INDUSTRIAL FLOW MEASUREMENT

MICHAEL ANTHONY CRABTREE

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To my wife Pam, without whose encouragement I would never have started and without whose help I would never have finished.

Abstract

This thesis discusses the intrinsic worth of a published work, 'Industrial Flow Measurement' (Appendix A), a handbook written and revised by the author over a period of 30 years. The author first discusses the need to measure flow and then moves on to the raison d'être of the handbook before looking at a brief history of flow measurement. Although not claiming that any single attribute of the handbook is unique, the author nonetheless postulates that because it incorporates several distinctive features, at a number of different levels, these agents combine to make it one-of-a- kind.

The author moves on to an overview of existing flow metering technologies discussed within the handbook. Finally, he looks at what he considers is a major gap in the collected body of knowledge – the field of multiphase and water-cut metering and provides a justification, not only for its inclusion in the future but for future investigation.

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Author's résumé

As a high-school drop-out Michael (Mick) Crabtree claims he was 'saved' from total ignominy by joining the Royal Air Force as an apprentice at the age of 16. Trained in aircraft instrumentation and guided missiles he completed a Higher National Certificate in Electrical Engineering, (with distinction in Mathematics) and concluded his service career seconded to the Ministry of Defence.

In 1966 he moved to South Africa where he was involved in the sales of industrial equipment and process control instrumentation. He later moved to a systems integration company, working at the forefront of technology on a variety of projects.
In 1981 he was appointed Editor and Managing Editor of South Africa's leading monthly journal dedicated to the process control instrumentation industries. In 1989 he founded his own company – specialising in feature writing, articles, and general PR for the industrial process control sector. During this period he also wrote and published seven technical handbooks on industrial process control: 'Flow Measurement', 'Temperature Measurement', 'Analytical On-line Measurement'; 'Pressure and Level Measurement'; 'Valves'; 'Industrial Communications' and 'The Complete Profibus Handbook'.

For the last twelve years he has been involved in technical training and consultancy and has run workshops on industrial instrumentation and networking throughout the world. During this period he has led more than 4500 engineers, technicians and scientists on a variety of practical training workshops covering the fields of Process Control (loop tuning), Process Instrumentation, Data Communications and Fieldbus Systems, Safety Instrumentation Systems, Project Management, On-Line Liquid Analysis, and Technical Writing and Communications.

After nearly 35 years spent in South Africa, he now lives in Wales, just outside Cardiff, having relocated to Britain about nine years ago.

1 Introduction

Over the past 60 years, the importance of flow measurement has grown, not only because of its widespread use for accounting purposes, such as the custody transfer of fluid from supplier to consumer, but also because of its application in manufacturing processes. Throughout this period, performance requirements have become more stringent – with unrelenting pressure for improved reliability, accuracy[1], linearity, repeatability and rangeability.

These pressures have been caused by major changes in manufacturing processes and because of several dramatic circumstantial changes such as the increase in the cost of fuel and raw materials, the need to minimise pollution, and the increasing pressures being brought to bear in order to adhere to the requirements for health and safety.

Industries involved in flow measurement and control include:

- food and beverage;
- medical;
- mining and metallurgical;
- oil and gas transport;
- petrochemical;
- pneumatic and hydraulic transport of solids;
- power generation;
- pulp and paper; and
- distribution.

[1] *In the field of process instrumentation the term 'accuracy' is generally defined as the ratio of the error to the full-scale or actual output, expressed as a percentage. Strictly speaking the term should be confined to generalised descriptions and not to specifications – where the term 'error' is preferred. However, the vast majority of instrumentation manufacturers continue to use the term 'accuracy'.*

Fluid properties can vary enormously from industry to industry. The fluid may be toxic, flammable, abrasive, radio-active, explosive or corrosive; it may be single-phase (clean gas, water or oil) or multi-phase (for example, slurries, wet steam, well-head petroleum, or dust laden gases). The pipe carrying the fluid may vary from less than 1 mm to many metres in diameter. Fluid temperatures may vary from close to absolute zero to several hundred degrees Celsius and the pressure may vary from high vacuum to many thousands of bar.

Because of these variations in fluid properties and flow applications, a wide range of flow metering techniques has been developed with each suited to a particular area. However, of the numerous flow metering techniques that have been proposed in the past, only a few have found widespread application and no one single flowmeter can be used for all applications.

2 Why measure flow?

There is of course no single answer. Flow measurement is normally concerned with the question of 'how much' – how much is produced or how much is used. For small quantities this can normally be achieved by volumetric measurement (e.g. pulling a pint of beer). But as the amount grows larger this becomes impractical and, for example, it becomes necessary to measure volumetric flow (e.g. dispensing fuel from a garage petrol pump).

However, most petrol pump calibration is carried out using a test measuring can, which is a purely volumetric measurement. On this basis, during hot weather, it would be prudent to purchase petrol early in the morning when the temperature is low so that you would end up with more mass per litre. Alternatively, a more practical and consistent approach would be to make use of a mass flow metering system.

A further use of a flow measuring system is to control a process. In closed loop regulatory control, there are several instances where the prime consideration is repeatability rather than accuracy. This is particularly true in a cascaded system where the prime objective is not to control the inner loop to an absolute value but rather to increment up or down according to the demands of the master. Another instance of where absolute accuracy is relatively unimportant is in controlling the level of a surge tank. Here, the requirement is to allow the level to vary between an upper and lower value and absorb the upstream surges – thus preventing them from being passed downstream.

Accuracy is of prime importance in automatic blending control, batching and, of course, custody transfer and fiscal metering. In fluid measurement, custody transfer metering involves the sale, or change of ownership, of a liquid or gas from one party to another. On the other hand, fiscal measurement involves the levering of taxes – again relating to the production or sale of a liquid or gas.

3 Background

The book, ‘Principles and Practice of Flow Meter Engineering’ by L.K. Spink [1], first published in 1930, is generally recognised as the first, and for many years the only, definitive collected ‘body of knowledge’ appertaining to industrial flow measurement. Undergoing nine revisions, the last addition was printed in 1978 – 21 years after Spink’s death.

In the flyleaf of this last addition the publishers lay claim to the book covering “… the latest developments in flow measurement”. A weighty tome, by anyone's standards, the book comes in at 575 pages. However, in essence ‘Principles and Practice of Flow Meter Engineering’ is a eulogy “…devoted primarily to the characteristics of flow rate measurement based on a differential pressure generated by the flow of liquid through a restriction (such as an orifice) inserted in a line.”

Only a single page is devoted to the magnetic flow meter. A single page is likewise devoted to the turbine meter. And barely a single paragraph is used to allude to ultrasonic, thermal, and vortex-shedding meters – already key players in the field of flow measurement.

Barely a single page is dedicated to the electrical pressure transmitter (already in common use in 1978) – contrasting noticeably with long descriptions covering a variety of mechanical-pneumatic type transmitters.

Readers, lured into purchase of the 9th edition of his book by the flyleaf promise of “new data on the target meter”, might be disappointed to discover less than two pages devoted to the subject. A similar enticement extends to the promise of new data on the Lo-Loss tube, which is similarly dismissed in approximately a page and a half.

