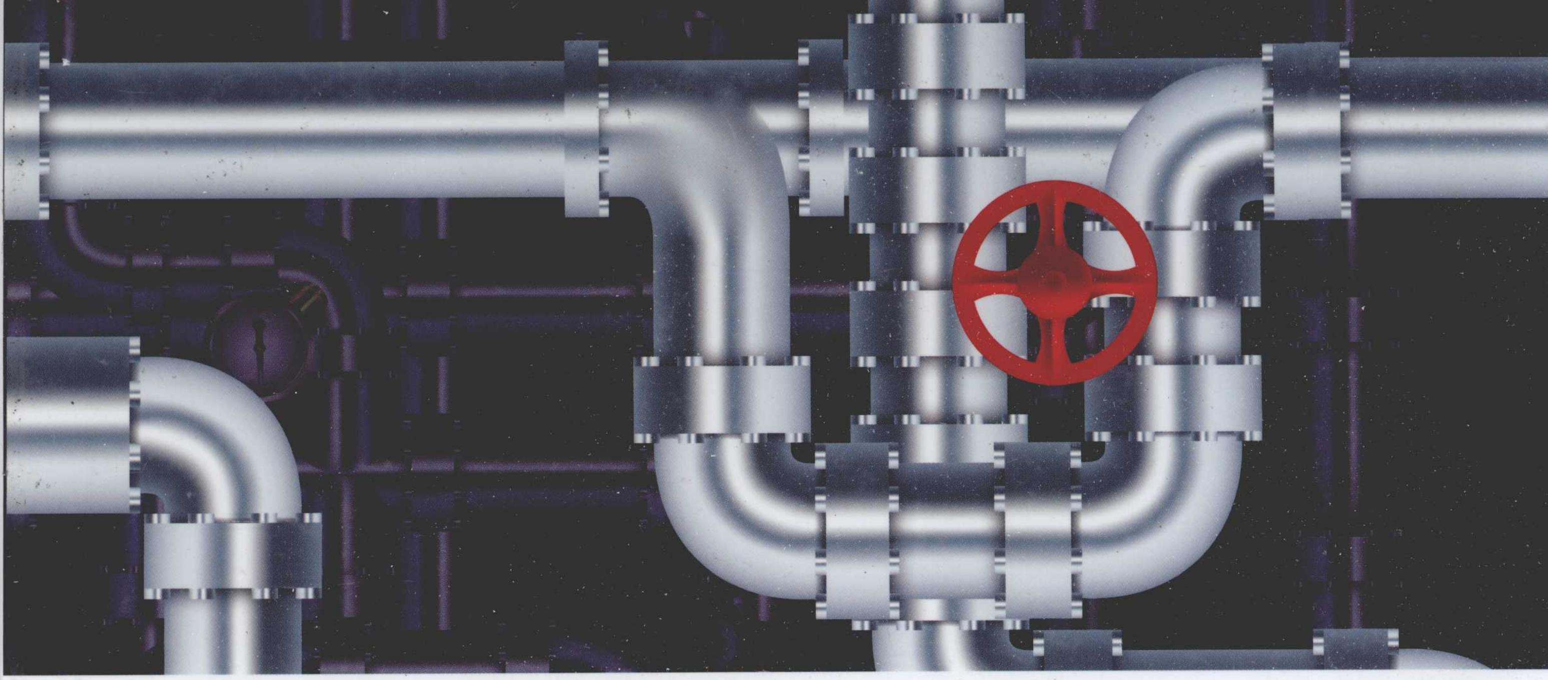
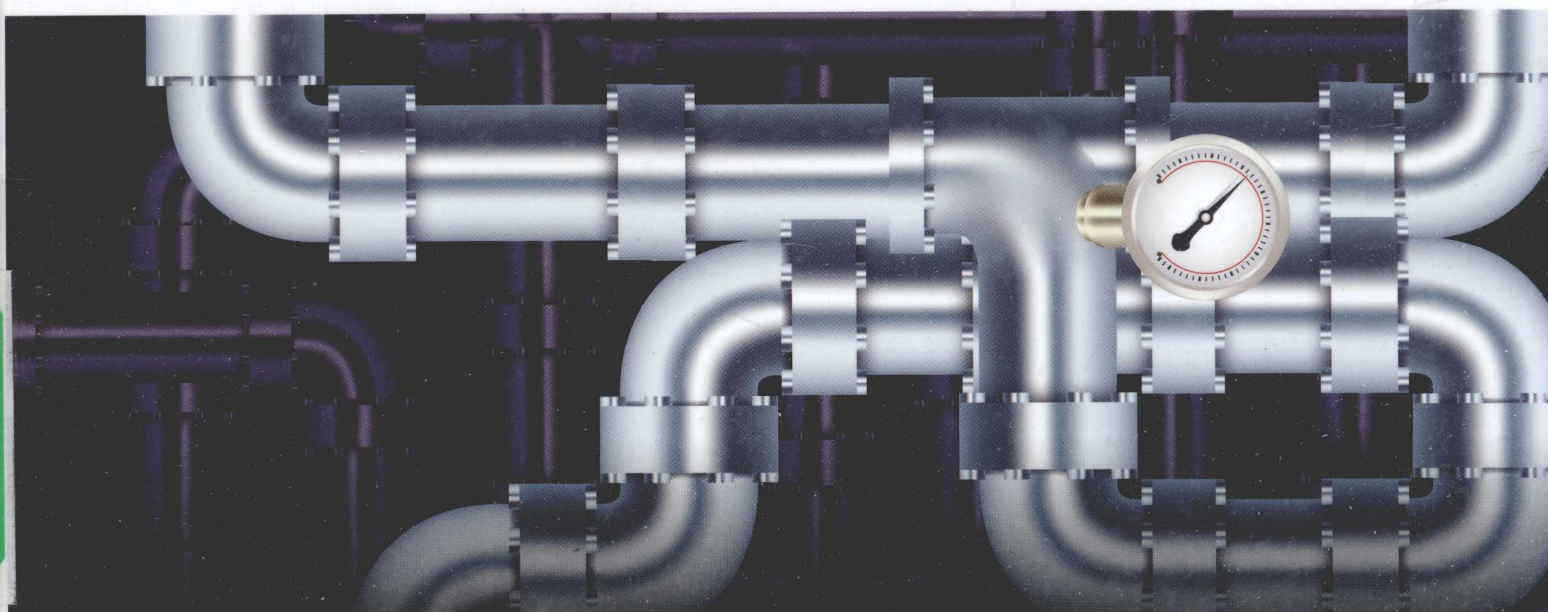


