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Condensation inside tubes: pressure drop in straight tubes with vertical downflow

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THE PREPARATION OF THIS DATA ITEM

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CONDENSATION INSIDE TUBES: pressure drop in straight tubes with vertical downflow

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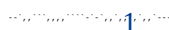
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CONDENSATION INSIDE TUBES: pressure drop in straight tubes with vertical downflow

1. NOTATION AND UNITS

		Units	
		SI	British
A	defined by Equation (4.15)	—	—
A', B	defined by Equations (4.11) and (4.12)	—	—
C	correlation constant in Equation (3.1)	—	—
Co	mean value of condensation number, from Equation (4.5)	—	—
C_1, C_2	defined by Equations (4.19) and (4.20)	—	—
CFR	correction factor for roughness, from Equation (3.1)	—	—
D	internal diameter of tube	m	ft
E	correction factor to be applied to estimated total pressure drop	—	—
Fr	Froude number, from Equation (4.6)	—	—
f	Fanning friction factor, from Equations (4.10) to (4.12)	—	—
g	acceleration due to gravity	m/s ² (9.81)	ft/h ² (4.17 × 10 ⁶)
g_c	constant of proportionality in Newton's 2nd law of motion	— (1.0)	lb ft/lbf h ² (4.17 × 10 ⁸)
h	specific enthalpy	J/kg	Btu/lb
L	total cooled length of tube	m	ft
L_1	cooled length of tube before condensing begins	m	ft
L_2	cooled length of tube over which condensing occurs	m	ft
L_d	downstream uncooled length of tube	m	ft
L_u	upstream uncooled length of tube	m	ft
$\dot{M}$	total mass flow rate inside tubes	kg/s	lb/h
$\dot{m}$	total mass flux, see Equation (4.1)	kg/s m ²	lb/h ft ²
N_T	number of tubes in parallel	—	—
p	static pressure	N/m ² (Pa)	lbf/ft ²
$\dot{Q}$	rate of heat transfer	W	Btu/h

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$\dot{q}$	mean heat flux, see Equation (4.2)	W/m ²	Btu/h ft ²
R	enhancement in two-phase pressure drop, see Equation (4.16)	–	–
Re_g	Reynolds number of vapour at quality of unity, from Equation (4.4)	–	–
Re_l	Reynolds number of liquid at quality of zero, from Equation (4.3)	–	–
S_r	slip ratio	–	–
s	standard deviation (see Section 5.5)	–	–
T	temperature	K	°F
$\dot{V}_r$	volumetric flow ratio, from Equation (4.18)	–	–
We	Weber number, from Equation (4.7)	–	–
x_g	quality (dryness fraction), see Equation (4.8)	–	–
z	distance along the tube from inlet	m	ft
Δp	pressure drop	N/m ²	lbf/ft ²
Δh_v	latent heat of vaporisation	J/kg	Btu/lb
ε	surface roughness	m	ft
ε_g	void fraction – fraction of tube occupied by vapour	–	–
η	dynamic viscosity of fluid	kg/s m	lb/ft h
μ	error in prediction of pressure drop in condensing flow using correlations for adiabatic flow	–	–
ρ	density of fluid	kg/m ³	lb/ft ³
σ	surface tension	N/m	lbf/ft

Extra subscripts

<i>expt</i>	experimentally measured value
<i>fm</i>	frictional plus momentum component
<i>fr</i>	frictional component
<i>g</i>	vapour
<i>in</i>	at inlet
<i>l</i>	liquid
<i>m</i>	mean
<i>out</i>	at outlet
<i>pred</i>	predicted value

<i>sat</i>	under saturation conditions
<i>T</i>	total
<i>tp</i>	two-phase
<i>v</i>	vertical
1	cooling single-phase vapour
2	cooling two-phase mixture

2. PURPOSE AND SCOPE OF THIS ITEM

This Data Item is one of a group on the condensation of vapours inside straight tubes of circular cross-section. The first Data Item, ESDU 89038¹⁰, deals with reflux condensation in vertical tubes, where the vapour flows up the tubes and the condensate drains down the tubes. This, the second Item, deals with the estimation of pressure drop of a single-component vapour in co-current downflow of vapour and condensate in vertical tubes.