Of course, it could be said of Spink's work that he spent most of his life in the oil and gas industries and was instrumental in the early work of the American Gas Association. In the oil and gas industry, in particular, conservatism is rife. A case in point is that in the USA, most graduate facility engineers are taught in, and make use of, the metric SI system (abbreviated from the French *Le **S**ystème **I**nternational d'Unités*). And yet, because of their mentoring program, they will have a reverted back to fps (the imperial 'foot-pound-second' system used extensively in USA) within a few years.

Generally regarded as the heir apparent to Spink, R.W. Miller's 'Flow Measurement Engineering Handbook' [2] weighs in at over 1000 pages. Although still referenced as a standard for orifice plate sizing, the 2nd Edition, published in 1989 still devoted less than 15 pages in total to the combined technologies of magnetic, ultrasonic and Coriolis metering.

Too many process engineers, having had extensive experience with measuring instruments and systems that have stood the test of time, see no reason to change. Consequently, they will cling to the familiar, despite numerous shortcomings when compared with the benefits offered by newer systems. And so, more than 50 years after Spink's death, the orifice plate still reigns supreme – not because of its technological superiority but because of the industry's unwillingness to accept and implement new ideas and new technologies.

4 History of flow measurement

Early flow measurement was centred round the question of disputation: ‘how much has he got’ versus ‘how much have I got’. As early as 5000 BC flow measurement was used to control the distribution of water through the ancient aqueducts of the early Sumerian civilisations from the Tigris and Euphrates rivers. Such systems were very crude, based on volume per time: e.g. diverting flow in one direction from dawn to noon, and diverting it in another direction from noon to dusk. And although not fully comprehending the principles, the Romans devised a method of charging for water supplied to baths and residences, based on the cross sectional areas of pipes.

The first major milestone in the field of flow technology occurred in 1738 when the Swiss physicist Daniel Bernoulli published his *Hydrodynamica* [3] in which he outlined the principles of the conservation of energy for flow. In it he produced an equation showing that an increase in the velocity of a flowing fluid increases its kinetic energy while decreasing its static energy. In this manner a flow restriction causes an increase in the flowing velocity and a fall in the static pressure – the basis of today’s differential pressure flow measurement.

The word ‘turbine’ is derived from the Latin *spinning top* and although the ancient Greeks ground flour using horizontal turbine wheels, the idea of using a spinning rotor or turbine to measure flow did not come about until 1790 when the German engineer, Reinhard Woltman, developed the first vane-type turbine meter for measuring flow velocities in rivers and canals.

Other types of turbine meter followed. In the late 1800’s Lester Pelton built the first Pelton water wheel that turned as a result of water jets impinging on buckets attached around the outside of the wheel. And in 1916 Forrest Nagler designed the first fixed-blade propeller turbine.

A third milestone occurred in 1832 when Michael Faraday attempted an experiment to use his laws of electromagnetic induction to measure flow. With the aim of measuring the water flow of the River Thames, Faraday lowered two metal electrodes, connected to a galvanometer, into the river from Waterloo Bridge. The intent was to measure the induced voltage produced by the flow of water through the earth's magnetic field. The failure of Faraday to obtain any meaningful results was probably due to electrochemical interference and polarization of the electrodes.

It was left to a Swiss Benedictine monk, Father Bonaventura Thürlemann, working in a monastery in Engelberg, to lay the foundations of this technology, with the publication of his scientific work, 'Methode zur elektrischen Geschwindigkeitsmessung in Flüssigkeiten.' (Method of Electrical Velocity Measurement in Liquids), [4] in 1941.

Unfortunately, although his work was sound, the technology of the time was insufficient to develop a practical system. Consequently, it was not until the mid 1950s that sufficient progress had been made in electronics to make it possible to produce a low voltage, interference free, measuring amplifier that was sufficiently sensitive and drift free. Despite the many advantages of this technology[2], initial conservatism slowed down its acceptance for use in industrial applications. The impetus required to initiate further research and general acceptance, came in 1962 when J. A. Shercliff published his decisive book ('The theory of electromagnetic flow-measurement'[5]), setting down a firm theoretical foundation on the principles of magnetic flowmeters.

The last milestone occurred only three years after Faraday conducted his original experiment when, in 1835, Gaspar Gustav de Coriolis, made the discovery of what is now termed the Coriolis effect, which led, nearly a century and a half later, to the development of the highly accurate direct measurement mass flow Coriolis meter.

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[2] *See Chapter 6, Section 6.14 ('Conclusions') of Appendix A for further details.*

5 The book: ‘Industrial flow measurement’ (Appendix A)

In 1979 the author wrote a handbook entitled ‘Industrial Flow Measurement – a definitive guide to the principles, selection and practice of industrial flow metering’. Published in South Africa, it sought to provide a complete body of knowledge for both the specialist and non-specialist instrumentation practitioner and to redress the apparent shortcomings prevalent in most of the available books dealing with flow measurement.

No single attribute of the handbook is unique. However, because it incorporates several distinctive features, at a number of different levels, these agents combine to make it one-of-a- kind.

During the last 30 years the handbook has been revised eight times and was last published as ‘Mick Crabtree’s Flow Handbook’. The use of the author’s name sought to capitalize on his credibility and his positive reputation for objectivity within the South African marketplace. The current (last revised in April 2009), unpublished, version (Appendix A) is entitled ‘Industrial Flow Measurement’ and represents some thirty years wealth of experiential knowledge gleaned from the author's experience working within a systems integration company and also feedback from more than 4000 technicians and engineers who have attended the author’s workshops.

The handbook makes use of a building block approach and is presented in a form suitable for two distinct classes of reader: the beginner, with no prior knowledge of the subject; and the more advanced technician.

The complete text is suitable for the advanced reader. However, those parts of the text, which involve a mathematical treatment which are not required by the beginner, are indicated by a mark (▶) at the beginning and (◀) at the end. Consequently, for the beginner the text may be read, with full understanding, by ignoring the marked sections.

In this manner two complete books are available at two different levels for two distinct classes of reader. This avoids a purely mathematical treatment in favour of a progressive journey that allows the reader a choice to firmly establish a knowledge foundation. Moving from knowledge, to comprehension, to application the handbook allows the reader to conduct a technical evaluation of the options based on rigid analysis. Ultimately, what the author achieved is a handbook that gets to grips with each technology in turn – explaining it in a detailed but understandable language. This enables specifiers to examine the choices and make an informed recommendation based on facts rather than vendors' sales pitches.

Another feature of the published handbook is that it carried advertising. Consequently, it was not sold directly to the public but was sent, free of charge, to nearly 5000 subscribers of a South African trade journal called 'Electricity and Control'. Income was thus generated by a combination of advertising revenue and direct sales of approximately 500 copies. The advantage of this approach to the advertisers is that they were offered a guaranteed target market and circulation. They were also offered, free of charge, a number of 'Product editorials' – short editorial items of approximately 200 words. The benefit accruing to the author was that he was fully appraised of all the latest products and technologies newly introduced into the market. On the downside, there were vendors (actually only two) who attempted to use their advertising 'clout' to influence the objectivity of the editorial. With the backing of the publisher, this pressure was ruled as inappropriate and their advertisements removed from the journal. Although drawing heavily on commercial literature and publications, the handbook was, nonetheless, able to seek and find an objectivity that was unavailable from vendor-resourced literature.