PIPE FLOW

A Practical and Comprehensive Guide

Donald C. Rennels — Hobart M. Hudson



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A Practical and Comprehensive Guide

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PIPE FLOW

Knowledge shared is everything.

Knowledge kept is nothing.

—Richard Beere,
Abbot of Glastonbury
(1493–1524)

PREFACE

This book provides practical and comprehensive information on the subject of pressure drop and other phenomena in fluid flow in pipes. The importance of piping systems in distribution systems, in industrial operations, and in modern power plants justifies a book devoted exclusively to this subject. The emphasis is on flow in piping components and piping systems where greatest benefit will derive from accurate prediction of pressure loss.

A great deal of experimental and theoretical research on fluid flow in pipes and their components has been reported over the years. However, the basic methodology in fluid flow textbooks is usually fragmented, scattered throughout several chapters and paragraphs; and useful, practical information is difficult to sort out. Moreover, textbooks present very little loss coefficient data, and those that are given are desperately out of date. Elsewhere, experimental data and published formulas for loss coefficients have provided results that are in considerable disagreement. Into the bargain, researchers have not accounted for all possible flow configurations and their results are not always presented in a readily useful form. This book addresses and fixes these deficiencies.

Instead of having to search and read through various sources, this book provides the user with virtually all the information required to design and analyze piping systems. Example problems, their setups, and solutions are provided throughout the book. Most parts of the book will be easily understood by those who are not experts in the field.

Part I (Chapters 1 through 7) contains the essential methodology required to solve accurately pipe flow problems. Chapter 1 provides knowledge of the physical properties of fluids and the nature of fluid flow. Chapter 2 presents the basic principles of conservation of mass, momentum, and energy, and introduces the concepts of head loss and energy grade line. Chapter 3 presents the conventional head loss equation and characterizes the two sources of head loss—surface friction and induced turbulence. Several compressible flow calculation methods are presented in Chapter 4. The straightforward setup of series, parallel, and branching flow networks, including sample problems, is presented in Chapter 5. Chapter 6 introduces the basic methodology for solving transient flow problems, with specific examples. A method to assess the uncertainty associated with pipe flow calculations is presented in Chapter 7.

