FLOW RESISTANCE: A DESIGN GUIDE FOR ENGINEERS

Erwin Fried

I. E. Idelchik

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Erwin Fried
General Electric Company

I. E. Idelchik
Industrial Research Institute, Moscow

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PREFACE

This book provides practical, applications-oriented data necessary for the design and evaluation of internal fluid system pressure losses. It was prepared for the practicing engineer, consultant, or designer who understands engineering and fluid flow fundamentals, but who needs an easy-to-use compilation of flow resistance coefficients in graphical or tabular form without the distraction of voluminous theory and text. It is based almost exclusively on material presented in the recently published *Handbook of Hydraulic Resistance*, Second Edition, by I. E. Idelchik, a translation from the Russian, which contains the most extensive compilation of pressure loss coefficients currently available in one volume.

The material in this book has been arranged in a convenient guidebook format so that it can be applied easily. The extensive coverage becomes self-evident when one reviews the hundreds of illustrations of flow passages and flow configurations. Most of these are sufficiently basic as to allow application to any shape of flow passage encountered in engineering practice. Each of the illustrations and flow coefficient graphs shows its limits of applicability. Source references are also shown, to allow for further data verification, if desired.

In any compilation of empirical data, the accuracy decreases with increasing complexity of the component, due to analysis of experimental uncertainties. This book is no exception. Thus, a good rule to follow is to check more than one source, if possible.

Since this guidebook is based on a Russian sourcebook, the symbols and nomenclature differ somewhat from U.S. practice. This, however, should provide no impediment to using the material, because the pictorial representations are quite clear and easy to follow. The nondimensionality of the pressure loss coefficients and the governing parameters allow their use in any suitable system of units.

Any work of this nature is subject to editorial or translation errors as well as data reporting errors. The publisher and I would be most grateful to the readers and users of this book for information on such items.

I would like to express my gratitude to Professor I. E. Idelchik, who passed away in 1987 after spending a lifetime in the theoretical and experimental investigation of fluid mechanics. For myself and many of my colleagues in the engineering profession, his name is synonymous with the concept of hydraulic resistance.

Erwin Fried

NOMENCLATURE

Symbol	Name of quantity	Abridged notation in SI units
a	speed of sound	m/s
a	critical speed of sound	m/s
a, b	sides of a rectangle	m
c_p and c_v	specific heats of gases at constant pressure and constant volume, respectively	J/kg °C
c_x	coefficient of drag	–
D, d	cross-section diameters	m
$D_h = 4F/\Pi$; $d_h = 4f/\Pi$	hydraulic or equivalent diameter (4 X hydraulic radius)	m
F, f	cross-sectional areas	m^2
$f = F_{or}/F_{gr}$	area ratio of a grid, orifice, perforated plate, etc.	–
G	mass flow rate of liquid (gas)	kg/s
g	gravitational acceleration	m/s^2
h	height	m
$k = c_p/c_v$	specific heat ratio	–
l	length of flow segment, depth of channel, or thickness of orifice	m
$\mathrm{M} = w/a$	Mach number	–
$M = 1/F \int_F (w/w_0)^2 \, dF$	coefficient of momentum (Boussinesq coefficient)	–
m	wetting intensity	m^3/m^3
m	exponent	–
$N = 1/F \int_F (w/w_0)^3 \, dF$	coefficient of kinetic energy	–
N	power	–
n	area ratio (degree of enlargement or reduction of cross section); polytropic exponent; number of elements	–
p	static pressure	Pa
p_0	total pressure or flow stagnation pressure	Pa

