Flow Measurement Handbook

INDUSTRIAL DESIGNS, OPERATING PRINCIPLES, PERFORMANCE, AND APPLICATIONS

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CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK http://www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA http://www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain

First published 2000

Printed in the United States of America

Typeface Stone Serif 9/12.5 pt. *System* LaTeX 2$_\varepsilon$ [TB]

A catalog record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data
Baker, R. C.
Flow measurement handbook : industrial designs, operating principles, performance, and applications / Roger C. Baker.
p. cm.
Includes bibliographical references.
ISBN 0-521-48010-8
1. Flow meters – Handbooks, manuals, etc. I. Title.
TA357.5.M43B35 2000
681′.28 – dc21 99-14190
CIP

ISBN 0 521 48010 8 hardback

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CHAPTER 1

Introduction

1.1 INITIAL CONSIDERATIONS

Some years ago at Cranfield, where we had set up a flow rig for testing the effect of upstream pipe fittings on certain flowmeters, a group of senior Frenchmen were being shown around and visited this rig. The leader of the French party recalled a similar occasion in France when visiting such a rig. The story goes something like this.

A bucket at the end of a pipe seemed particularly out of keeping with the remaining high tech rig. When someone questioned the bucket's function, it was explained that the bucket was used to measure the flow rate. Not to give the wrong impression in the future, the bucket was exchanged for a shiny new high tech flowmeter. In due course, another party visited the rig and observed the flowmeter with approval. "And how do you calibrate the flowmeter?" one visitor asked. The engineer responsible for the rig then produced the old bucket!

This book sets out to guide those who need to make decisions about whether to use a shiny flowmeter, an old bucket, nothing at all, or a combination of these! It also provides information for those whose business is the design, manufacture, or marketing of flowmeters. I hope it will, therefore, be of value to a wide variety of people, both in industry and in the science base, who range across the whole spectrum from research and development through manufacturing and marketing. In my earlier book on flow measurement (Baker 1988/9), I provided a brief statement on each flowmeter to help the uninitiated. This book attempts to give a much more thorough review of published literature and industrial practice.

This first chapter covers various general points that do not fit comfortably elsewhere. In particular, it reviews recent guidance on the accuracy of flowmeters (or calibration facilities).

The second chapter reviews briefly some essentials of fluid mechanics necessary for reading this book. The reader will find a fuller treatment in Baker (1996), which also has a list of books for further reading.

A discussion of how to select a flowmeter is attempted in Chapter 3, and some indication of the variety of calibration methods is given in Chapter 4, before going in detail in Chapters 5–17 into the various high (and low) tech meters available. Chapter 18 deals with probes, Chapter 19 gives a brief note on modern control systems, and Chapter 20 provides some reflections on manufacturing and markets. Finally, Chapter 21 raises some of the interesting directions in which the technology is likely to go in the future.

In this book, I have tried to give a balance between the laboratory ideal, the manufacturer's claims, the realities of field experience, and the theory behind the practice. I am very conscious that the development and calibration laboratories are sometimes misleading places, which omit the problems encountered in the field (Stobie 1993), and particularly so when that field happens to be the North Sea. In the same North Sea Flow Measurement Workshop, there was an example of the unexpected problems encountered in precise flow measurement (Kleppe and Danielsen 1993), resulting, in this case, from a new well being brought into operation. It had significant amounts of barium and strontium ions, which reacted with sulfate ions from injection water and caused a deposit of sulfates from the barium sulfate and strontium sulfate that were formed.

With that salutary reminder of the real world, we ask an important – and perhaps unexpected – question.

1.2 DO WE NEED A FLOWMETER?

Starting with this question is useful. It may seem obvious that anyone who looks to this book for advice on selection is in need of a flowmeter, but for the process engineer it is an essential question to ask. Many flowmeters and other instruments have been installed without careful consideration being given to this question and without the necessary actions to ensure proper documentation, maintenance, and calibration scheduling being taken. They are now useless to the plant operator and may even be dangerous components in the plant. Thus before a flowmeter is installed, it is important to ask whether the meter is needed, whether there are proper maintenance schedules in place, whether the flowmeter will be regularly calibrated, and whether the company has allocated to such an installation the funds needed to achieve this ongoing care. Such care will need proper documentation.