A further feature of the handbook lies in the more than 200 explanatory line drawings and graphs, which, with only a few exceptions, were originated and drawn, or redrawn, by the author.

6 Conclusions

The basis of this thesis, 'Industrial Flow Measurement', is to address the complete range of modern flow measuring technologies in an easily accessible format. Although the situation is changing, there is still a scarcity of literature collected in a single body of knowledge that allows technicians and engineers to access a single usable up-to-date reference point.

Two notable exceptions include: 'Flow Measurement Handbook' by Roger C. Baker [6] and 'Fluid Flow Measurement – A Practical Guide to Accurate Flow Measurement' by E. Loy Upp and Paul J. LaNasa [7]. Bakers book is particularly comprehensive and covers a number of technologies and additional material that is not found in Appendix A. However last published in 2000 and 2002 respectively, both publications necessarily exclude some of the advances in flow technology (high accuracy Coriolis; ultrasonic custody transfer; conditioning orifice plate; high accuracy magnetic flowmeters with signature analysis) that are addressed in Appendix A.

6.1 Pros, cons and limitations of existing technologies

Many attempts have been made to categorise flow metering technologies. Several, including Spink, have merely split the technologies into two divisions: head-loss metering and non head-loss metering – a simple enough categorisation but one that is not only far too simplistic but one that is also somewhat dismissive of many of the modern additions to the technology as a whole.

Another approach, used by Dr. Jesse Yoder, Flow Research, Inc. [8] is to classify the technologies into:

- new-technology flow meters; and
- traditional-technology flow meters.

In its way, this approach is equally dismissive of the traditional technologies that include head-loss meters. In some instances considerable work has been carried out to dramatically improve the shortcomings of these previously restricted technologies.

In Appendix A, (Industrial Flow Measurement) the author has used neither of these two approaches, seeking rather to look at each technology in turn and to weigh them according to their importance in industry as a whole, rather than any specific sector. To this effect the technologies are discussed in the following categories:

- Positive displacement.
- Inferential.
- Oscillatory.
- Differential pressure.
- Electromagnetic.
- Ultrasonic.
- Mass flow.
- Open channel.

When examined in detail these eight divisions encompass a total of 33 different technologies. In the following discourse the author will briefly discuss each one of these technologies in turn.

6.2 Positive displacement (Chapter 2 of Appendix A).

Positive displacement meters separate defined volumes of the medium from the flow stream and move them from the inlet to the outlet in discrete packages. By totalising the number of packages, the total volume passed in a given time is provided. With moving parts that are subject to wear, positive displacement meters are, with a few exceptions, part of a shrinking market sector. One of these exceptions, and one most commonly met, is the nutating disc or 'wobble' meter which is used extensively, particularly in the USA, for residential water service metering.

Because of their high accuracy, positive displacement meters are also to be found in another major market sector: custody transfer and fiscal metering applications in the oil and gas industries.

In spite of their high accuracy; the need for a clean medium; their high expense; and, as mentioned previously, their susceptibility to wear; positive displacement meters being are gradually being replaced by other ‘modern’ approaches such as turbine, ultrasonic and Coriolis meters.

6.3 Inferential (Chapter 3 of Appendix A)

This group, which includes turbine, propeller, and impeller type meters, infers the displacement of undefined volumes of the flowing medium as it passes from the inlet to the outlet. Unlike the positive displacement meter, the volume is not geometrically defined. Typically, the flowing fluid impinges on a blade or paddle causing it to rotate at an angular velocity that is directly proportional to the fluid flow rate. The rotational velocity is measured by a proximity transducer (usually magnetic) that produces an output pulse for each passage of a blade – with each pulse representing a distinct volume of the displaced fluid.

Again, expensive, and subject to wear, the turbine meter is commonly used in custody transfer applications in the oil and gas industry. However, the need for an on-site meter prover calibration skid, to compensate for variations in the viscosity of the medium, has caused a decline in its market share – slowly giving way to ultrasonic and Coriolis metering. Many users, however, cling to the ‘tried, true and tested’ technologies of yesteryear for the very reason that an on-site meter prover skid ***is*** available and that calibration can be verified immediately.

6.4 Oscillatory (Chapter 4 of Appendix A)

This group includes vortex, vortex precession, and fluidic type meters – all involving different physical principles. The common denominator, however, is that in all three, the primary device generates an oscillatory motion of the fluid whose frequency is detected by a secondary measuring device that produces an output signal that is proportional to fluid velocity.

Since their introduction by Eastech in 1969 [9] and subsequently by Yokogawa in 1972 [10] the vortex flow meter has made huge strides in market penetration – especially in the field of steam metering where other technologies such as ultrasonic and Coriolis fall short due to the high temperatures encountered.

However, unlike magnetic, ultrasonic and Coriolis based meters, vortex meters are intrusive, with the bluff body producing an unrecoverable pressure drop – albeit a small one. Another problem is the requirement for comparatively long straight runs of piping after a discontinuity such as an elbow or a valve – typically a minimum of 40 pipe diameters. A further problem that plagued early models was their sensitivity to external vibration. This has largely been overcome through the use of digital signal processing but remains an area of concern.

6.5 Differential pressure (Chapter 5 of Appendix A)

Often referred to as 'head loss' meters, differential pressure flow meters encompass a wide variety of meter types that includes: orifice plates; V-cone, venturi tubes and nozzles; Lo-Loss tubes (that encompass the Dall tube); target meters, pitot tubes and variable area meters. Indeed, the measurement of flow using differential pressure is still the most widely used technology.

An important advantage of differential type meters over other instruments is that the measurement is based on the accurately measurable dimensions of the primary device and they do not necessarily require direct flow calibration. In addition, they offer excellent reliability, reasonable performance and modest cost. Furthermore, differential type meters can be used on liquid or gas applications[3].

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[3] *For gas flow applications account should be taken of the gas expansion factor (= 1 for liquid). See Chapter 5, Section 5.2.3 ('Gas flow') of Appendix A for further details.*

A long-held bias towards this technology, exemplified by the orifice plate, remains in force throughout the world despite a myriad of disadvantages:

- high permanent pressure head loss;
- poor accuracy – typically 2 to 3% at best;
- low turndown ratio[4] – typically from 3:1;
- accuracy is affected by fluctuations in the density, pressure and viscosity and by erosion and physical damage to the restriction;
- long straight pipe runs are required – for custody transfer applications, for example, the American Gas Association (AGA) requires 95 pipe diameters of straight pipe upstream of the measurement point;
- the output is not linearly related to flowrate – thus entailing square root extraction; and
- there are a large number of potential leakage points[5].