Symbol	Name of quantity	Abridged notation in SI units
p_{ex}	excess pressure	Pa
Δp	overall pressure difference	Pa
P_{dr}	drag force	N
Q	volumetric flow rate	m^3/s
R	gas constant	J/kg K
R_h	hydraulic radius ($\frac{1}{4}D_h$)	m
R	radii of cross sections of a circular pipe or curved pipe length	
$\mathrm{Re} = wD_h/\nu$	Reynolds number	–
S, s	spacing (distance between rods in a bundle of pipes, between grid holes, etc.) length of a free jet	m
S_0	surface area	m^2
S_m	frontal area of a body in a flow	m^2
$T(t)$	thermodynamic temperature	K (°C)
T_0	thermodynamic flow stagnation temperature (total temperature)	K
U	internal energy	J/kg
v	specific volume; side discharge (inflow) velocity	m^2/kg; m/s
w	stream velocity	m/s
w'	longitudinally fluctuating stream velocity	m/s
z	dust content	g/m^2
z	dust capacity	kg/m^2
α	central angle of divergence or convergence; angle of a wye or tee branching; angle of stream incidence	degrees
δ	angle of turning (of a branch, elbow); angle of valve opening	
δ	thickness of a wall, boundary layer, or wall layer; height of joint	m
Δ	equivalent uniform roughness of walls	m
Δ_0	mean height of wall roughness protuberances	m
$\bar{\Delta}_0 = \Delta_0/D_h$; $\bar{\Delta} = \Delta/D_h$	relative roughness of walls	–
$\epsilon = F_{con}/F_0$	coefficient of jet contraction	–
ϵ'	porosity (void fraction)	–
$\epsilon_T = \sqrt{\overline{w'^2}}/w_0$	degree of turbulence	–
$\zeta = \Delta p/(\rho w^2/2) = K$	coefficient of fluid resistance (pressure loss coefficient), K in the US literature	–
ζ_{loc}, K_{loc}	coefficient of local fluid resistance	–
ζ_{fr}, K_{fr}	coefficient of friction resistance of the segment of length l	–
η (μ in US literature)	dynamic viscosity	Pa s
$\eta_{\text{п}}$	cleaning coefficient	–

Symbol	Name of quantity	Abridged notation in SI units
$\lambda = \zeta_{fr}/(l/D_h)$	friction coefficient [friction resistance of the segment of relative unit length (l/D_h = 1]; i.e., friction factor	--
$\lambda = f$ in US literature	friction factor	—
$\lambda = w/a.$	relative (reduced) stream velocity	—
μ	discharge coefficient: mass concentration of suspended particles in flow	—
ν	kinematic viscosity	m^2/s
ρ	density of liquid (gas)	kg/m^2
Π	cross-sectional (wetted) perimeter	m
ϕ	velocity coefficient	—

SUBSCRIPTS

Subscripts listed for the quantities F, f, D, d, Π, a, b, w, ρ, Q, and p refer to the following cross sections or pipe segments:

0	governing cross section or minimum area
1	larger cross section in the case of expansion or contraction of the flow segment
2	larger cross section after equalization of the stream velocity
k	intermediate cross section of curved channel (elbow, branch) or the working chamber of the apparatus
con	contracted jet section at the discharge from an orifice (nozzle)
or	orifice or a single hole in the perforated plate or screen
gr	front of the perforated plate, screen, orifice
br, st, ch	side branch, straight passage, and common channel of a wye or tee, respectively
out	outlet
∞	velocity at infinity

Subscripts 0, 1, 2, k, and g at l refer, respectively, to the straight inlet, straight outlet, intermediate (for a curved channel), and diffuser pipe lengths, l.

Subscripts at Δp and ζ refer to the following forms of the fluid resistances:

l	local
fr	friction
ov	overall
tot	total resistance of an impedance in the network
out	total resistance of a diffuser or a branch at the outlet from the network
int	internal resistance of a diffuser
exp	resistance to flow expansion in a diffuser
sh	shock resistance at sudden enlargement of the cross section
b and st	resistance of a branch and straight passage of a wye or tee (for the resistance coefficients reduced to the velocity in respective branch pipes)
r.b., r.st.	resistance coefficients of the side branch and of the straight passage of a wye or tee reduced to the velocity in a common channel of a wye or tee

