



Boiling inside tubes: saturated wet-wall heat transfer with mixtures

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BOILING INSIDE TUBES: saturated wet-wall heat transfer with mixtures

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. PURPOSE AND SCOPE OF THIS DATA ITEM	4
3. INTRODUCTION	4
4. VAPOUR-LIQUID EQUILIBRIUM	6
5. PUBLISHED DATA AND CORRELATIONS	8
5.1 Available Data	8
5.2 Published Correlations	8
5.3 Sensible Heat Transfer	8
6. A NOTE ABOUT THE CALCULATION OF VAPOUR-LIQUID EQUILIBRIUM AND MIXTURE PROPERTIES	9
7. CALCULATION PROCEDURE FOR THE LOCAL HEAT FLUX IN THE BOILING ZONE	9
7.1 Introduction	9
7.2 Data Required	9
7.3 Preliminary Calculations	10
7.4 Iterative Calculations	12
7.5 Using the Heat Flux to Calculate the Tube Length for a Given Duty	13
8. WORKED EXAMPLE	14
8.1 Data Required	14
8.2 Preliminary Calculations	15
8.3 Iterative Calculations	16
8.4 Calculation of Tube Length	16
9. COMMENT ON ERRORS AND APPLICABILITY	18
10. REFERENCES AND DERIVATION	19
FIGURES 1 to 5	22 to 24
APPENDIX A DETAILS OF CALCULATION METHODS	27
A1. Palen and Small (Derivation 34).	27
A2. The Modified Silver Method (Derivation 33).	27

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1. NOTATION AND UNITS

		Units	
		SI	British
Bo	boiling number, see Equation (7.18)	—	—
C_D	dimensional constant used in Palen and Small method. See Equation (7.22) and Appendix A	1/°C	1/°F
C_{dr}	function of density ratio, see Equation (7.10)	—	—
C_{pr}	function of reduced pressure, see Equation (7.9)	—	—
c_{pg}	vapour phase specific heat capacity at constant pressure	J/kg K	Btu/lb °F
c_{pl}	liquid phase specific heat capacity at constant pressure	J/kg K	Btu/lb °F
D	tube diameter	m	ft
E	boiling enhancement factor, see Equation (7.19)	—	—
E_{cb}	convective boiling enhancement factor, see Equation (7.11)	—	—
h	mixture specific enthalpy at quality x_g	J/kg	Btu/lb
h_1	mixture specific enthalpy at start of step along tube length	J/kg	Btu/lb
h_2	mixture specific enthalpy at end of step along tube length	J/kg	Btu/lb
$\dot{M}$	mixture total mass flow rate in tube	kg/s	lb/h
$\dot{M}_g$	vapour mass flow rate	kg/s	lb/h
$\dot{M}_l$	liquid mass flow rate	kg/s	lb/h
$\tilde{M}$	mixture mean relative molar mass (molecular weight)	—	—
$\tilde{M}_H$	relative molar mass (molecular weight) of heavy component	—	—
$\tilde{M}_L$	relative molar mass (molecular weight) of light component	—	—
$\dot{m}$	total (gas and liquid) mass flux	kg/m ² s	lb/ft ² h
p_c	mixture mean critical pressure	bar	lb/ft ²

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p_r	mixture reduced pressure, see Equation (7.8)	—	—
p_s	system pressure	bar	lb/ft ²
Pr_g	vapour Prandtl number, see Equation (7.6)	—	—
Pr_l	liquid Prandtl number, see Equation (7.3)	—	—
$\dot{q}$	heat flux	W/m ²	Btu/h ft ²
$\dot{q}_{cb}$	heat flux, neglecting nucleation and mixture effects, see Equation (7.14)	W/m ²	Btu/h ft ²
Re_g	actual vapour Reynolds number	—	—
Re_{l0}	Reynolds number with all flow as liquid, see Equation (7.2)	—	—
S	nucleate suppression factor, see Equation (7.20)	—	—
T	temperature	K or °C	°F
T_{bub}	bubble point temperature	K or °C	°F
T_{dew}	dew point temperature	K or °C	°F
T_H	heating fluid temperature	K or °C	°F
T_s	system temperature	K or °C	°F
U	overall heat transfer coefficient, see Equation (7.26)	W/m ² K	Btu/h ft ² °F
U'	combined heat transfer coefficient for heating fluid, wall and any fouling	W/m ² K	Btu/h ft ² °F
U_{cb}	overall heat transfer coefficient, ignoring any nucleation and mixture effects, see Equation (7.13)	W/m ² K	Btu/h ft ² °F
x	mass fraction of light component in liquid phase	—	—
x_g	quality, see Equation (4.1)	—	—
x_i	mass fraction of light component in feed to vaporiser	—	—
$\tilde{x}$	mole fraction of light component in liquid phase	—	—
$\tilde{x}_i$	mole fraction of light component in feed to vaporiser	—	—
y	mass fraction of light component in vapour phase	—	—
$\tilde{y}$	mole fraction of light component in vapour phase	—	—

