Encyclopedia of Chemical Processing and Design

23

Executive Editor John J. McKetta

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23 Fluid Flow, Two-Phase Design to Froth Flotation

MARCEL DEKKER, INC. NEW YORK AND BASEL

Library of Congress Cataloging in Publication Data (Revised)
Main entry under title:

Encyclopedia of chemical processing and design.

Includes bibliographical references.
1. Chemical engineering—Dictionaries. 2. Chemistry, Technical—Dictionaries. I. McKetta, John J. II. Cunningham, William Aaron.
TP9.E66 660.2'8'003 75-40646
ISBN 0-8247-2451-8 (v. 1)

MARCEL DEKKER, INC.
270 Madison Avenue, New York, New York, 10016

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 75-40646
ISBN: 0-8247-2473-9

Current printing (last digit):
10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

International Advisory Board

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Conversion to SI Units

To convert from	To	Multiply by
acre	square meter (m^2)	4.046×10^3
angstrom	meter (m)	1.0×10^{-10}
are	square meter (m^2)	1.0×10^2
atmosphere	newton/square meter (N/m^2)	1.013×10^5
bar	newton/square meter (N/m^2)	1.0×10^5
barrel (42 gallon)	cubic meter (m^3)	0.159
Btu (International Steam Table)	joule (J)	1.055×10^3
Btu (mean)	joule (J)	1.056×10^3
Btu (thermochemical)	joule (J)	1.054×10^3
bushel	cubic meter (m^3)	3.52×10^{-2}
calorie (International Steam Table)	joule (J)	4.187
calorie (mean)	joule (J)	4.190
calorie (thermochemical)	joule (J)	4.184
centimeter of mercury	newton/square meter (N/m^2)	1.333×10^3
centimeter of water	newton/square meter (N/m^2)	98.06
cubit	meter (m)	0.457
degree (angle)	radian (rad)	1.745×10^{-2}
denier (international)	kilogram/meter (kg/m)	1.0×10^{-7}
dram (avoirdupois)	kilogram (kg)	1.772×10^{-3}
dram (troy)	kilogram (kg)	3.888×10^{-3}
dram (U.S. fluid)	cubic meter (m^3)	3.697×10^{-6}
dyne	newton (N)	1.0×10^{-5}
electron volt	joule (J)	1.60×10^{-19}
erg	joule (J)	1.0×10^{-7}
fluid ounce (U.S.)	cubic meter (m^3)	2.96×10^{-5}
foot	meter (m)	0.305
furlong	meter (m)	2.01×10^2
gallon (U.S. dry)	cubic meter (m^3)	4.404×10^{-3}
gallon (U.S. liquid)	cubic meter (m^3)	3.785×10^{-3}
gill (U.S.)	cubic meter (m^3)	1.183×10^{-4}
grain	kilogram (kg)	6.48×10^{-5}
gram	kilogram (kg)	1.0×10^{-3}
horsepower	watt (W)	7.457×10^2
horsepower (boiler)	watt (W)	9.81×10^3
horsepower (electric)	watt (W)	7.46×10^2
hundred weight (long)	kilogram (kg)	50.80
hundred weight (short)	kilogram (kg)	45.36
inch	meter (m)	2.54×10^{-2}
inch mercury	newton/square meter (N/m^2)	3.386×10^3
inch water	newton/square meter (N/m^2)	2.49×10^2
kilogram force	newton (N)	9.806