Part II (Chapters 8 through 19) presents consistent and reliable loss coefficient data on flow configurations most common to piping systems. Experimental test data and published formulas from worldwide sources are examined, integrated, and arranged into widely applicable equations—a valuable resource in this computer age. The results are also presented in straightforward tables and diagrams. The processes used to select and develop loss coefficient data for the various flow configurations are presented so the user can judge the merits of the results and the researcher can identify areas where further research is needed.

Friction factor, the main element of surface friction loss, is presented in Chapter 8 as an adjunct to quantifying the various features that contribute to head loss.

The flow configurations presented in Chapters 9 through 14 (entrances, contractions, expansions, exits, orifices, and flow meters) all exhibit some degree of flow contraction and/or expansion. As such, they have been treated as a family; where sufficient data for any one particular configuration were lacking, they were augmented by sufficient data in another.

Elbows, pipe bends, coils, and miter bends are presented in Chapter 15. The intricacies of converging and diverging flow through pipe junctions (tees) are presented in Chapter 16. Pipe joints are covered in Chapter 17, and valve information is offered in Chapter 18. The internal geometry of threaded (screwed) pipe fittings is discontinuous, creating additional pressure loss; and they are covered separately in Chapter 19.

Part III (Chapters 20 through 23) examines flow phenomena that can affect the performance of piping systems. Cavitation, when local pressure falls below the vapor pressure of a liquid, is studied in Chapter 20. Chapter 21 provides a brief depiction of flow-induced vibration in piping systems; water hammer and column separation are investigated. Situations where temperature rise in a flowing liquid may be of interest are presented in Chapter 22. Flow behavior in horizontal openings at low flow rates is evaluated in Chapter 23.

The book's nomenclature was selected so that it would be familiar to engineers worldwide. The book employs two systems of units: the English gravitational system (often called the U.S. Customary System or USCS) and the International System (or SI for Système International). Conversions between and within the two systems are provided in the appendix.

This book represents industrial experience gained working together at Aerojet General Corporation, Liquid Rocket Engine Test Division, and later, working separately at General Electric Company, Nuclear Energy Division, and at Westinghouse Electric Corporation, Oceanic Division. We are indebted to the many engineering colleagues who helped shape our experience in the field of fluid flow. We especially appreciate Dr. Phillip G. Ellison's helpful comments and suggestions.

We acknowledge the understanding and support of our wives, Bel and Joan.

Donald C. Rennels
Hobart M. Hudson

NOMENCLATURE

Symbol	Definition	Units: English	Units: International System (SI)
	Roman Symbols		
A	Area	ft^2	m^2
a	Acceleration	ft/s^2	m/s^2
a	Acoustic velocity	ft/s	m/s
B	Bulk modulus	lb/in^2	N/m^2
C	Coefficient	Dimensionless	
c_p	Specific heat at constant pressure	Btu/lb-°F	J/kg-°C (N-m/kg-°C)
c_v	Specific heat at constant volume	Btu/lb-°F	J/kg-°C (N-m/kg-°C)
D	Diameter	ft	m
d	Diameter	in	mm
E	Modulus of elasticity	lb/in^2	N/m^2
E	Mechanical energy (per unit time, i.e., power)	ft-lb/s	N-m/s
e	Absolute roughness	in	mm
F	Factor	Dimensionless	
F	Force	lb	N ($kg\text{-}m/s^2$)
f	Friction factor (Darcy)	Dimensionless	
G	Mass flow rate per unit area	$lb/s\text{-}ft^2$	$kg/s\text{-}m^2$
g	Acceleration of gravity	ft/s^2	m/s^2
H	Head	ft	m
h	Enthalpy	Btu/lb	J/kg (N-m/kg)
J	Mechanical equivalent of heat	ft-lb/Btu	N-m/J (=1)
K	Loss coefficient (i.e., total pressure loss coefficient)	Dimensionless	
L	Length	ft	m
l	Length	in	mm
ln	Natural logarithm	Dimensionless	
log	Base-10 logarithm	Dimensionless	
M	Mach number	Dimensionless	
m	Mass[a]	slug ($lb_f\text{-}s^2/ft$)	kg

