FLOW MEASUREMENT HANDBOOK

Flow Measurement Handbook is a reference for engineers on flow measurement techniques and instruments. It strikes a balance between laboratory ideas and realities of field experience and provides practical advice on design, operation and performance of flowmeters.

It begins with a review of essentials: accuracy, flow, selection and calibration methods. Each chapter is then devoted to a flowmeter class and includes information on design, application, installation, calibration and operation.

Among the flowmeters discussed are differential pressure devices such as orifice and Venturi; volumetric flowmeters such as positive displacement, turbine, vortex, electromagnetic, magnetic resonance, ultrasonic and acoustic; multiphase flowmeters; and mass meters such as thermal and Coriolis. There are also chapters on probes, verification and remote data access.

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Flow Measurement Handbook

INDUSTRIAL DESIGNS, OPERATING PRINCIPLES, PERFORMANCE, AND APPLICATIONS

Second Edition

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To Liz

and all the family

Cambridge University Press
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Preface

This is a book about flow measurement and flowmeters written for all in the industry who specify and apply, design and manufacture, research and develop, maintain and calibrate flowmeters. It provides a source of information both on the published research, design and performance of flowmeters, and also on the claims of flowmeter manufacturers. It will be of use to engineers, particularly mechanical and process engineers, and also to instrument companies' marketing, manufacturing and management personnel as they seek to identify future products.

I have concentrated on the mechanical and fluid engineering aspects and have given only as much of the electrical engineering details as is necessary for a proper understanding of how and why the meters work. I am not an electrical engineer and so have not attempted detailed explanations of modern electrical signal processing. I am also aware of the speed with which developments in signal processing would render out of date any descriptions that I might give.

I make the assumption that the flowmeter engineer will automatically turn to the appropriate standard and I have, therefore, tried to minimise reproducing information which should be obtained from those excellent documents. I recommend that those involved in new developments should keep a watching brief on the regular conferences which carry much of the latest developments in the business, and are illustrated by the papers in the reference list.

I hope, therefore, that this book will provide a signpost to the essential information required by all involved in the development and use of flowmeters, from the field engineer to the chief executive of the entrepreneurial company which is developing its product range in this technology.

In this book, following introductory chapters on accuracy, flow, selection and calibration, I have attempted a clear explanation of each type of flowmeter so that the reader can easily understand the workings of the various meters. I have, then, attempted to bring together a significant amount of the published information which enlightens us on the performance and applications of flowmeters. The two sources for this are the open literature and the manufacturers' brochures. I have also introduced, to a varying extent, the mathematics behind the meter operations, but to avoid disrupting the text, I have consigned some of this to the appendices at the end of the chapters.

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However, by interrogating the appropriate databases for flowmeter papers it rapidly becomes apparent that inclusion of references to all published material is unrealistic. I have attempted a selection of those which appeared to be more relevant and available to the typical reader of this book. However, it is likely that, owing to the very large number of relevant papers, I have omitted some which should have been included.

Topics not covered in this book, but which might be seen as within the general field of flow measurement, are: metering pumps, flow switches, flow controllers, flow measurement of solids and granular materials, open channel flow measurement, hot wire local velocity probes or laser Doppler anemometers and subsidiary instrumentation.

In this second edition, I have left in much of the original material, as I am aware of the danger of losing sight of past developments and unnecessary reinvention. I have attempted to bring up to date items which are out of date, but am conscious that I may have missed some, and I have attempted to introduce the new areas and new developments of which I have become aware. In two areas where I know myself to be lacking in first-hand knowledge, I have changed the focus of the chapters and greatly reduced their length. Modern Control Methods has gone and been replaced by Remote Data Access Systems, and the chapter on manufacturing by a brief chapter entitled Final Considerations which touches on manufacturing variation and ISO quality standards and also takes in final comments.

I have included three new chapters covering magnetic resonance flowmeters, sonar and acoustic flowmeters and verification. They are brief chapters, but represent new developments since the first edition. I have also separated multiphase flowmeters into another new chapter, but have done so recognising that my knowledge of the subject is minimal and the coverage in the chapter is very superficial.