USEFUL CONVERSIONS OF UNITS

Physical quantity	Given in ⟶ / Gives ⟵	Multiplied by ⟶ / Divided by ⟵	Gives / Given in	Approximate or useful relationship
Length	ft	0.3048	m	$3\frac{1}{4}$ ft ≃ 1 m
	in	25.4 (exact)	mm	1 in ≃ 25 mm
	mil	0.0254	mm	
	yard	0.9144	m	
	mile (mi)	1 609.3	m	1 mi ≃ 1.6 km
	km	0.621388	mi	
Area	ft^2	0.092903	m^2	100 ft^2 ≃ 9 m^2
	in^2	645.16	mm^2	1 in^2 ≃ 650 mm^2
	acre	4 047.0	m^2	
Volume	ft^3	0.028317	m^3	35 ft^3 ≃ 1 m^3
	U.S. gal	0.003785	m^3	260 gal ≃ 1 m^3
	U.S. gal	3.785	liter (L)	1 gal ≃ $3\frac{3}{4}$ L
	L (liter)	0.2642	U.S. gal	1 L ≃ 0.26 gal
	Brit. gal	0.004546	m^3	
	U.S. gal	0.13368	ft^3	
	barrel (U.S. pet.)	0.15898	m^3	
	barrel (U.S. pet.)	42	U.S. gal	
Velocity	ft/s	0.3048	m/s	10 ft/s ≃ 3 m/s
	m/s	3.2808	ft/s	
	ft/min	0.00508	m/s	100 ft/min ≃ 0.5 m/s
	mi/h	1.6093	km/h	30 mi/h ≃ 48 km/h
	km/h	0.6214	mi/h	50 km/h ≃ 31 mi/h
	knots	1.852	km/h	
Mass	lb_m	0.45359	kg	1 lb_m ≃ .45 kg
	kg	2.2046	lb_m	1 kg ≃ 2.2 lb_m
	metric ton	2 204.6	lb_m	metric ton = 10^3 kg
	ton (2 000 lb_m)	907.18	kg	
Force	lb_f	4.44822	N = kg m/s^2	
	lb_f	0.45359	kg_f	1 N ≈ 0.1 kg_f
	kg_f	2.2046	lb_f	≈ 0.22 lb_f
	kg_f	9.80665	N	
	dyne	0.00001 (exact)	N	
Amount of substance	lb_m-mol	453.6	kmol	
	g-mol	1.000	mol	
	kg-mol	1.000	kmol	
	mol	1 000	kmol	
Mass flow rate	lb_m/h	0.0001260	kg/s	10^3 lb/h ≃ .13 kg/s
	kg/s	7 936.51	lb_m/h	
	lb_m/s	0.4536	kg/s	
	lb_m/min	0.00756	kg/s	

Reprinted from International System of Units (SI), J. Taborek, in *Heat Exchanger Design Handbook*, pp. xxvii–xxix, Hemisphere, Washington, D.C., 1984.