Z	parameter given by Equation (7.15)	—	—
α_b	nucleate boiling heat transfer coefficient, neglecting effect of mixtures, see Equation (7.21)	W/m ² K	Btu/h ft ² °F
α_{bm}	nucleate boiling heat transfer coefficient, taking into account effect of mixtures, see Equation (7.22)	W/m ² K	Btu/h ft ² °F
α_c	convective boiling heat transfer coefficient, neglecting effect of mixtures, see Equation (7.23)	W/m ² K	Btu/h ft ² °F
α_{cb}	convective heat transfer coefficient, neglecting effect of nucleation and mixtures, see Equation (7.12)	W/m ² K	Btu/h ft ² °F
α_g	single phase vapour heat transfer coefficient, see Equation (7.7)	W/m ² K	Btu/h ft ² °F
α_{l0}	single phase liquid heat transfer coefficient at point of incipient boiling, see Equation (7.4)	W/m ² K	Btu/h ft ² °F
α_m	final boiling heat transfer coefficient, see Equation (7.24)	W/m ² K	Btu/h ft ² °F
α_{nb}	nucleate boiling heat transfer coefficient, see Equation (7.17)	W/m ² K	Btu/h ft ² °F
Δh_v	mixture mean latent heat of vaporisation	J/kg	Btu/lb
Δz	step length along tube	m	ft
η_g	vapour phase dynamic viscosity	kg/m s	lb/ft h
η_l	liquid phase dynamic viscosity	kg/m s	lb/ft h
λ_g	vapour phase thermal conductivity	W/m K	Btu/h ft °F
λ_l	liquid phase thermal conductivity	W/m K	Btu/h ft °F
ρ_g	vapour phase density	kg/m ³	lb/ft ³
ρ_l	liquid phase density	kg/m ³	lb/ft ³

2. PURPOSE AND SCOPE OF THIS DATA ITEM

Vaporisers and evaporators are used in a wide variety of industrial situations. ESDU 85041 (Derivation 37) describes the problems that may occur in thermal rating a vaporiser, and provides a calculation method. The method (Derivation 37) is restricted to situations in which the phases are thermodynamically saturated and the heated wall is covered with liquid (so called wet-wall conditions). It is assumed that the liquid is in turbulent flow in the single-phase region before the start of boiling. The calculation method is assumed to apply to vertical up-flow and to horizontal flow in which the velocities are sufficiently high to avoid gross stratification of the flow. Some of the general features of the situation are reviewed briefly in Section 3 of this present Data Item.

ESDU 85041 is restricted to the boiling of pure liquids. The present Data Item extends the method to the case of boiling of mixtures of liquids. The method chosen can be used for multi-component mixtures as well as for binary mixtures. The principal difficulty in applying the method for mixtures of many liquids is the calculation of the relevant vapour–liquid equilibria. This calculation is outside the scope of this Data Item, but the necessary information is produced by many modern computer flow-sheeting packages.

3. INTRODUCTION

This Data Item (and ESDU 85041) is concerned with saturated wet-wall boiling. In this region the heat transfer mechanism is simplified by two factors.

- (a) The flow is saturated rather than sub-cooled, so once vapour is formed there is no tendency for that vapour to re-condense to form liquid again.
- (b) The flow is well away from the condition where the heat flux exceeds the critical heat flux. If the critical heat flux is exceeded the rate of heat transfer drops suddenly as the heat transfer mechanism changes dramatically. Typically the heat transfer surface becomes covered with vapour instead of liquid. This vapour ‘insulates’ the hot surface from the boiling liquid, and so the heat transfer coefficient falls greatly.

In saturated wet-wall boiling the total boiling heat transfer coefficient may be divided into two parts: one which is identifiable as concerned with nucleate boiling, and one concerned with convective boiling.