(*Continued*)

Symbol	Definition	Units: English	Units: International System (SI)
m	Molecular weight	lb/mol_{lb}	kg/mol_{kg}
$\dot{m}$	Mass flow rate[a]	slug/s (lb_f-s/ft)	kg/s
m	Moisture content	Dimensionless	
N_{Fr}	Froude number	Dimensionless	
N_{Re}	Reynolds number	Dimensionless	
n	Number of mols	Dimensionless	
n	Ellipse major/minor axis ratio	Dimensionless	
P	Pressure	lb/ft^2	N/m^2 (pascal)
p	Pressure	lb/in^2	N/cm^2
p	Pitch	in	mm
Q	Volumetric flow rate	ft^3/s	m^3/s
Q	Heat flux	Btu/s	J/s (N-m/s)
q	Volumetric flow rate	gal/min	—
R	Individual gas constant	ft-lb/lb-°R[a]	N-m/kg-K
$\bar{R}$	Universal gas constant	ft-lb/mol-°R[a]	N-m/mol-K
R_P	Pressure ratio	Dimensionless	
R	Radius	ft	m
r	Radius	in	mm
T	Absolute temperature	°R	K
t	Common temperature	°F	°C
t	Time	s	s
t	Thickness	in	mm
U	Internal energy	Btu/lb	N-m/kg
u	Local velocity	ft/s	m/s
V	Average velocity	ft/s	m/s
V	Volume	ft^3	m^3
v	Specific volume	ft^3/lb	m^3/kg
W	Weight flow rate	lb/h	N/h
w	Weight	lb	N
$\dot{w}$	Weight flow rate	lb/s	N/s
x	Horizontal distance	ft	m
Y	Expansion factor	Dimensionless	
y	Radial location of local velocity	in	mm
y	Vertical distance	ft	m
Z	Elevation	ft	m
z	Compressibility factor	Dimensionless	
	Greek Symbols		
α	Bend angle or diffuser included angle	degrees	degrees
β	Diameter ratio	Dimensionless	
γ	Ratio of specific heats c_p/c_v	Dimensionless	
Δ	Finite difference (prefix)	Dimensionless	
ε	Absolute roughness	ft	m
θ	Momentum correction factor	Dimensionless	
λ	Jet contraction ratio	Dimensionless	
μ	Absolute (dynamic) viscosity	lb-sec/ft^2	N-sec/m^2 (Pascal-sec)
ν	Kinematic viscosity	ft^2/sec	m^2/sec
π	pi (3.14159 . . .)	Dimensionless	
ρ_m	Mass density	slug/ft^3 (lb_f-sec^2/ft^4)	kg/m^3

Symbol	Definition	Units: English	Units: International System (SI)
ρ_w	Weight density	lb_f/ft^3	N/m^3
σ	Uncertainty	%	%
ϕ	Kinetic energy correction factor	Dimensionless	
ψ	Angle	degrees	degrees
ω	Acentric factor	Dimensionless	
	Subscripts		
o	Orifice or nozzle throat	Not defined	
1	Inlet or upstream	Not defined	
2	Outlet or downstream	Not defined	
a	Atmosphere	Not defined	
b	Velocity profile function exponent	Not defined	
b	Bend	Not defined	
c	Critical state	Not defined	
r	Reduced value	Not defined	
t	Total	Not defined	
x	Component in *x*-direction	Not defined	
y	Component in *y*-direction	Not defined	
z	Component in *z*-direction	Not defined	
	Superscripts		
′	Absolute value or derivative	Not defined (e.g., f')	
–	Average of initial and final values	Not defined (e.g., $\bar{x}$)	
·	Time derivative (rate)	Not defined (e.g., $\dot{w}$)	

[a] See Section 1.1 in Chapter 1, "Fundamentals," for the treatment of these units. There are instances identified in the text where lb_m is used instead of lb_f to simplify formulas for use with the English system and SI.

ABBREVIATION AND DEFINITION

Btu	British thermal unit	min	minutes
cP	centipoise	mol	moles
ft	feet	kg	kilograms
g	grams	m	meters
h	hours	mm	millimeters
in	inches	N	newtons
J	joules	P	poise
lb	pounds	s	seconds

CONTENTS