The techniques for precise measurement of flow are increasingly important today when the fluids being measured, and the energy involved in their movement, may have a very high monetary value. If we are to avoid being prodigal in the use of our natural resources, then the fluids among them should be carefully monitored. Where there might be pressure to cut corners with respect to standards and integrity, we need to ensure that in flow measurement these features are given their proper treatment and respect.

Acknowledgements

My knowledge of this subject has benefitted from many others with whom I have worked and talked over the years. These include colleagues from industry, national laboratories and academia, visitors and students, whether on short courses or longer-term degree courses and research. I hope that this book does justice to all that they have taught me.

In writing this book, I have drawn on information from many manufacturers, and some have been particularly helpful in agreeing to the use of information and diagrams. I have acknowledged these in the captions to the figures. Some went out of their way to provide artwork, and I am particularly grateful to Katrin Faber and Ruth O'Connell.

In preparing this second edition, I have been conscious of the many changes and advances in the subject, and so I have depended on many friends and colleagues, near and far, to read sections for me and to comment, criticise and correct them. In the middle of already busy lives they kindly made time to do this for me. In particular I would like to thank:

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I have had the privilege of being based back at my alma mater for the past 15 years, and they have been some of the most enjoyable of my working life. I am very grateful to Mike Gregory, who was key in making this possible; to Ian Hutchings, with whom I have collaborated; and to others of the Department of Engineering, particularly librarians and technical support staff, who have facilitated my experimental and theoretical research. I have also appreciated the friendship of the late Yousif Hussain, who provided a strong industrial link over this period.

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I have also been grateful for the help and encouragement given to me by many in the preparation of this book. It would be difficult to name them, but I am grateful for each contribution.

I have found the support of my family invaluable and particularly that of Liz, my wife, whose patience with my long hours at the computer, her willingness to assist with her proofreading skills, her encouragement and help at every stage, have made the task possible and I cannot thank her enough.

Finally, I am grateful to Cambridge University Press for the opportunity of preparing this second edition.

Nomenclature

Chapter 1

c_i	sensitivity coefficient
$f(x)$	function for normal distribution
K	K factor in pulses per unit flow quantity
k	coverage factor
M	mean of a sample of n readings
m	index
$N(\mu,\sigma^2)$	normal curve
n	number of measurements, index
p	probability, index
$\bar{q}$	mean of n measurements q_j, index
q_j	test measurement
q_v	volumetric flow rate
r	index
s	index
$s(\bar{q})$	experimental standard deviation of mean of group q_j
$s(q_j)$	experimental standard deviation of q_j
t	Student's t
U	expanded uncertainty
$u(x_i)$	standard uncertainty for the ith quantity
$u_c(y)$	combined standard uncertainty
x	coordinate
x_i	result of a meter measurement, input quantities
$\bar{x}$	mean of n meter measurements
y	output quantity
z	normalised coordinate $(x-\mu)/\sigma$
μ	mean value of data for normal curve
ν	degrees of freedom
σ	standard deviation (σ^2 variance)

$\Phi(z)$	area under normal curve e.g. $\Phi(0.5)$ is the area from $z = -\infty$ to $z = 0.5$
$\phi(z)$	function for normalised normal distribution

Chapter 2

A	cross-section of pipe
c	local speed of sound
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
D	diameter of pipe
d	diameter of flow conditioner plate holes
f_D	Darcy friction factor: $f_D = 4f_F$
f_F	Fanning friction factor
g	acceleration due to gravity
H	Hodgson number Equation (2.13)
K	pressure loss coefficient
L	length of pipe (sometimes given as a multiple of D e.g. 5D)
M	Mach number
n	index as in Equation (2.4)
p	pressure
p_0	stagnation pressure
Δp_{loss}	pressure loss across a pipe fitting
q_v	volumetric flow rate
q_m	mass flow rate
R	radius of pipe
Re	Reynolds number
r	radial coordinate (distance from pipe axis)
T	temperature
T_0	stagnation temperature
V	velocity in pipe, total volume of pipework used in Hodgson number
V_0	velocity on pipe axis, maximum axial velocity at a cross-section
V_{rms}	fluctuating component of velocity
$\bar{V}$	mean velocity in pipe
v	local fluid velocity
v_τ	friction velocity $v_\tau = \sqrt{\frac{\tau_w}{\rho}}$
x	distance from pipe axis in horizontal plane
y	distance from the pipe wall $= (R - r)$
y_1	viscous sublayer thickness
y_2	extent of buffer layer
z	elevation above datum