- (a) Nucleate boiling is the process where vapour bubbles are formed at the heated surface and then move into the surrounding liquid. This type of boiling is dependent on the detailed nature of the surface and on the way in which the liquid phase interacts with it. Nucleate boiling usually predominates when the quality (the fraction of the mass flow that is vapour) is low and the heat flux is high. Nucleate boiling experiments are often performed by placing heating elements in a pool of liquid: this is a pool boiling experiment.
- (b) Convective boiling takes place without the assistance of bubble formation. The heat is conducted and convected from the heated surface through a thin liquid film, and evaporation takes place at the interface between the liquid film and the vapour. Convective boiling usually predominates when the quality is high and the heat flux is high. Convective boiling experiments are typically performed using the flow through a heated tube: this is a flow boiling experiment.

Often the two types of boiling are regarded as taking place simultaneously, one gradually taking over from the other as the heat flux or the temperature difference between the heated surface and the liquid varies.

Using a mixture of components rather than a single, pure component alters many of the phenomena of boiling. In particular, two features are worth noting.

- (a) There is no longer a simple saturation temperature at which the evaporation takes place. With a single-component (pure) liquid the saturation temperature depends only on the pressure. As the pressure increases, so does the saturation temperature. With a mixture, the lightest component (the one with the highest volatility, that is the lowest saturation temperature at the system pressure) evaporates preferentially. The remaining mixture thus has a higher boiling point. Thus the saturation temperature depends not only on the pressure, but also on the molar composition of the mixture. With a pure component, as evaporation proceeds, the temperature stays constant (if the pressure is assumed to be constant) and so all the heat supplied goes to evaporate the liquid. With a mixture, as heat is supplied, not only does evaporation take place, but also the temperature of the system increases. Thus the heat supplied must go not only to evaporate some of the liquid, but also to heat up both phases.
- (b) As a mixture is being evaporated, there exists the probability that variations in molar composition between various points will alter the boiling of the mixture. These mass transfer effects are not well understood.

From the above effects, four types of influence of mixtures on flow boiling heat transfer can be envisaged.

- (i) The nucleate boiling heat transfer will be affected by mass transfer effects. Nucleate boiling heat transfer occurs when the nucleation of vapour bubbles occurs at small imperfections or cavities on the heated surface. The bubbles initially grow rapidly and the vapour is formed from the liquid immediately surrounding the bubble. This liquid is slightly superheated. In a mixture, this layer of liquid around the bubble becomes denuded of light component, and so the saturation temperature of this layer increases. This increase in the local saturation temperature causes the evaporation rate to be reduced. The variations in local composition in the liquid phase tend to be reduced by diffusion within the liquid and by any bulk mixing within the liquid phase.
- (ii) Similar effects also occur in convective boiling, except that there is inevitably a considerable bulk motion of the liquid, and almost always turbulent flow, to dissipate any composition variations developed in the bulk liquid. In convective boiling the composition variations develop as in nucleate boiling because the light component tends to evaporate preferentially. That also increases the saturation temperature of the remaining liquid in the interface region, and again reduces the evaporation rate.
- (iii) As the fluid flows along the channel, the liquid phase temperature is increasing as the composition changes. Some of the heat must go to providing this 'sensible heat' transfer to raise the temperature of the liquid.
- (iv) Similarly, the vapour phase temperature must also increase, and there must also be a vapour phase 'sensible heat' transfer to raise the temperature of the vapour.

Any complete understanding of mixture boiling must therefore include all these four types of influence. However, almost all the work on boiling has been on boiling in a pool of liquid where the mechanism is nucleate boiling. The experiments have been 'differential', that is there is only a tiny change in liquid or vapour composition. Thus what is being studied in these experiments is the mass transfer effects in nucleate boiling and that alone. Not only do such experiments yield no information about convective boiling, they also give no information about the sensible heat transfers.

Before examining the problem in detail, the more relevant facts about vapour-liquid equilibrium effects will be reviewed.

4. VAPOUR-LIQUID EQUILIBRIUM

Figure 1 shows a vapour-liquid equilibrium diagram for a well behaved ideal binary mixture with a fairly wide boiling range. The nomenclature usually used is that $\tilde{x}$ is the mole fraction of the light component in the liquid phase, and that $\tilde{y}$ is the mole fraction of the light component in the vapour phase. Such a diagram is for a fixed pressure, here 1.0 bar. In actual boiling processes the pressure changes as the fluid flows along the heated channel, and so the vapour-liquid equilibrium needs to be known as a function of pressure also. However in many cases this is a relatively minor consideration.