Even some of the perceived advantages, such as simple construction and relatively low cost, do not hold up well when examined a little closer. Yes, construction of the primary element, the orifice plate, is relatively simple. And yes, the primary element is relatively inexpensive. However, there is a lot of ancillary equipment associated with the primary element: the isolation valves; the impulse tubing; the 3- or 5-way valve manifold valve; and the differential pressure transmitter itself [11].

On relatively small pipelines, of 100 mm diameter (DN 100) or less, these costs, taken together as a system, can well exceed the cost of alternative technologies such as a magnetic or vortex metering.

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[4] *The turn-down ratio is the ratio of the maximum flow rate to the minimum flow rate. See Chapter 1, Section 1.9.2 of Appendix A for further details.*

[5] *See Chapter 5, Section 5.9.2 ('Multiple leakage points') of Appendix A for further details.*

However, several vendors have been at pains to address some of the issues. Companies including Honeywell [12], Emerson (Rosemount) [13], and ABB [14] have introduced Multivariable Pressure Transmitters that provide direct simultaneous measurement of not only of the differential pressure but also static pressure, and temperature. Built-in processing provides direct calculation of mass flow [15] and extends the turndown ratio to 10:1.

Another radical innovation, introduced by Emerson, is the Conditioning Orifice Plate [16]. In place of the conventional concentric round hole (orifice) through which the liquid flows the Conditioning Orifice Plate makes use of four equally spaced holes that are arranged in such a fashion as to leave a metal section of the plate in the centre of the pipe. This causes the flow to condition[5] itself as it is forced through the four holes. The arrangement reduces swirl and irregular flow profiles and removes the requirement for a flow conditioner to the extent that only a total of 4 pipe diameters (2D up-stream and 2D down-stream) is required. Furthermore, the discharge coefficient uncertainty (U_{Cd}), a major factor in determining accuracy, is in many cases reduced to ±0.5% from a typical value of ±1.0%.

A further innovation in the field of head loss metering is the V-Cone Flowmeter from McCrometer – a patented technology that features a centrally-located cone inside the flow tube that interacts with the fluid and creates a region of lower pressure immediately downstream of the cone. The pressure difference is measured between the upstream static line pressure tap, placed slightly upstream of the cone, and the downstream low pressure tap located in the downstream face of the cone.

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[5] *Flow conditioning ensures that the flow regime is a fully developed turbulent profile, free of swirl. See Chapter 1, Section 1.3.3 of Appendix A for further details.*

Major features of the V-Cone Flowmeter include:

- 0 to 3 diameters of upstream straight run piping and 0 to 1 diameters downstream;
- primary element accuracy of ±0.5% of reading with a repeatability of ±0.1% or better;
- turndown ratio 10:1 with Reynolds numbers as low as 8000; and
- suitable for use with dirty fluids.

6.6 Electromagnetic (Chapter 6 of Appendix A)

A period of some 120 years elapsed from Faraday's early experiments to measure the flow rate of the River Thames in 1832 to the introduction of the first practical electromagnetic flow meter by Tobimeter [17] in 1952. Since then more than 30 manufacturers have entered the arena and this type of meter generates more revenue than any other type. Magnetic flow meters are widely used in the potable water, wastewater and chemical industries. And because they can conform to sanitary requirements they are also widely used in the food and beverage and pharmaceutical industries.

Magnetic flow meters are almost the ideal flow meter. Positive features include:

- unrestricted pipe and therefore no pressure drop;
- short inlet/outlet sections (5D/2D);
- linear relationship between flow and measurement (no square root extraction required);
- insensitive to axisymmetrical flow profile changes (laminar to turbulent);
- turndown ratio of 40:1 or better;
- inaccuracy of better than ±0.1% of actual flow over full range;
- no recalibration requirements;
- bi-directional measurement;
- no taps or cavities; and
- not limited to clean fluids.

But, there is one major drawback to electromagnetic flow meters – they require a conductive fluid. This precludes their use to measure gases, steam, ultrapure water, and all hydrocarbons.

Huge strides have been made in reducing the limit for conductivity. For most modern d.c. field driven instruments the minimum conductivity was about 1 μS/cm. However modern instruments employ a variety of technologies, including capacitively coupled meters that can be used on liquids with conductivity levels down to 0.05 μS/cm. Although this is close to the upper hydrocarbon limit of 0.0017 μS/cm for crude oil it falls far short of even jet fuel (150 – 300 pS/cm).

Another disappointment is in the flow measurement of pure and ultrapure water. The conductivity of ultrapure water extends down to 0.1 μS/cm and would therefore appear to be covered by the extended range down to 0.05 μS/cm. However in order to meet these requirements use is made of very high input impedance amplifiers in the range 10^{13} to 10^{14} Ω or even more and these are very susceptible to electrical noise. Unfortunately water, being a bipolar vibratory molecule, produces relatively large amplitudes of electrical noise that tend to swamp the amplifiers used to gain this sensitivity.

Development effort is mainly centred on producing better reliability; better accuracy (already down to ±0.1%); and better automatic diagnostics to the correct functioning of the meter, based on signature analysis of the signal.

6.7 Ultrasonic (Chapter 7 of Appendix A)

First introduced in 1963 by Tokyo Keiki [18] there are now more than 35 manufacturers. Some of the earliest meters were based on the Doppler shift method and generally proved to be most unsatisfactory – with inaccuracies of up to 10%. The introduction of the transit time meter gave a well needed boost to the technology – albeit that the measurement was restricted to clean liquids. Early models used only a single path through the pipe, making the measurement extremely susceptible to variations in the flow profile – a measurement variation of up to 33% could be expected with a change from laminar to turbulent flow. The use of dual-path meters reduced the laminar/turbulent dependency to less than 1% but was offset by the increased cost.

However it was the only when Krohne [19] introduced their five-beam custody-transfer system into the oil and gas industry, following three years of trials, that the technology started to be taken seriously. The system was capable of providing accuracies of down to ±0.15% on liquids. Subsequently, several other companies have produced ultrasonic custody transfer meters making use of four to six beams.

The last observation, regarding ultrasonic flow meters, is that despite claims from a number of manufacturers, clamp-on meters have generally failed to produce any meaningful or consistent results. Indeed, their shortcomings have been so apparent that they have tended to tarnish the reputation of the ultrasonic technology as a whole. Because the ultrasonic beam must not only traverse the medium, but also the pipe wall plus any external coatings, each interface contributes an unspecified amount of refraction. Consequently, positioning the downstream transducer, in order to obtain a meaningful signal, proves very difficult indeed. Furthermore, any change in the characteristics of the liquid, which affects the speed of sound, will have a direct effect on the refraction angle.

6.8 Mass flow (Chapter 8 of Appendix A)

In the chemical industry, most reactions are realised on a stoichiometric basis which stresses the relationship between the relative quantities of the substances taking part in a reaction, rather than the volume. And thus a system that measured mass flow directly was a major breakthrough.

Traditionally the measurement of mass flow entailed measuring the volumetric flow rate and multiplying it by the measured density. Density measurement is normally achieved through the use of a nuclear gamma-ray based densitometer that is generally regarded as being expensive, imprecise, and potentially dangerous. The Coriolis meter measures mass flow directly, to a very high accuracy (better than ±0.1%). It is also capable of providing a direct read out of density. Indeed, in many applications, particularly the food and beverages industries, the measurement of density is often the prime measurement.