γ	ratio of specific heats
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ	shear stress
τ_w	wall shear stress: $\tau_w = f_F \dfrac{\rho \bar{V}^2}{2}$

Subscripts

1,2	pipe sections

Chapter 4

C_d	concentration of tracer in the main stream at the downstream sampling point
C_{dmean}	mean concentration of tracer measured downstream
C_i	concentration of tracer in the injected stream
C_u	concentration of tracer in the main stream upstream of injection point (if the tracer material happens to be present)
c_i	sensitivity coefficient
K_{fm}	mass flowmeter factor
k_S	factor for the weigh scale
M_n	net mass of liquid collected in calibration
M_D	weight of deadweight
M_s	conventional mass of material of density 8,000 kg/m^3
M_L	mass of water in weigh tank
M_G	mass of air displaced
ΔM_{LDV}	change in mass within the connection pipe between the flowmeter and the weir
m_{CAL}	reading of the weigh scale when loaded with deadweights
m_L	weigh scale reading
P	pulse count
p	pressure
q_v	volumetric flow rate in the line
q_{vi}	volumetric flow rate of injected tracer
R	gas constant for a particular gas
T	temperature
t	collection time during calibration
V	amount injected in the sudden injection (integration) method
v	specific volume
ρ	liquid density
ρ_D	actual density of deadweight

ρ_G	air density
ρ_{LW}	liquid density

Chapter 5

A	function of Re_D
a_1	expression in orifice plate-bending formula
a_ε	constant
b_ε	constant
C	discharge coefficient
C_{Re}	part of discharge coefficient affected by Re
C_{Taps}	part of discharge coefficient which allows for position of taps
C_∞	discharge coefficient for infinite Reynolds number
$C_{Small\ orifice}$	correction for small orifice sizes
c_1	expression in orifice plate-bending formula
c_ε	constant
D	pipe diameter (ID)
D'	orifice plate support diameter
d	orifice diameter
E	thickness of the plate, velocity of approach factor $(1-\beta^4)^{-½}$
E_T	total error in the indicated flow rate of a flowmeter in pulsating flow
E^*	elastic modulus of plate material
e	thickness of the orifice (Figure 5.3), Napierian constant
F	correction factor used to obtain the mass flow of a (nearly) dry steam flow
f	frequency of the pulsation
H	Hodgson number
h	thickness of orifice plate
K	loss coefficient, related to the criterion for Hodgson number
L_1	$= l_1/D$
L'_2	$= l'_2/D'$ signifies that the measurement is from the downstream face of the plate.
l_1	distance of the upstream tapping from the upstream face of the plate
l'_2	distance of the downstream tapping from the downstream face of the plate. $'$ signifies that the measurement is from the downstream face of the plate.
M'_2	$= 2L'_2/(1-\beta)$
M_1	numerical value defined in text
n	index
p	static pressure
p_u	upstream static pressure