Physical quantity	Given in ⟶ / Gives ⟵	Multiplied by ⟶ / Divided by ⟵	Gives / Given in	Approximate or useful relationship
Volume flow rate	U.S. gal/min	6.309 x 10^{-5}	m^3/s	
	U.S. bbl/day	0.15899	m^3/day	
	U.S. bbl/day	1.84 x 10^{-6}	m^3/s	
	ft^3/s	0.02832	m^3/s	
	ft^3/min	0.000472	m^3/s	
Mass velocity (mass flux)	lb_m/h ft^2	1.356 x 10^{-3}	kg/s m^2	
	kg/s m^2	737.5	lb_m/h ft^2	
Energy (work) (heat)	Btu[b]	1 055.056	J = N m = W s	1 Btu ≃ 1 000 J
	Btu	0.2520	kcal	1 kcal ≃ 4 Btu
	Btu	778.28	ft lb_f	
	kcal	4 186.8	J	1 kcal ≃ 4 000 J
	ft lb_f	1.3558	J	
	W h	3 600	J	
Power	Btu/h	0.2931	W = J/s	10^6 Btu/h ≃ 300 kW
	W	3.4118	Btu/h	
	kcal/h	1.163	W	
	ft lb_f/s	1.3558	W	1 000 kW ≃ 3.5 x 10^6 Btu/h
	hp (metric)	735.5	W	
	Btu/h	0.2520	kcal/h	
	tons refrig.	3 516.9	W	
Heat flux	Btu/h ft^2	3.1546	W/m^2	1 000 Btu/h ft^2 ≃ 3.2 kW/m^2
	W/m^2	0.317	Btu/h ft^2	
	kcal/cm^2 s	41.868	W/m^2	
Heat transfer coefficient	Btu/h ft^2 °F	5.6784	W/m^2 K	1 000 Btu/h ft^2 °F ≃ 5 600 W/m^2 K
	W/m^2 K	0.1761	Btu/h ft^2 °F	
	kcal/cm^2 s °C	41.868	W/m^2 K	
Heat transfer resistance	(Btu/h ft^2 °F)$^{-1}$	0.1761	(W/m^2 K)$^{-1}$	0.001 (Btu/h ft^2 °F)$^{-1}$ ≃ 0.000 18 (W/m^2 K)$^{-1}$
	(W/m^2 K)$^{-1}$	5.6784	(Btu/h ft^2 °F)$^{-1}$	
Pressure	lb_f/in^2 (psi)	6.8948	kN/m^2 = kPa	1 psi ≃ 7 kPa
	kPa	0.1450	psi	14.5 psi ≃ 100 kPa
	bar	100	kPa	
	lb_f/ft^2	0.0479	kPa	
	mm Hg (torr)	0.1333	kPa	1 000 kPa = 1 MPa ≃ 150 psi
	in Hg	3.3866	kPa	
	mm H_2O	9.8067	Pa	
	in H_2O	249.09	Pa	1 in H_2O ≃ .25 kPa
	at (kg_f/cm^2)	98.0665	kPa	
	atm (normal)	101.325	kPa	atm = 760 mmHg
Mass flux	lb_m/ft^2 s	4.8824	kg/m^2 s	
	lb_m/ft^2 h	0.001356	kg/m^2 s	

Physical and Transport Properties

Physical quantity	Given in ⟶ / Gives ⟵	Multiplied by ⟶ / Divided by ⟵	Gives / Given in	Approximate or useful relationship
Thermal conductivity	Btu/ft h °F	1.7308	W/m K	steel ≃ 50 W/m K
	W/m K	0.5778	Btu/ft h °F	water (20°C) ≈ 0.6 W/m K
	kcal/m h °C	1.163	W/m K	air (STP) ≃ 24 mW/m K
Density	lb_m/ft^3	16.0185	kg/m^3	
	kg/m^3	0.06243	lb_m/ft^3	62.4 lb_m/ft^3 ≃ 1 000 kg/m^3
	lb_m/U.S. gal	119.7	kg/m^3	
Specific heat capacity	Btu/lb_m °F	4 186.8	J/kg K	1 Btu/lb_m °F ≃ 4.2 kJ/kg K
	kcal/kg °C	4 186.8	J/kg K	
Enthalpy	Btu/lb_m	2 326	J/kg	
	kcal/kg_m	4 186.8	J/kg	
Dynamic (absolute) viscosity	centipoise (cP)	0.001	kg/m s	kg/m s = N s/m^2 = Pa s
	poise (P)	0.1	Pa s	
	cP	1.000	mPa s	
	cP	1 000	μPa s	water (100°C), 0.31 cP
	lb_m/ft h	0.0004134	Pa s	
	lb_m/ft h	0.4134	cP	
	cP	2.4189	lb_m/ft h	air (100°C), 0.021 cP
	lb_m/ft s	1.4482	Pa s	

Physical quantity	Given in ⟶ / Gives ⟵	Multiplied by ⟶ / Divided by ⟵	Gives / Given in	Approximate or useful relationship
Kinematic viscosity	stoke (St), cm²/s	0.0001	m²/s	
	centistoke (cSt)	10^{-6}	m²/s	
	ft²/s	0.092903	m²/s	
Diffusivity	ft²/s	0.092903	m²/s	
Thermal diffusivity	m²/h	0.0002778	m²/s	
	ft²/s	0.092903	m²/s	
	ft²/h	25.81×10^{-6}	m²/s	
Surface tension	dyne/cm	0.001	N/m	
	dyne/cm	6.852×10^{-5}	lb_f/ft	
	lb_f/ft	14.954	N/m	
Temperature relations:	$°C = \frac{5}{9}[°F - 32]$	$°C = (°F + 40)\frac{5}{9} - 40$	$\Delta T(°C) = \frac{5}{9}\Delta T(°F)$	$K = °C + 273.15$
	$°F = \frac{9}{5}(°C) + 32$	$°F = (°C + 40)\frac{9}{5} - 40$	$\Delta T(°F) = \frac{9}{5}\Delta T(°C)$	$R = °F + 459.67$
Miscellaneous:	Acceleration of gravity (standard):	$g = 9.806\,65$ m/s²		
	Gas constant:	$R = 8\,314.3$ m N/K kmol		
	Stefan-Boltzmann constant:	$5.669\,7 \times 10^{-8}$ W/m² K⁴		
		1.714×10^{-9} Btu/ft² h R⁴		