To convert from	To	Multiply by
kip	newton (N)	4.45×10^3
knot (international)	meter/second (m/s)	0.5144
league (British nautical)	meter (m)	5.559×10^3
league (statute)	meter (m)	4.83×10^3
light year	meter (m)	9.46×10^{15}
liter	cubic meter (m^3)	0.001
micron	meter (m)	1.0×10^{-6}
mil	meter (m)	2.54×10^{-6}
mile (U.S. nautical)	meter (m)	1.852×10^3
mile (U.S. statute)	meter (m)	1.609×10^3
millibar	newton/square meter (N/m^2)	100.0
millimeter mercury	newton/square meter (N/m^2)	1.333×10^2
oersted	ampere/meter (A/m)	79.58
ounce force (avoirdupois)	newton (N)	0.278
ounce mass (avoirdupois)	kilogram (kg)	2.835×10^{-2}
ounce mass (troy)	kilogram (kg)	3.11×10^{-2}
ounce (U.S. fluid)	cubic meter (m^3)	2.96×10^{-5}
pascal	newton/square meter (N/m^2)	1.0
peck (U.S.)	cubic meter (m^3)	8.81×10^{-3}
pennyweight	kilogram (kg)	1.555×10^{-3}
pint (U.S. dry)	cubic meter (m^3)	5.506×10^{-4}
pint (U.S. liquid)	cubic meter (m^3)	4.732×10^{-4}
poise	newton second/square meter ($N \cdot s/m^2$)	0.10
pound force (avoirdupois)	newton (N)	4.448
pound mass (avoirdupois)	kilogram (kg)	0.4536
pound mass (troy)	kilogram (kg)	0.373
poundal	newton (N)	0.138
quart (U.S. dry)	cubic meter (m^3)	1.10×10^{-3}
quart (U.S. liquid)	cubic meter (m^3)	9.46×10^{-4}
rod	meter (m)	5.03
roentgen	coulomb/kilogram (c/kg)	2.579×10^{-4}
second (angle)	radian (rad)	4.85×10^{-6}
section	square meter (m^2)	2.59×10^6
slug	kilogram (kg)	14.59
span	meter (m)	0.229
stoke	square meter/second (m^2/s)	1.0×10^{-4}
ton (long)	kilogram (kg)	1.016×10^3
ton (metric)	kilogram (kg)	1.0×10^3
ton (short, 2000 pounds)	kilogram (kg)	9.072×10^2
torr	newton/square meter (N/m^2)	1.333×10^2
yard	meter (m)	0.914

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Fluid Flow, Two-Phase Design

Here is the simplest and least frustrating method for sizing pipes when two-phase flow exists in a pipeline. Also presented are useful tips that exploit the inherent flexibility in the distribution of pressure losses in a piping system so that the designer can obtain reasonable sizes for pipes and components.

Two-phase-flow theories and experiments have a threefold significance for the process-piping designer. It has been shown that:

1. If the vapor content of a liquid line increases, the friction loss is greater than the single-phase liquid pressure loss, and is greater than the pressure loss calculated with the average density.
2. For a given vapor–liquid ratio and associated physical properties, a characteristic flow pattern develops.
3. Between the various flow patterns, unit pressure losses can differ when comparing borderline cases.

Piping design for two-phase flow has been investigated by a great number of researchers through rational and empirical steps [1, 2]. And limitations, generalizations and simplifications have been introduced for providing practical methods of design.

We will assume here that two-phase flow is isothermal, turbulent in both the liquid and vapor phases, and steady (liquid and vapor move with the same velocity), and that pressure loss is not more than 10% of the absolute downstream pressure.

An often-asked question is: How accurate are two-phase-flow calculations? If actual pipelines closely resemble the experimental conditions, deviations are small. The application of correlations for two-phase flow to process-piping design is arbitrary. Experiments are usually done with small-diameter, straight, and relatively short pieces of horizontal or vertical pipe. Under laboratory conditions, flow patterns are kept constant and flow conditions consistent. However, most process piping probably has changing flow patterns in various segments of the line because of the three-dimensional pipe configurations in which one finds horizontal and vertical runs, elevation changes, offsets, branch connections, manifolds, pipe components, reducers, and other restrictions. Sizable deviations can be expected in prediction of friction loss compared to actually measured values. Because of this, pipe runs for two-phase flow should be short and simple.

We present here the simplest, and in its practical application the least frustrating, method of design from among the many available ones. Let us compute the resistance for two-phase flow in two main steps. These are:

