF was the correlation of Katto and Ohno⁶. The equations are rather cumbersome, but they may be preferable to tabular methods for inclusion in computer programs. Their accuracy is discussed further in Section 6.

5. PROCEDURE FOR CALCULATING THE CRITICAL HEAT FLUX (CHF) IN VERTICAL TUBES

It must be remembered that the procedure is approximate (see Section 6) so an adequate safety margin must be allowed in design. In a recirculating vaporiser the maximum outlet quality may considerably exceed the mean value, owing to maldistribution of the boiling fluid between the many tubes in parallel or to maldistribution and uneven temperature distribution in the heating fluid.

5.1 Data Required for Calculation Procedure

The following information is required:

internal diameter of the tubes (D),

mass flow rate of the boiling fluid ($\dot{M}$),

number of tubes in parallel (N_T),

saturation pressure of the boiling fluid (p_s),

temperature of the boiling fluid (T_c),

temperature of the heating fluid (T_H),

combined heat transfer coefficient of the heating fluid, the wall and any fouling, referred to the internal diameter (U),

physical properties of the boiling fluid: - relative molecular mass ($\tilde{M}$), critical pressure (p_c), latent heat of vaporisation (Δh_v), vapour density (ρ_g), liquid specific heat capacity (c_{pl}), dynamic viscosity (η_l), thermal conductivity (λ_l), density (ρ_l) and surface tension (σ).

With a recirculating vaporiser, it is also necessary to know the outlet quality ($x_{g,out}$). This is the reciprocal of the recirculation ratio, which may be specified; otherwise a suitable value must be chosen. Many steam generators are designed for a recirculation ratio of 10, giving $x_{g,out} = 0.1$. With a once-through vaporiser it is also necessary to be able to estimate the post-dryout heat transfer coefficient; this will be the subject of another Data Item.

5.2 Relationship between Heat Flux and Quality

ESDU 85041⁷ gives a procedure in Section 6 for estimating the local heat flux, $\dot{q}$, at selected values of the quality, x_g . The length of tube needed to reach each of the selected values of the quality can then be found as described in Section 7. The procedure is summarised here.

- (1) Determine the mass flux

$$\dot{m} = \frac{4 \dot{M}}{\pi D^2 N_T} \quad (5.1)$$

- (2) Determine the Reynolds number for the flow of the liquid at the point of incipient boiling from

$$Re_{l0} = \dot{m}D/\eta_l. \quad (5.2)$$

If $Re_{l0} \leq 4000$ the method may underpredict the heat flux at low qualities.

- (3) Estimate the heat transfer coefficient at the point of incipient boiling from

$$\alpha_{l0} = 0.023 Re_{l0}^{0.8} \eta_l^{0.4} c_{pl}^{0.4} \lambda_l^{0.6} / D. \quad (5.3)$$

- (4) Estimate the local values of α , the heat transfer coefficient of the boiling liquid, at each of the selected values of the quality, by following the procedure in Steps (6) to (17) in Section 6 of ESDU 85041⁷.

- (5) Calculate the local overall heat transfer coefficient at each of the selected values of the quality from

$$U(1/U' + 1/\alpha)^{-1}. \quad (5.4)$$

- (6) Calculate the corresponding values of heat flux from

$$\dot{q} = U(T_H - T_C). \quad (5.5)$$

- (7) Calculate L , the length of tube required to reach each of the selected values of the quality, as described in Section 7 of ESDU 85041⁷.

For liquids other than water, go to Step (9).

5.3 Estimation of Critical Heat Flux for Water/Steam in 8 mm Tube

- (8) Determine $\dot{q}_{cr}^*$, the critical heat flux in an 8 mm tube, by linear interpolation in Table 10.4, where values are given in kW/m² for selected values of

p_s saturation pressure, in bar (1 bar = 10⁵ N/m²),

$\dot{m}$ mass flux, in kg/s m², calculated from Equation (5.1),

x_g thermodynamic quality, from Equation (3.1).

Go on to Section 5.5.

5.4 Estimation of Critical Heat Flux for any Single-component Fluid in 8 mm Tube

- (9) Calculate the density ratio, ρ_l/ρ_g .

- (10) Calculate ψ , the non-dimensional mass flux parameter defined in Equation (4.3), for flow in an 8 mm tube at the prevailing mass flux from

$$\psi^* = \dot{m} \left(\frac{0.008}{\sigma \rho_l} \right)^{1/2}. \quad (5.6)$$