The two major challenges currently facing the manufacturers of Coriolis meters are pipeline size and pressure containment. Currently the largest pipeline size available is DN 300 (12 inches), available from Rheonik [20] making use of dual curved (Ω-shaped) shaped flow tubes. However, at this size the pressure is limited to 60 bar. A lot of research has also been aimed at further developing straight-tube technology. To this end, Krohne recently introduced a straight-tube model suitable for DN 250 (10 inch) and pressures up to 80 bar [21].

6.9 Open channel (Chapter 9 of Appendix A)

Little future development is expected in this field. Ninety percent of all applications make use of specialised ultrasonic level sensors capable of providing level measurement accuracy down to ±0.25%. Built-in software is now available that translates the level measurement into flow rate according to the discharge equation that is specific to the primary measuring element e.g. a weir or flume [22].

7 Future directions

A major gap in this collected a body of knowledge is specific to the oil and gas industry – the field of multiphase and water-cut metering. The remainder of this section details why this is such a crucial Issue.

7.1 The need for multiphase flow metering

During the life of an oil well the output components change dramatically. This is illustrated in Diagram 1 which shows how the delivery of oil and gas decreases over the life of the well with a commensurate increase in the delivery of water. In its early life a typical well might deliver 90% oil and less than 10% water. Ideally the gas cap forces the produced fluids out under pressure for some period of time. In midlife, as the gas cap pressure falls, pumps may be required to bring the fluids to the surface, which might now comprise about 50% oil and 50% water. In later life, with almost no gas, artificial lift is required in order to raise fluid to the surface and obtain maximum oil recovery which may now possibly comprise less than 20% oil and 80% or more water. Artificial lift systems include: rod pumping using a pumping jack (often referred to as a nodding donkey) as a prime mover; gas lifting (gas injection); hydraulic pumping (water injection); and centrifugal pumping. A combination of gas and/or water injection and pumps might be required to bring the fluid to the surface.

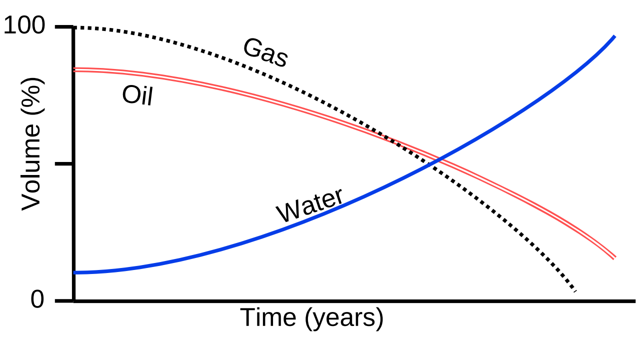

Diagram 1. Illustration showing how the delivery of oil and gas decreases over the life of the well with a commensurate increase in the delivery of water.

At the well-head surface, the three constituents (oil, gas, and water) are separated using a series of 2, 3 or more separators. A typical separator (as illustrated in Diagram 2) involves three principles to realise physical separation: momentum, gravity settling, and coalescing [23].

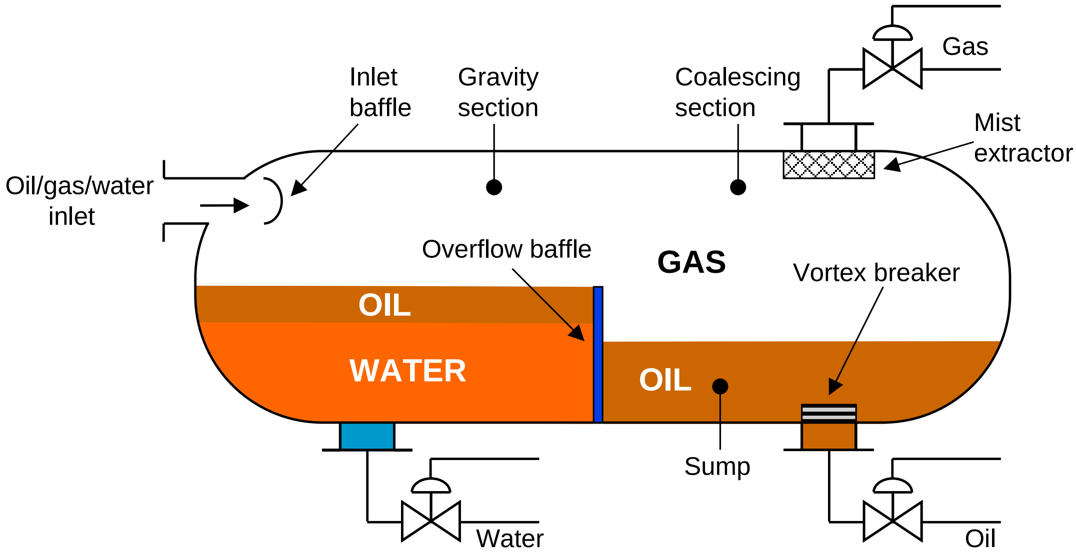

Diagram 2. A typical horizontal 3-phase separator.

In the representative system shown, the flow through the inlet nozzle impinges on a diverter baffle that produces an abrupt change of direction. Since the momentum of the heavier oil/water phase particles is greater than that of the gas, they cannot turn as rapidly and separation occurs.

Enhanced separation of the entrained droplets occurs in the gravity section where the gas moves at a relatively low velocity – with little turbulence. If the gravitational force acting on the droplet is greater than the drag force of the gas flowing around the droplet, liquid droplets will settle out of a gas phase.

In the coalescing section, a mist extractor (normally comprising a series of vanes or a knitted wire mesh pad) removes the very small droplets of liquid from the gas by impingement on a surface where they coalesce.

And finally, oil-water separation occurs in the sump where, using an overflow baffle, the two immiscible liquid phases (oil and water) separate within the vessel by virtue of their differences in density.

A critical factor that determines the efficacy of this process is that sufficient retention time be provided in the separator to allow for gravity separation to take place. This can vary from 30 seconds up to three minutes – depending on the size of the separator, the inflow, the gas/oil ratio (GOR) and the oil/water ratio.

The oil output from a first stage separator should typically contain 1 - 3% water with (possibly) up to 0.5% gas. The water output should typically contain less than 300 ppm of oil. In order to achieve this balance, tight control of the three component outflows must be applied which must be balanced against the inflow. And this, quite simply, is where the problem lies – accurate and reliable, simultaneous measurement of the input multiphase flow.