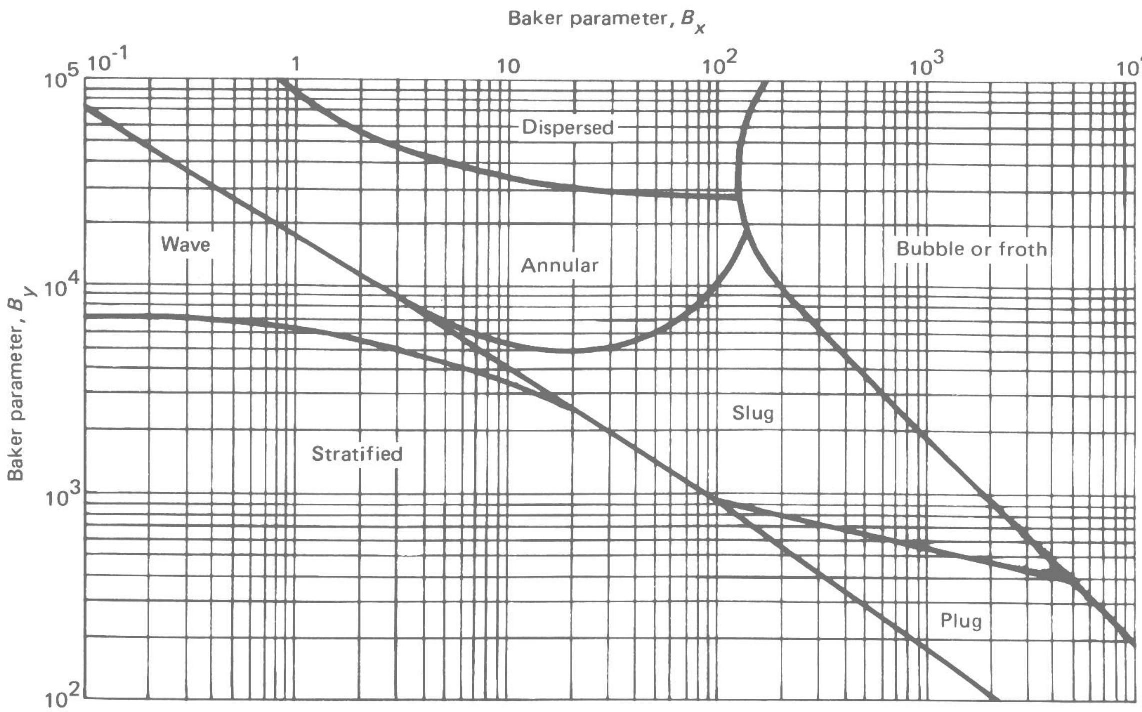
Select a possible flow pattern by calculating the coordinates of a flow-region chart.

Determine unit pressure losses by calculating only the vapor-phase unit loss, corrected by an applicable correlation for two-phase flow.

Two-Phase-Flow Regions: Baker Parameters

We select two-phase-flow patterns [3] from Fig. 1. The borders of the various flow patterns in Fig. 1 are shown as lines. In reality, these borders have rather broad transition zones [4].

We can establish a particular flow region from the Baker parameters, B_x



Two-Phase Flow Correlations						
Dispersed	Bubble	Slug	Stratified	Wave	Plug	Annular
Use Fig. 3 and Eq. (3)	$\phi = \dfrac{14.2\,X^{0.75}}{(W_l/A)^{0.1}}$	$\phi = \dfrac{1{,}190\,X^{0.815}}{(W_l/A)^{0.-5}}$ Avoid slug flow	$\phi = \dfrac{15{,}400\,X}{(W_l/A)^{0.3}}$ Horizontal pipe	Use Fig. 5 and Eq. (9) and (10) Horizontal pipe	$\phi = \dfrac{27{,}315\,X^{0.855}}{(W_l/A)^{0.17}}$	$\phi = aX^b$ $a = 4.8 - 0.3125\,d$ $b = 0.343 - 0.021\,d$ d = I.D. of pipe, in For pipe 12-in and over, use d = 10.

Courtesy: Mr. Ovid Baker and The Oil and Gas Journal.

FIG. 1. Baker parameters determine the type of two-phase flow and the appropriate two-phase-flow correlation sets unit loss.

and B_y. From data supplied or usually available to the piping designer, the Baker parameters can be expressed as:

$$B_y = 2.16 W_v / A\sqrt{\rho_l \rho_v} \tag{1}$$

B_y depends on the vapor-phase flow rate, vapor and liquid densities, and pipe size. The practical significance of pipe size is that by changing pipe diameters, the type of flow might also be changed, which in turn changes friction losses in the pipe.

$$B_x = 531\left(\frac{W_i}{W_v}\right)\left(\frac{\sqrt{\rho_l \rho_v}}{\rho_l^{2/3}}\right)\left(\frac{\mu_l^{1/3}}{\sigma_l}\right) \tag{2}$$