The water industry in the United Kingdom has provided examples of the problems associated with unmaintained instruments. Most of us who are involved in the metering business will have sad stories of the incorrect installation or misuse of meters. Reliability-centered maintenance recognizes that the inherent reliability depends on the design and manufacture of an item, and if necessary this will need improving (Dixey 1993). It also recognizes that reliability is preferable in critical situations to extremely sophisticated designs, and it uses failure patterns to select preventive maintenance.

In some research into water consumption and loss in urban areas, Hopkins et al. (1995) found that obstacles to accurate measurements were

- ☐ buried control valves,
- ☐ malfunctioning valves,
- ☐ valve gland leakage,
- ☐ hidden meters that could not be read, and
- ☐ locked premises denying access to meters.

They commented that "water supply systems are dynamic functions having to be constantly expanded or amended. Consequently continuous monitoring, revisions and amendments of networks records is imperative. Furthermore, a proper programme of inspection, maintenance and subsequent recording must be operative in respect of inter alia:

- networks,
- meters,
- control valves,
- air valves,
- pressure reducing valves,
- non-return valves."

They also commented on the poor upstream pipework at the installation of many domestic meters.

So I make no apology for emphasizing the need to assess whether a flowmeter is actually needed in any specific application.

If the answer is yes, then there is a need to consider the type of flowmeter and whether the meter should be measuring volume or mass. In most cases, the most logical measure is mass. However, by tradition and industrial usage, there are places where volume measurement may be the norm, and as a result, the regulations have been written for volume measurement. This results in a Catch-22 situation. The industry and the regulations may, reasonably, resist change to mass flow measurement until there is sufficient industrial experience, but industrial experience is not possible until the industry and the regulations allow. The way forward is for one or more forward-looking companies to try out the new technology and obtain field experience, confidence in the technology, and approval.

In this book, I have made no attempt to alert the reader to the industry-specific regulations and legal requirements, although some are mentioned. Some regulations are touched on by the various authors, and Miller (1996) is a source of information on many documents. The main objective of the Organisation International de Métrologie Légale (OIML) is to prevent any technical barriers to international trade resulting from conflicting regulations for measuring instruments. With regard to flow measurement, it is particularly concerned with the measurement of domestic supplies and industrial supplies of water and gas (Athane 1994). This is because there are two parties involved, the supplier and the consumer, and the consumer is unlikely to be able to ascertain the correct operation of the meter. In addition these measurements are not monitored continually by the supplier, the meters may fail without anyone knowing, the usage is irregular and widely varying in rate, the measurements are not repeatable, and the commodities have increased in value considerably in recent years.

In order to reduce discussions and interpretation problems between manufacturers and authorized certifying institutes, the European Commission is mandating the European standardization body (CEN/CENELEC) to develop harmonized standards that will give the technical details and implementation of the requirements based on OIML recommendations. These are such that a measuring instrument complies with essential requirements, assuming that the manufacturer has complied with them (Nederlof 1994).

The manufacturer will also be fully aware of the electromagnetic compatibility (EMC), which relates to electromagnetic interference. In particular, the EMC characteristics of a product are that

- ❑ the level of electromagnetic disturbance generated by the instrument will not interfere with other apparatus, and
- ❑ the operation of the instrument will not be adversely affected by electromagnetic interference from its environment.

In order to facilitate free movement within the European area the CE mark identifies products that conform to the European essential requirements, and all products must be so marked within the European Economic Area (DTI 1993, Chambers 1994).

First, we consider the knotty problem of how accurate the meter should be.