7.1.1 Multiphase flow

A multiphase mixture of three different components (oil, water and gas) is a complex phenomenon producing a variety of flow regimes whose distribution, in both space and time, differ from each. Several different types of flow regimes are illustrated in Diagram 3 and can be broadly grouped into: dispersed flow (bubble flow); separated (stratified and annular) and intermittent (piston and slug flow) [24]. Because they are dynamic, these flow regimes usually fall outside the control of an engineer or operator and are difficult to predict and model.[6]

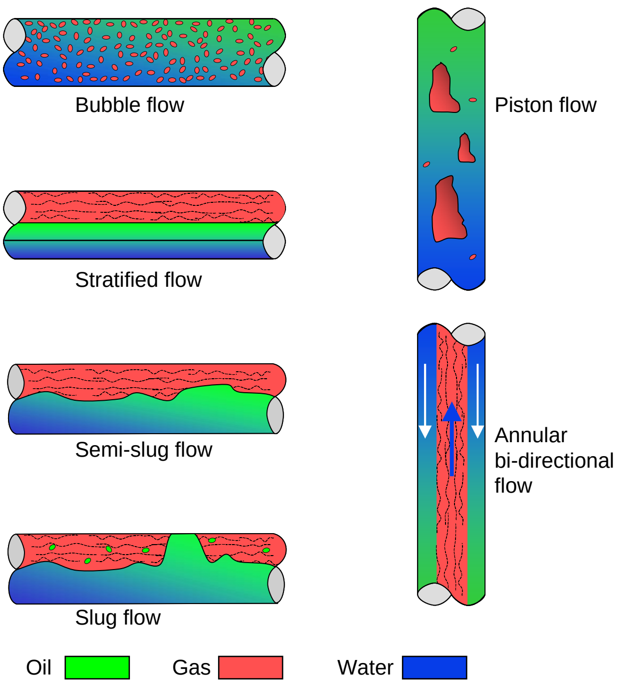

Diagram 3. Flow regimes can be broadly grouped into: dispersed flow (bubble flow); separated (stratified and annular) and intermittent (piston and slug flow).

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[6] *Akio Tomiyama, Masahiro Tanaka, et al, (Kobe University, Tokyo) have been working in the field of multiphase flow for the last 10 years. In recent computational work [25] they have demonstrated an ability to accurately model the three dimensional structure of multiphase flows – including time dependent variations in the shapes and sizes of the individual gas bubbles.*

It should be stressed that the flow regime illustrated in Diagram 3 showing annular bi-directional flow is only one of several possibilities. Generally, the liquid velocity in the film (which is likely to be a homogeneous mixture of oil and water) is in the upward direction adjacent to the gas – decreasing with increasing radial position so that it ***may*** be in the downward direction adjacent to the pipe wall.

7.1.2 Separation-type flow metering

The technology required to measure any one of these regimes is already complex. A further complicating consideration is that the multiphase mixture pressure may vary from almost 0 to 2000 bar and the temperature can vary from -40 to 200° C.

For a single technology to cover them all, borders on the insurmountable. On this basis, the traditional method is to split the multiphase steam into discrete phases, using a test separator, with the measurement taking place on a single phase (or in the case of oil-water mixtures, two phase) stream [26]. The compact upstream separation device provides a relatively liquid-free gas stream and a liquid stream – with each metered separately. The metering methods most commonly used are:

Gas: orifice plate; turbine
Liquid: orifice plate; turbine; Coriolis

A major problem with this method lies in separating the production stream into its component parts. Indeed, rarely can complete phase separation occur and entrapment of phases within each other is common [27].

7.1.3 In-line multiphase flow metering (MPFM)

Generally, full multiphase stream measuring systems make use of two or more sensors that combine the data to yield individual phase flow rates. A major difficulty in exploring the technologies used in multiphase flow metering is that manufacturers are inclined towards a high degree of secrecy in order to preserve their competitive edge in what could prove to be a highly rewarding and lucrative market. Estimates indicate that installed costs of a single MPFM can range from US$100,000 to US$500,000 – depending on size and application [28].

One such system, PhaseWatcher, from Schlumberger, comprises a Venturi tube combined with a nuclear dual energy fraction meter [29]. The Venturi tube is fitted with differential pressure, static pressure, and temperature measuring transducers for temperature corrected flow measurement. The nuclear measuring section comprises a Barium source and dual-energy fraction detector used to measure two different photon energy levels – high energy for measuring density and low energy to calculate the water-oil ratio.

Other technologies include: a combination of microwave sensor and positive displacement flowmeter (Agar), capacitance and inductance sensors (FlowSys, Roxar), and venturi tube and nuclear densitometers (Schlumberger, Haimo, Roxar).

Extensively tested by a large number of oil companies, conventional wisdom indicates that, despite claims by the vendors, no one solution appears to be totally satisfactory. The author's spot opinion poll, conducted amongst more than twenty current, and former facilities (topside offshore platforms) engineers and operational staff indicates a deep cynicism regarding the claims by many vendors and that often calibration is referenced back to both the empirical experience, and sometimes even priori feelings and instincts of, the operational staff.

7.2 Water-cut metering

Water-cut meters measure the water content (cut) of an oil/water mixture, expressed in % by volume, and are typically used in the oil and gas industry to measure: the water-cut of oil flowing from a well; produced oil from a separator; crude oil transfer in pipelines and in loading tankers. As with MPFM, several technologies are available including: oscillatory; capacitive; microwave dielectric; and infrared (IR).

One such system, from Phase Dynamics [30], makes use of 'oscillator load pull [7]' in which an RF oscillator (150 to 500 MHz) sets up a standing wave within a resonant chamber through which the oil/water mixture flows.

---

[7] *'Oscillator load pull' is a measure of how much an oscillator changes its frequency when the load that is connected to it changes.*

Because the relative permittivity (ε_r) of water (68 - 80) and oil (2.5) are very different, changes in the water-cut vary the velocity of the RF, which in turn, changes the phase. Ultimately, the phenomenon of 'oscillator load pull' changes the oscillator frequency itself – depending on the water content.

Another system from Weatherford [31] relies on the preferential absorption of infrared radiation in the 'near' region in which, at the operating frequency of the sensor, water is the transmitting phase while oil is the attenuating medium (Diagram 4).

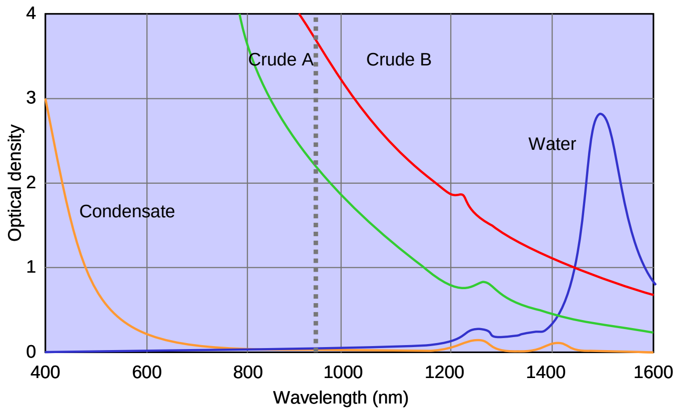

Diagram 4. Spectral properties of two crude oils compared with condensate and water (courtesy Weatherford).

Red Eye meters measure the volumetric proportion of oil in a mixture of oil and water by passing a beam of infrared light through the stream. Accuracy is maintained under a wide range of conditions by taking into account not only the directly transmitted beam, but also light scattered forward and backward across the gap. Water transmits close to 100% of the emitted radiation while crude oil typically transmits less than 10% of the light.