In Eq. (2), we can substitute the ratio of percent liquid to percent vapor for W_l/W_v, and

$$\sqrt{\rho_l \rho_v}/\rho_l^{2/3} = (\rho_v)^{0.5}/(\rho_l)^{0.166}$$

B_x depends on the weight–flow ratio and the physical properties of the liquid and vapor phases. Once calculated, B_x does not change with alternative pipe diameters. The position of the B_x line in Fig. 1 changes only if the liquid–vapor proportion changes and, to a much lesser extent, if the physical properties of the concurrently flowing liquid and vapor change. This can occur in long pipelines where relatively high friction losses reduce the pressure. Consequently, the vapor content of the mixture increases with a corresponding decrease in vapor density. The B_x line will shift somewhat to the left.

In Eq. (2), σ_l is the liquid-phase surface tension [7, 8]. For the surface tension of water at various temperatures, see the chart by Yaws and Setty [9]. For the surface tension of paraffinic hydrocarbons and mixtures, consult the *Engineering Data Book* [10].

The intersection of B_x and B_y in Fig. 1 determines the flow region for the calculated liquid–vapor ratio and the physical properties of the liquid and vapor. With increasing vapor content, the point of intersection moves up and to the left.

Unit Losses for Two-Phase Flow

The calculations of unit losses for vapor–liquid mixtures are based on the method of Lockhart and Martinelli [5]. Only the essential relationships are repeated here. We will use these with the customary data for practical piping design. The general equation is:

$$\Delta p_{100\text{(two-phase)}} = \Delta p_{100\text{(vapor)}} \phi^2 \tag{3}$$

We calculate the pressure drop of the vapor phase by assuming that only vapor flows in the pipeline. We then correct the calculated vapor-phase unit loss with the correlations shown in Fig. 1. Most of these correlations result from experiments with large-scale, horizontal industrial piping [4].

The forms of the correlations (in Fig. 1) are identical:

$$\phi = aX^b \tag{4}$$

where a includes the vapor-phase flow rate and the pipe's cross-section, and b is a constant (in annular flow, only pipe diameters appear as variants in a and b), and X is the Lockhart-Martinelli, two-phase-flow modulus:

$$X^2 = \Delta p_{100(\text{liquid})}/\Delta p_{100(\text{vapor})} \tag{5}$$

In Eq. (5), $\Delta p_{100(\text{liquid})}$ is calculated by assuming only liquid flows in the pipe, and $\Delta p_{100(\text{vapor})}$ by assuming only vapor flows in the same size pipe. The modulus, X^2, remains constant for one set of flow conditions and is independent of pipe size within two to three sequential diameters.

After inserting Darcy's equation in the numerator and denominator of Eq. (5) and simplifying, the two-phase-flow modulus becomes:

$$X^2 = (W_l/W_v)^2(\rho_v/\rho_l)(f_l/f_v) \tag{6}$$

where f_l is the liquid-phase and f_v the vapor-phase friction factor. The modulus can be obtained directly by calculating the liquid-phase and vapor-phase Reynolds numbers and using Fig. 2. (Alternatively, friction factors can be determined from Figs. 5 and 6, *Chem. Eng.*, p. 65 (December 23, 1974).)

Reynolds numbers are calculated separately for the vapor and liquid phases by using the same pipe diameter, corresponding flow rates, and viscosities from:

$$N_{\text{Re}} = 6.31\, W/d\mu$$

A convenient form of Darcy's equation for unit pressure-loss calculations in pipelines for liquid or vapor is restated here:

$$\Delta p_{100} = 0.000336(fW^2)/d^5\rho \tag{7}$$

In Eq. (7), we use the same diameter for the liquid-phase and vapor-phase calculations, and the corresponding phase flow rate, density, and friction factor. Also, in Eq. (7), we must use the Moody friction factors from Fig. 2.

A generalized form suggested by Blazius for the Lockhart-Martinelli relation expresses the friction factors for turbulent flow as:

$$f_l = 0.046/(N_{\text{Re}})_l^{0.2}$$

$$f_v = 0.046/(N_{\text{Re}})_v^{0.2}$$