1.3 HOW ACCURATE?

There continues to be inconsistency about the use of terms that relate to accuracy and precision. This stems from a slight mismatch between the commonly used terms and those that the purists and the standards use. Thus we commonly refer to an accurate measurement, when strictly we should refer to one with a small value of uncertainty. We should reserve the use of the word *accurate* to refer to the instrument. A high quality flowmeter, carefully produced with a design and construction to tight tolerances and with high quality materials as well as low wear and fatigue characteristics, is a precise meter with a quantifiable value of repeatability. Also, it will, with calibration on an accredited facility, be an accurate meter with a small and quantifiable value of measurement uncertainty. In the context of flowmeters, the word *repeatability* is preferred to *reproducibility*. The meanings are elaborated on later, and I regret the limited meaning now given to *precision*, which I have used more generally in the past and shall slip back into in this book from time to time! In the following chapters, I have attempted to be consistent in the use of these words. However, many claims for accuracy may not have been backed by an accredited facility, but I have tended to use the phrase “measurement uncertainty” for the claims made.

Hayward (1977) used the story of William Tell to illustrate precision. William Tell had to use his cross-bow to fire an arrow into an apple on his little son’s head. This was a punishment for failing to pay symbolic homage to an oppressive Austrian ruler. Tell succeeded because he was an archer of great skill and high accuracy.

An archer’s ability to shoot arrows into a target provides a useful illustration of some of the words related to precision. So Figure 1.1(a) shows a target with all the shots in the bull’s-eye. Let us take the bull’s-eye to represent ±1%, within the first ring ±3%, and within the second ring ±5%. Ten shots out of ten are on target, but how many will the archer fire before one goes outside the bull’s-eye? If the archer, on average, achieves 19 out of 20 shots within the bull’s-eye [Figure 1.1(b)], we say that the archer has an uncertainty of ±1% (the bull’s-eye) with a 95% confidence level (19 out of 20 on the bull’s-eye: $19 \div 20 = 0.95 = 95 \div 100 = 95\%$).

Suppose that another archer clusters all the arrows, but not in the bull’s-eye, Figure 1.1(c). This second archer is very consistent (all the shots are within the same size circle as the bull’s-eye), but this archer needs to adjust his aim to correct the offset. We could say that the second archer has achieved high repeatability of ±1%, but with a bias of 4%. We might even find that 19 out of 20 shots fell within the top left circle so that we could say that this archer achieved a repeatability within that circle of ±1% with a 95% confidence. Suppose this archer had fired one shot a day, and they had all fallen onto a small area [Figure 1.1(c)], despite slight changes in wind, sunshine, and archer's mood, then we term this good day-to-day repeatability. But how well can we depend on the archer's bias? Is there an uncertainty related to it?

Finally, a third archer shoots 20 shots and achieves the distribution in Figure 1.1(d). One has missed entirely, but 19 out of 20 have hit the target somewhere. The archer has poor accuracy, and the uncertainty in this archer's shots is about five times greater than for the first, even though the confidence level at which this archer performs is still about 95%.

If the third archer has some skill, then the bunching of the arrows will be greater in the bull's-eye than in the next circle out, and the distribution by ring will be as shown in Figure 1.1(e).

We shall find that the distribution of readings of a flowmeter results in a curve approximating a Normal distribution with a shape similar to that for the shots. Figure 1.1(f) shows such a distribution where 95% of the results lie within the shaded area and the width of that area can be calculated to give the uncertainty, ±1% say, of the readings with a 95% confidence level. In other words, 19 of every 20 readings fall within the shaded area.