p_d	downstream static pressure
p_1	static pressure at upstream tapping
p_2	static pressure at downstream tapping
Δp	differential pressure, pressure drop between pulsation source and meter
q_m	mass flow rate
q_v	volumetric flow rate
Re	Reynolds number
Re_D	Reynolds number based on the pipe ID
r	radius of upstream edge of orifice plate
T_f	temperature of the fluid at flowing conditions
t	time
V	volume of pipework and other vessels between the source of the pulsation and the flowmeter position
$\bar{V}$	mean velocity in pipe with pulsating flow
V_cl	centre line velocity
V_max	maximum velocity
V_rms	rms value of unsteady velocity fluctuation in pipe with pulsating flow
x	dryness fraction, displacement of the centre of the orifice hole from the pipe axis (m)
α	$= CE$ the flow coefficient
β	diameter ratio d/D
γ	ratio of specific heats
δq_m	small changes or errors in q_m etc.
ε	expansibility (or expansion) factor
ε_1	expansibility (or expansion) factor at upstream tapping
κ	isentropic exponent
ρ	density
ρ_1	density at the upstream pressure tapping
ρ_g	density of gas
ρ_l	density of liquid
σ_y	yield stress for plate material
θ	angle defined in Figure 5.B.1 caused by deposition on the leading face of the orifice plate
$\Phi_\mathrm{fo}{}^2$	ratio of two-phase pressure drop to liquid flow pressure drop
ϕ	maximum allowable percentage error in pulsating flow

Chapter 6

C	coefficient of discharge
C_tp	coefficient for wet-gas flow equation
C_dry	discharge coefficient for fully dry gas

C_{fullywet}	discharge coefficient for fully wet gas $X \geq X_{\text{lim}}$ where $X_{\text{lim}} = 0.016$
D	pipe ID
d	throat diameter
E	velocity of approach factor $= 1/\sqrt{(1-\beta^4)}$
Fr_{g}	superficial gas Froude number
$\mathrm{Fr}_{\mathrm{g,th}}$	Froude number at the throat
g	gravitational acceleration
n	index
p_1	upstream pressure tapping
p_2	downstream pressure tapping
Δp	differential pressure
$q_{\mathrm{m,g}}$	mass flow rate of gas
$q_{\mathrm{m,l}}$	mass flow rate of liquid
q_{m}	mass flow rate
q_{tp}	apparent flow rate when liquid is present in the gas stream
q_{v}	volume flow rate
Ra	roughness criterion
Re	Reynolds number
V_{sg}	superficial gas velocity
β	diameter ratio *d/D*
ε	expansibility (or expansion) factor
κ	isentropic exponent
ρ_1	density at upstream pressure tapping
ρ_{l}	liquid density
$\rho_{1,\mathrm{g}}$	gas density at upstream tapping point
τ	pressure ratio $\frac{p_2}{p_1}$
ϕ	defined in Equation (6.1)

Chapter 7

A_2	outlet cross-sectional area
A_*	throat cross-sectional area
a	constant
b	constant
C	discharge coefficient
C_{R}	$= C_*\sqrt{Z}$
C_*	critical flow function
$C_{*\mathrm{i}}$	critical flow function for a perfect gas
c	speed of sound
c_{p}	specific heat at constant pressure
c_{v}	specific heat at constant volume
c_*	speed of sound in the throat

d	throat diameter
d_2	outlet diameter
l	dimension given in Figure 7.5
M	Mach number
M_1	Mach number at inlet when stagnation conditions cannot be assumed
$\mathbf{M}$	molecular weight
n	exponent in Equation (7.10)
p_o	stagnation pressure
p_1	pressure at inlet when stagnation conditions cannot be assumed
p_{2i}	ideal outlet pressure
p_{2max}	actual maximum outlet pressure
p_*	throat pressure in choked conditions
q_m	mass flow
$\mathbf{R}$	universal gas constant
Re_d	Reynolds number based on the throat diameter
r	toroid radius
T_o	stagnation temperature
T_*	throat temperature in choked conditions
Z	compressibility factor
Z_o	compressibility factor at stagnation conditions
β	$= d/D$
γ	ratio of specific heats
ε	error
κ	isentropic exponent
ν	kinematic viscosity
θ	angle given in Figure 7.5
μ_0	dynamic viscosity of gas at stagnation conditions
ρ_*	density of gas in the throat
ρ_o	density at stagnation conditions

Chapter 8

A	cross-sectional area of the pipe, constant
A'	constant
A_f	cross-sectional area of float
A_x	cross-sectional area of tapering tube at height x
A_2	annular area around float, annular area around target
a	area of target
B	constant
C	coefficient
C_0 to C_4	constants in curve fit for target meter discharge coefficient
C_c	contraction coefficient
C_d	coefficient of discharge