[a] Even though the abbreviations s and h were introduced only with the SI, they are used here throughout for consistency.
[b] Note: the caloric and Btu are based on the International Standard Table values. The thermochemical calorie equals 4.184 J (exact) and is used in some older texts.

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CHAPTER

ONE

GENERAL INFORMATION

1-1 GENERAL GUIDELINES

This design guide is intended to enable the practicing engineer to analyze and evaluate the flow resistance or pressure loss coefficient for most flow passage types, devices, and components. In keeping with the assumption that the user of this design guide has some understanding of engineering fundamentals, only that material necessary to use the charts and graphs presented herein will be provided. Should the user want to delve into the subject in greater depth, the source book for this design guide, *Handbook of Hydraulic Resistance* by I. E. Idelchik, published by Hemisphere Publishing Corporation, 1986, should be consulted. This source book will be cited throughout this text as "Idelchik." All references cited in Idelchik are shown herein, to allow the user access to the original sources of the data. For basic fluid mechanics information the user is referred to any convenient or familiar fluid mechanics text. For completeness and convenience, a list of recent fluid mechanics texts is included in the bibliography of this chapter.

Following are some general guidelines to get the most usefulness from this book.

1. All sketches, diagrams, and graphs are self-explanatory, with flow direction, areas, and other features indicated.
2. Particular attention should be paid to the limits of applicability shown on each of the tables and graphs. These are usually expressed in terms of Reynolds number or in terms of geometric parameters.
3. It is assumed that the inlet and exit conditions are ideal, i.e., there are no flow profile distortions, unless otherwise indicated. There exists only a very limited amount of data on the effect of the inlet flow distortion or inlet swirl for most flow devices. Since each

application involving distorted flow is unique, it is recommended that experimental methods be considered when such conditions exist and pressure loss is of importance.

4. Unless otherwise indicated, the data shown herein apply to Newtonian fluids considered homogeneous, incompressible, and involving neither work nor energy addition. The pipe or duct walls are considered rigid.
5. For graphs dealing with components involving a change in area, particular attention should be paid to the graph, whether the value of the pressure loss coefficient is based on the inlet, minimum, or exit area.
6. The nondimensionality of the parameters of most of the graphs allows their use in any convenient system of units.
7. The basic reference data given in this book are the static pressure loss coefficients, or K-factor as used in the US literature. This term can be considered the overall static pressure loss coefficient for the component of interest. It includes the nonrecoverable losses within the component as well as the frictional and the recoverable losses. The frictional losses are usually considered negligible when compared to the nonrecoverable losses and generally are neglected unless stated otherwise in the graphs.
8. If one considers how the pressure loss coefficient ζ is evaluated experimentally, this becomes evident. It is the measured static pressure drop Δp, divided by the dynamic or velocity head, ρw_2^2, for the component. Thus,