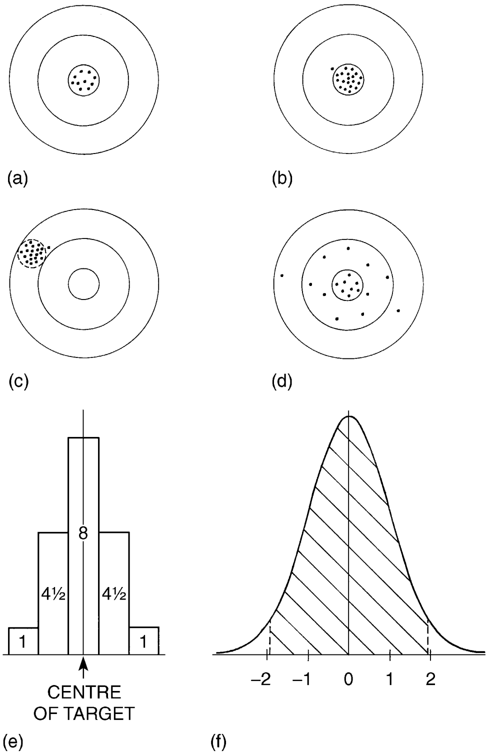

Figure 1.1. Precision related to the case of an archery target. **(a)** Good shooting – 10 out of 10 arrows have hit the bull's-eye. An accurate archer? **(b)** Good shooting? – 19 out of 20 arrows have hit the bull's-eye. An accurate archer and a low value of uncertainty (±1%) with a 95% confidence level. **(c)** Shots all fall in a small region but not the bull's-eye. Good repeatability (±1%) but a persistent bias of 4%. **(d)** Shots, all but one, fall on the target – 19 out of 20 have hit the target. A ±5% uncertainty with 95% confidence level. **(e)** Distribution of shots in (d) on a linear plot, assuming that we can collapse the shots in a ring semicircle onto the axis. **(f)** The Normal distribution, which is a good approximation for the distribution of flowmeter readings.

With this simplistic explanation, we turn to the words that relate to precision.

Accuracy

It is generally accepted that *accuracy* refers to the truthfulness of the instrument. An instrument of high accuracy more nearly gives a true reading than an instrument of low accuracy. Accuracy, then, is the quality of the instrument. It is common to refer to a measurement as accurate or not, and we understand what is meant. However, the current position is that accuracy should be used as a qualitative term and that no numerical value should be attached to it. It is, therefore, incorrect to refer to a measurement's accuracy of, say, 1%, when, presumably, this is the instrument's measurement uncertainty, as is explained later.

Repeatability

In a process plant, or other control loop, we may not need to know the accuracy of a flowmeter as we would if we were buying and selling liquid or gas, but we may require repeatability within bounds defined by the process. *Repeatability* is the value below which the difference between any two test results, taken under constant conditions with the same observer and with a short elapsed time, are expected to lie with 95% confidence.

Precision

Precision is the qualitative expression for repeatability. It should not take a value and should not be used as a synonym for accuracy.

Uncertainty

Properly used, *uncertainty* refers to the quality of the measurement, and we can correctly refer to an instrument reading having an uncertainty of ±1%. By this we mean that the readings will lie within an envelope ±1% of the true value. Each reading will, of course, have an individual error that we cannot know in practice, but we are interested in the relationship of the readings to the true value. Because *uncertainty* is referred to the true value, by implication it must be obtained using a national standard document or facility. However, because it is a statistical quantity, we need also to define how frequently the reading does, in fact, lie within the envelope; hence the confidence level.

Confidence level

The *confidence level*, which is a statement of probability, gives this frequency, and it is not satisfactory to state an uncertainty without it. Usually, for flow measurement, this is 95%. We shall assume this level in this book. A confidence level of 95% means that we should expect on average that 19 times out of 20 (19/20 = 95/100 = 95%) the reading of the meter will fall within the bracket specified (e.g., ±1% of actual calibrated value).

Linearity

Linearity may be used for instruments that give a reading approximately proportional to the true flow rate over their specified range. It is a special case of *conformity* to a curve. Note that both terms really imply the opposite. *Linearity* refers to the closeness within which the meter achieves a truly linear or proportional response. It is usually defined by stating the maximum deviation (or nonconformity, e.g., ±1% of flow rate) within which the response lies over a stated range. With modern signal processing, linearity is probably less important than conformity to a general curve. *Linearity* is most commonly used with such meters as the turbine meter.