Whilst the scope of this Data Item is the pressure drop inside the tubes of a condenser, in practice the dominant pressure drop is often that at inlet to the tubes; this is dealt with in Section 6.1.

The prediction of pressure drop in a condenser is required for the design of downstream plant. It is also required so that the saturation temperature can be determined at the outlet and in some cases at several points along the tube. An excessive pressure drop may lead to a considerable reduction in temperature, resulting in “temperature pinch” and fall in heat flux at some point along the condenser.

A data bank on pressure drop in condensing flow through straight tubes has been collected from the literature, for ESDU by staff at Harwell Laboratory, as described in Section 5, and is used to develop the prediction method presented here.

It is suggested in Section 4.9 of ESDU 85041⁸ that pressure drop in **boiling** flow might be estimated in the manner recommended by ESDU for adiabatic flow in References 2, 3 and 4. Section 3 summarises the procedure and describes some correlations that have more recently appeared in the literature. A new procedure has been developed for estimating the pressure drop in condensing flow through straight lengths of tube, based on certain assumptions. This procedure is similar to that developed for estimating the pressure drop in boiling flow in ESDU 89039¹¹. It is based on the following assumptions:

- (1) the orientation is vertical with downward flow,
- (2) local values of the heat flux at various points along the cooled region of the tubes have been calculated,
- (3) the liquid and vapour are in equilibrium, so any superheat at inlet is removed before condensing begins,
- (4) flow is annular/dispersed (see Section 4.2),
- (5) the physical properties of the liquid and vapour do not change significantly along the tubes, apart from a reduction in the density of the vapour resulting from pressure drop,
- (6) the total pressure drop is less than 10% of the absolute pressure,
- (7) the accuracy of the pressure drop in condensing flow calculated from correlations for adiabatic flow can be improved by the application of a correction factor derived from experimental data.

The total pressure drop can be estimated by following the numbered steps in Section 4. This is illustrated by the example in Section 7.

Section 5 discusses the data bank and compares the measured and predicted values of the pressure drop. An assessment of the accuracy of the predictions is made.

Section 6 discusses the prediction of the overall pressure drop in an industrial vertical tubeside condenser.

3. PUBLISHED CORRELATIONS FOR PRESSURE DROP IN ADIABATIC TWO-PHASE FLOW AND THEIR APPLICATION TO CONDENSING FLOW

From a balance of force and momentum it can be shown that the pressure gradient in two-phase flow is the sum of three components, as follows:

- (1) frictional component, see ESDU 76018²,
- (2) gravitational component, see ESDU 77016³,
- (3) momentum-change component (sometimes called “acceleration”) see ESDU 78001⁴.

The total pressure drop over a straight length of tube is determined by integrating the sum of these components of the pressure gradient with respect to the distance along the tube.

During condensation the values of the components change considerably with decreasing quality (defined in Section 4.2). It was decided to analyse the data for two-phase pressure drop with condensing flow by comparing the measured values with values predicted by using the best available correlations for adiabatic flow. Only minor attempts have been made to improve on the correlations that have been published in the open literature. From the analysis it has been possible to provide a system of correction factors that can be applied to the total pressure drop predicted as described now for adiabatic flow. The three following sub-sections describe the methods used and the reasons for choosing them.

3.1 Frictional Component

This is the loss of pressure resulting from friction at the wall of the tube. In the de-superheating zone of a condenser it can be determined from the properties of the vapour using the normal procedures for single-phase flow. It is then necessary to determine how much the frictional component changes as the quality decreases.

Since the issue of ESDU 76018², Friedel⁶ has published an improved pressure drop correlation for two-phase friction in vertical and horizontal unheated straight channels. Using 25 000 measurements he showed that his method was an improvement on the previously recommended methods. The method of Friedel has now become the generally accepted procedure for estimating the frictional component of two-phase in-tube pressure drop, provided that the viscosity of the liquid is less than 1000 times that of the vapour⁷.

The evidence on the effects of **roughness** on two-phase pressure drop is sparse, but it has been shown that an increase in the roughness of the surface of the tube gives a smaller contribution to the two-phase than to the single-phase pressure drop. This is because, in two-phase flow, the roughness of the vapour-liquid interface tends to have a greater influence than the roughness of the wall (except for extremely rough tubes). Chisholm⁵ has suggested that this can be allowed for by applying a correction factor, *CFR*, to the two-phase term in the equation used for estimating the frictional component of the pressure drop.