$$\zeta = \frac{\Delta p}{\rho w^2/2}$$

9. The basic pressure loss equation to be used with the data given in this book is

$$\Delta p = \zeta \frac{\rho w^2}{2}, \text{ in consistent units}$$

10. The overall static pressure drop is considered a positive quantity if the sign convention used in this book is followed. Therefore, a static pressure rise, such as in a diffuser, will show up as negative quantity.
11. The effect of Reynolds number on the pressure loss coefficient is most pronounced at low values ($Re < 10^5$). At higher values of Re it can be assumed as independent of Re, unless otherwise stated.
12. When there is no indication of the Reynolds number at which the value of ζ was obtained, it may be assumed that the given value of ζ is virtually independent of Re. However, in the case of purely laminar flow ($Re < 2 \cdot 10^3$), the value of ζ is only an approximation.
13. For the determination of Reynolds numbers in noncircular ducts, an equivalent or hydraulic diameter must be used. It is defined as four times the cross-sectional flow area divided by the wetted perimeter Π, with both measured in a direction perpendicular to the flow. If as usual, the fluid fills the entire cross-section of the duct, this definition is equivalent to the relation

$$D_h = \frac{4F}{\Pi}$$

14. For a few simple configurations we have the following hydraulic diameter D_h,

Circle of Diameter D	D
Square with side a	a
Rectangle with sides a, b	$2ab/(a + b)$
Parallel plates separated a distance a	$2a$
Annular duct of cylinders, D_1, D_2	$D_1 - D_2$

15. Property data, such as viscosity, density, etc., can be obtained from any consistent source available to the user. It is purposely omitted here to keep the size of this book to a minimum.
16. For gases and steam, the variation of density is sometimes very important. If the calculation shows that the resulting pressure drop is such as to change the density, then the piping system can be subdivided and the calculation can be done on a section-by-section basis. In that method, the exit conditions of one section become the inlet conditions of the next section. For condensing steam the density can change quite rapidly and the segmentation method becomes important. It should be noted that the segmentation method is only an approximation, but with judicious selection of segments it can provide acceptable engineering results.
17. Most values of the pressure loss coefficient shown in this book are valid for Mach numbers of less than 0.3 unless otherwise stated.
18. The value of the overall pressure losses in a piping network can be evaluated by use of electrical resistance network methods or by use of one of the several computer programs currently available. This book will provide the necessary pressure loss coefficients ζ, or K-factors.
19. In a piping or ducting network, the pressure losses in each segment can be calculated as if the others did not exist and the pressure losses added. However, if the components are close to one another, the exit conditions of one may affect the entry conditions of the following component. Engineering judgement must be applied in such a case.
20. When a system is analyzed for pressure losses, it is often convenient to use the entry or similar dimension as the reference dimension, because the loss coefficient ζ depends on the velocity, which is a function of the cross section.

    In general, with variable density along the flow, the resistance coefficient ζ, based on the velocity in any given section (area F_1), is calculated for another section (area F_2) using the relation

$$\zeta_1 = \zeta_2 \left(\frac{F_1}{F_2}\right)^2 \left(\frac{\rho_1}{\rho_2}\right)$$

For the case of no change in density, the usual case, this is simplified and becomes a most useful relation, which can be used to normalize any system.

$$\zeta_1 = \zeta_2 \left(\frac{F_1}{F_2}\right)^2$$

21. A few comments need to be made about the calculation of friction losses in a system. When the straight runs of pipe are significant in relation to the flow obstructions or components, then it is advisable to calculate the friction losses for these *straight runs* and add them to the other section losses. The friction loss, ζ_{fr} or K_{fr}, can be treated like another loss coefficient, ζ or K-factor, by use of the following relation.

$$\Delta p = (\Sigma \zeta_{fr} + \Sigma \zeta_i) \frac{\rho w^2}{2}$$

In American practice this becomes

$$\Delta p = (\Sigma K_{fr} + \Sigma K_i) \frac{\rho w^2}{2}$$

where $K_{fr} = \zeta_{fr} = f(1/D)$ is the friction loss coefficient, and $K_i = \zeta_i$ is the static pressure loss coefficient from this book.

22. When friction factors are required for solution of an overall system, the graphs and tables allow the use of any friction factor sources familiar to the user, such as Moody or Fanning charts. It should be noted that the value of the Moody friction factor is 4 times that of the Fanning friction factor. This is due to the way the hydraulic diameter is defined. A convenient way to tell which of these two friction factors is given is by inspection of the laminar friction factor. If f is $^{16}/_{Re}$, then it is Fanning. If it is $^{64}/_{Re}$, it is Moody.

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