The Red Eye Water-Cut Meter claims not to be affected by variation or changes in the properties of the water since the NIR radiation does not interact with the components of field-produced brine.

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APPENDIX A

INDUSTRIAL FLOW MEASURMENT

INDUSTRIAL FLOW MEASUREMENT

Author: Michael A. Crabtree

11 Stallcourt Avenue
Llantwit Major
CF 61 1TE
UK

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Foreword

This handbook is presented in a form suitable for two distinct classes of reader: the beginner, with no prior knowledge of the subject; and the more advanced technician.

The complete text is suitable for the advanced reader. However, those parts of the text, which involve a mathematical treatment which are not required by the beginner, are indicated by a mark (▶) at the beginning and (◀) at the end. Consequently, for the beginner the text may be read, with full understanding, by ignoring the marked sections.

In this manner two complete books are available at two different levels for two distinct classes of reader.

Chapter 1. Basic properties of fluids

Chapter 1
Basic properties of fluids

1.1 Basic fluid properties

One of the most important primary properties of a fluid (liquid or gas) is its **viscosity** — its resistance to flow or to objects passing through it. Conceptually, viscosity might be thought of as the 'thickness' of a fluid. In essence it is an internal frictional force between the different layers of the fluid as they move past one another. In a liquid, this is due to the cohesive forces between the molecules whilst in a gas it arises from collisions between the molecules.

Different fluids possess different viscosities: treacle is more viscous than water and gearbox oil (SAE 90) is more viscous than light machine oil (for example 3-in-1). A comparison of various fluids is shown in Table 1.1.

Table 1.1. Comparison of the viscosities of various fluids.

Fluid	Temperature (°C)	Viscosity μ (Pa.s)
Molasses	20	100
Glycerine	20	1.5
Engine oil (SAE 10)	30	0.2
Milk	20	5×10^{-3}
Blood	37	4×10^{-3}
Water	0	1.8×10^{-3}
Ethyl alcohol	20	1.2×10^{-3}
Water	20	1×10^{-3}
Water	100	0.3×10^{-3}
Air	20	0.018×10^{-3}
Water vapour	100	0.013×10^{-3}
Hydrogen	0	0.009×10^{-3}

If the fluid is regarded as a collection of moving plates, one on top of the other, then when a force is applied to the fluid, shearing occurs and the viscosity is a measure of the resistance offered by a layer between adjacent plates.

Figure 1.1 shows a thin layer of fluid sandwiched between two flat metal plates of area A — the lower plate being stationary and the upper plate moving with velocity v. The fluid directly in contact with each plate is held to the surface by the adhesive force between the molecules of the fluid and those of the plate. Thus the upper surface of the fluid moves at the same speed v as the upper plate whilst the fluid in contact with the stationary plate remains stationary. Since the stationary layer of fluid retards the flow of the layer just above it and this layer, in turn, retards the flow of the next layer, the velocity varies linearly from zero to V, as shown.

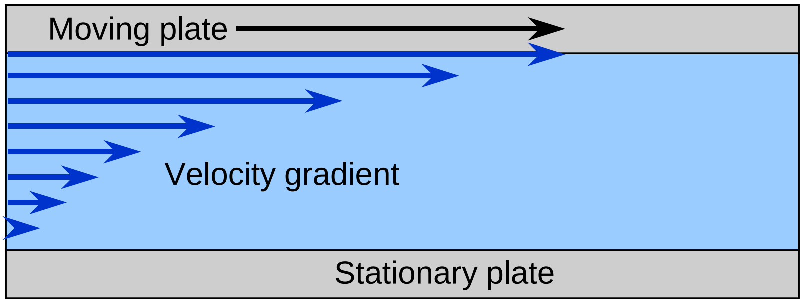


Figure 1.1. When a thin layer of fluid is sandwiched between two flat metal plates, shearing occurs and the upper surface of the fluid moves at the same speed as the upper plate whilst the fluid in contact with the stationary plate remains stationary.

▶ The relative force acting on the layers is called the ***shear stress*** (the force per unit area). In Figure 1.1, the fluid flows under the action of the shear stress due to the motion of the upper plate. It is also clear that the lower plate exerts an equal and opposite shear stress to satisfy a 'no-slip' condition at the lower stationary surface.

It follows, therefore, that at any point in the flow, the velocity at which the layers move relative to each other, referred to as the ***shear rate***, is directly proportional to the shear stress :

Shear rate ∝ Shear stress

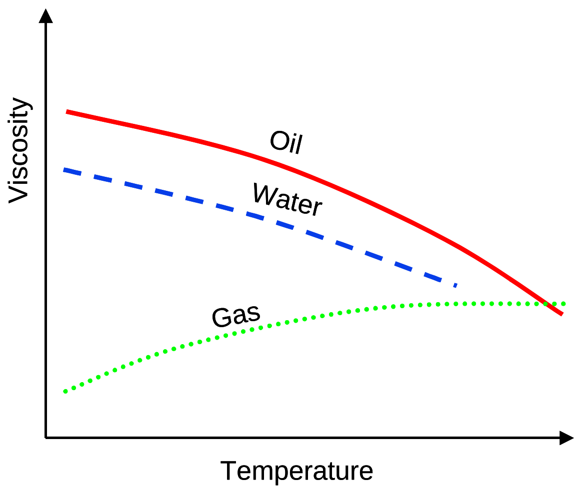
or: **Shear stress = μ. Shear rate**

where μ is the ***viscosity*** — the ratio of shear stress and shear rate.

These days, viscosity is expressed as ***absolute or dynamic viscosity*** measured in Pascal-Seconds (Pa.s).

Formerly, viscosity was expressed as ***relative viscosity*** – the ratio of the liquid's absolute viscosity with respect to the viscosity of water. Here, the unit of measurement was the centipoise (cP) or, in the case of gases, micropoise (μP) where:

1 Pa.s = 1000 cP



As shown in Figure 1.2, the viscosity of a fluid depends strongly on temperature and generally decreases when the temperature increases. Gases, however, show the opposite behaviour and the viscosity increases for increasing temperature.

Figure 1.2. The viscosity of fluids is strongly dependent on temperature.

Subsequently, Table 1.1 lists the viscosity of various fluids at specified temperatures – with the viscosity of liquids such as motor oil, for example, decreasing rapidly as temperature increases.

The viscosity of a fluid also depends on pressure but, surprisingly, pressure has less effect on the viscosity of gases than on liquids.

A pressure increase from 0 to 70 bar (in air) results in only an approximate 5% increase in viscosity. However, with methanol, for example, a 0 to 15 bar increase results in a 10-fold increase in viscosity. Some liquids are more sensitive to changes in pressure than others.

Viscosity related to the density of a fluid is termed the ***kinematic viscosity***. Kinematic viscosity is given by:

$$v = \mu / \rho$$

where:

v = kinematic viscosity measured in m^2/s;
μ = dynamic viscosity measured in Pa.s; and
ρ = density of the liquid (kg/m^3).