This is given by

$$CFR = \frac{1 + 10^{-C\varepsilon/D}}{2} \quad (3.1)$$

where *C* is a correlating constant, ε is the surface roughness and *D* the internal diameter of the tube. Thus for a smooth pipe, $\varepsilon = 0$ and *CFR* = 1.0. As the roughness increases, *CFR* tends to 0.5.

The policy adopted in the Data Item on pressure drop in boiling flow¹¹ was to use the simplified version of Friedel’s correlation for the frictional component and to multiply the second term, which is zero for

single-phase flow, by CFR obtained from Equation (3.1). It was found that the closest agreement between experimental and predicted pressure drop was obtained with $C = 220$. In the absence of any data on the effect of roughness on pressure drop in condensing flow, the same value of C is assumed in this Data Item and is incorporated in the last term in Equation (4.16).

3.2 Gravitational Component

This is zero in flow along a horizontal tube. In flow up a vertical tube it is the pressure change along the length required to support the weight of the liquid and vapour in the tube. In downward flow in a vertical or inclined tube, the liquid may flow as a falling film on the wall, in which case the gravitational component of pressure drop is small. Alternatively the liquid may bridge the tube, and this may lead to an overall increase in pressure at low qualities when the rise in pressure due to gravity exceeds the loss of pressure due to friction.

Premoli *et al.*¹ give an empirical correlation for evaluating mixture density in two-phase adiabatic flow up vertical channels, based on an experimental investigation carried out at C.I.S.E. in Milan. This correlation is shown to be reliable by ESDU³ and has also been recommended elsewhere⁷.

In downward flow, gravity produces a rise in pressure except at the bottom of a total condenser when the condensate runs down the wall as a falling film. This Data Item is confined to annular/dispersed flow where the gravity term is relatively small. In the absence of any data on downward adiabatic flow, the method of Premoli *et al.*¹ is used in Section 4.5 for estimating the density in two-phase vertical flow.

3.3 Momentum Component

This is the change in pressure resulting from a change in momentum flux along a straight duct. In condensing flow the reduction in quality causes a reduction in momentum flux, which leads to a rise in pressure. At high velocity this may be more than counteracted by the increase in specific volume resulting from pressure drop.

The total momentum component of pressure drop depends only on the mass flux and the difference between the specific volume of the mixture at outlet and that at inlet. Hence it is not necessary to integrate along the straight length of tube (unless local pressures are required).

ESDU 78001⁴ assesses two methods for predicting the increase in the momentum flux. The simpler of the two methods of calculation is based on the assumption that the two phases are intimately mixed, thus forming a homogeneous mixture. This method is used in this Data Item.

4. PROCEDURE FOR PREDICTING PRESSURE DROP IN CONDENSING FLOW

This section describes how it is possible to predict the pressure drop through a cooled tube with condensing flow using the correlations recommended in the previous section. It is applicable to downflow in a vertical tube. Section 4.7 shows how the accuracy of the calculation can be improved by applying a correction factor based on the analysis of the data bank described in Section 5.

4.1 Data Required and Preliminary Calculations

The following information is required, using a self-consistent system of units, as in Section 1:

specific enthalpy at inlet and outlet, h_{in} and h_{out} , or quality, see Equation (4.8), $x_{g,in}$ and $x_{g,out}$,

internal diameter, D , surface roughness, ε , and number of tubes in parallel, N_T , (some values of ε can be found in Derivations 9 and 18),

upstream uncooled length, L_u , cooled length, L , and downstream uncooled length, L_d ,

mass flow rate of condensing fluid, $\dot{M}$,

rate of heat transfer, $\dot{Q}$,

pressure and temperature at inlet, p_{in} and T_{in} , or at outlet, p_{out} and T_{out} ,

physical properties of the condensing fluid:

latent heat of vaporisation, Δh_v ,

density of liquid and vapour, ρ_l and ρ_g ,

dynamic viscosity of liquid and vapour, η_l and η_g ,

surface tension of liquid against its vapour, σ ,

relationship between saturation temperature, T_{sat} , and pressure, p ,

relationship between ρ_g and T_{sat} ,

Other properties may be assumed to be independent of T_{sat} .

At this stage, the following preliminary calculations should be carried out.

- (1) Determine the total mass flux from

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