Referring to Figure 1, consider what happens if a liquid of known composition, say $\tilde{x}_i = 0.4$, is being heated from a low temperature, say 50 °C. Until the temperature reaches 73.0 °C it remains as liquid. At this temperature, the bubble point line is reached in Figure 1. Thus the bubble point temperature, T_{bub} , at which the first bubble of vapour is formed, is equal to 73.0 °C. The first vapour bubble has a very different composition from the bulk composition of the liquid ($\tilde{x} = 0.4$); in fact $\tilde{y} = 0.845$. As the temperature increases, compositions of the liquid and the vapour change. By the time the temperature has reached 85 °C, $\tilde{x} = 0.220$ and $\tilde{y} = 0.670$. When the temperature reaches 97.8 °C, the dew point line is reached. Thus the dew point temperature, T_{dew} , at which the first liquid is formed when a vapour is cooled is equal to 97.8 °C. Here at the dew point the vapour has a composition $\tilde{y} = 0.4$ (as now all the original liquid with this composition has been vaporised), but the last liquid to be vaporised has a very different composition, $\tilde{x} = 0.095$.

So far the quality of the mixture, x_g , has not been considered. The quality is the mass fraction of the total flow which is vapour, or

$$x_g = \frac{\dot{M}_g}{(\dot{M}_l + \dot{M}_g)}, \quad (4.1)$$

where $\dot{M}_g$ is the mass flow rate of the vapour phase, and

$\dot{M}_l$ is the mass flow rate of the liquid phase.

The quality is calculated from the mass fractions of the light component corresponding to the molar fractions $\tilde{x}_i$, $\tilde{x}$ and $\tilde{y}$. The mass fraction of the light component, x_i , is calculated from

$$x_i = \frac{\tilde{x}_i \tilde{M}_L}{\tilde{x}_i \tilde{M}_L + (1 - \tilde{x}_i) \tilde{M}_H}, \quad (4.2)$$

where $\tilde{M}_L$ and $\tilde{M}_H$ are the relative molar masses (molecular weights) of the light and the heavy component respectively. The equations for x and y are similar to Equation (4.2):

$$x = \frac{\tilde{x} \tilde{M}_L}{\tilde{y} \tilde{M}_L + (1 - \tilde{x}) \tilde{M}_H}, \quad (4.3)$$

$$y = \frac{\tilde{y} \tilde{M}_L}{\tilde{y} \tilde{M}_L + (1 - \tilde{y}) \tilde{M}_H}. \quad (4.4)$$

In the above example $\tilde{M}_L = 120$ and $\tilde{M}_H = 90$. Hence when $\tilde{x}_i = 0.4$, $x_i = 0.471$. At 85 °C when $\tilde{x} = 0.220$ and $\tilde{y} = 0.670$, $x = 0.273$ and $y = 0.730$.

From mass balances on the total flow, and on one of the phases, it may be shown that

$$x_g = \frac{x_i - x}{y - x}, \quad (4.5)$$

where x_i is the mass fraction of the light component in the inlet liquid,

x is the mass fraction of the light component in the liquid phase part way through the vaporisation, and

y is the mass fraction of the light component in the vapour phase part way through the vaporisation.

For example, in the above case $x_i = 0.471$, and at 85 °C, $x = 0.273$, and $y = 0.730$, so that

$$x_g = \frac{0.471 - 0.273}{0.730 - 0.273} = \frac{0.198}{0.457} = 0.433. \quad (4.6)$$

Hence, from the equilibrium diagram, the relationship between temperature, liquid and vapour compositions and quality can be ascertained. For the example shown in Figure 1 the variations of $\tilde{x}$, $\tilde{y}$, and x_g with temperature are shown in Figure 2.

From data such as these the enthalpy of the mixture (both components, liquid and vapour) can be calculated. Figure 3 shows the enthalpy, h , for the example in Figure 1, relative to 0 °C, as the system temperature increases from 73.0 °C (the bubble point temperature) to 97.8 °C (the dew point temperature). The value of dT/dh is shown in Figure 4. This quantity is used in some calculation methods. Its significance is explained in Section 7 on the calculation method.