Kinematic viscosity was formerly measured in centistokes (cSt) where:

$$1 \; m^2/s = 10^6 \; cSt$$

1.2 Non-Newtonian fluids

Most fluids used in engineering systems exhibit Newtonian behaviour in that, for a given value of pressure and temperature, the shear stress is directly proportional to the shear rate. Thus, if the shear stress is plotted against shear rate the result is a straight line passing through the origin (Figure 1.3).

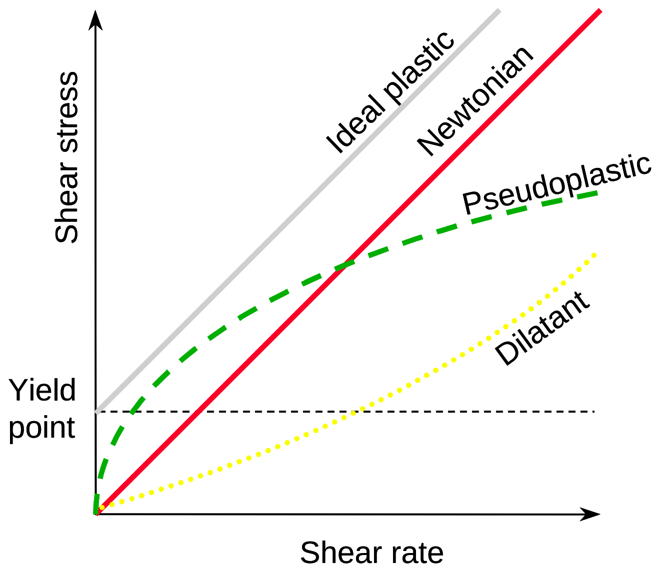


Figure 1.3. The shear stress plotted against shear rate for a number of materials. For Newtonian materials the shear stress plotted against shear rate results in a straight line passing through the origin.

Certain fluids, however, do not exhibit this behaviour. Examples include: tar, grease, printers' ink, colloidal suspensions, hydrocarbon compounds with long-chain molecules, and polymer solutions. In addition, some fluids, called viscoelastic fluids, do not immediately return to a condition of zero shear rate when stress is removed.

1.2.1 The ideal plastic

The so-called ***Ideal plastics*** or ***Bingham fluids*** exhibit a linear relationship between shear stress and shear rate. However, such substances only flow after a definite yield point has been exceeded (Figure 1.3).

When at rest, these materials possess sufficient rigidity to resist shear stresses smaller than the yield stress. Once exceeded, however, this rigidity is overcome and the material flows in much the same manner as a Newtonian fluid.

Examples of materials exhibiting this type of behaviour include: tar; chewing gum; grease; slurries; sewage slugs; and drilling muds.

1.2.2 Pseudoplastic

A pseudoplastic substance, such as printer's ink, is characterised by polymers and hydrocarbons which possess long-chain molecules and suspensions of asymmetric particles. Although exhibiting a zero yield stress, the relationship between shear stress and shear rate is non-linear and the viscosity decreases as the shear stress increases.

1.2.3 Dilatant

Dilatant materials also exhibit a non-linear relationship between shear stress and shear rate and a zero yield stress. However, in this case, the viscosity increases as the shear stress increases.

This type of behaviour is found in highly concentrated suspensions of solid particles. At low rates of shear, the liquid lubricates the relative motion of adjacent particles, thereby maintaining relatively low stress levels. As the shear rate increases, the effectiveness of this lubrication is reduced and the shear stresses are increased. ◀

1.3 Velocity profiles

One of the most important fluid characteristics affecting flow measurement is the shape of the velocity profile in the direction of flow.

1.3.1 Ideal profile

In a frictionless pipe in which there is no retardation at the pipe walls, a flat 'ideal' velocity profile would result (Figure 1.4) in which all the fluid particles move at the same velocity.

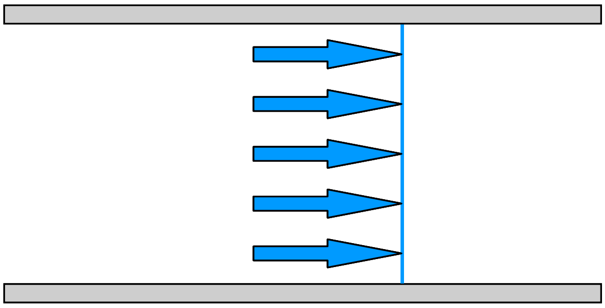


Figure 1.4. A flat 'ideal' velocity profile.

1.3.2 Laminar flow

We have already seen, however, that real fluids do not 'slip' at a solid boundary but are held to the surface by the adhesive force between the fluid molecules and those of the pipe. Consequently, at the fluid/pipe boundary, there is no relative motion between the fluid and the solid.

At low flow rates the fluid particles move in straight lines in a laminar manner — with each fluid layer flowing smoothly past adjacent layers with no mixing between the fluid particles in the various layers. As a result the flow velocity increases from zero, at the pipe walls, to a maximum value at the centre of the pipe and a velocity gradient exists across the pipe.

The shape of a fully developed velocity profile for such a laminar flow is parabolic, as shown in Figure 1.5, with the velocity at the centre equal to twice the mean flow velocity. Clearly, if not corrected for, this concentration of velocity at the centre of the pipe can compromise the flow computation.

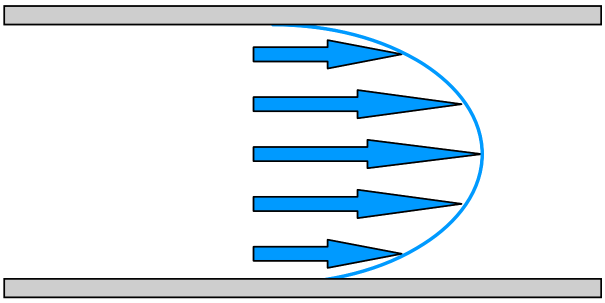


Figure 1.5. A laminar 'parabolic' velocity profile.

1.3.3 Turbulent flow

One of the earliest investigators into fluid flow was Osborne Reynolds (1842-1912) who conducted a number of experiments using what is now termed a Reynolds instrument – a device that injects ink into the flow stream (Figure 1.6).

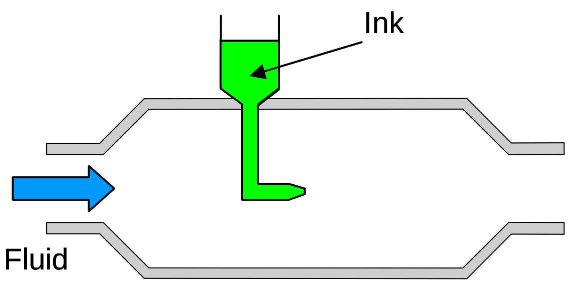


Figure 1.6. Reynolds's instrument injects ink into the flow stream in order to observe the flow regime (Courtesy Emerson).

For a given pipe and liquid, as the flow rate increases, the laminar path of an individual particle of fluid is disturbed and is no longer straight. This is called the transitional stage (Figure 1.7).

As the velocity increases further the individual paths start to intertwine and cross each other in a disorderly manner so that thorough mixing of the fluid takes place. This is termed turbulent flow.

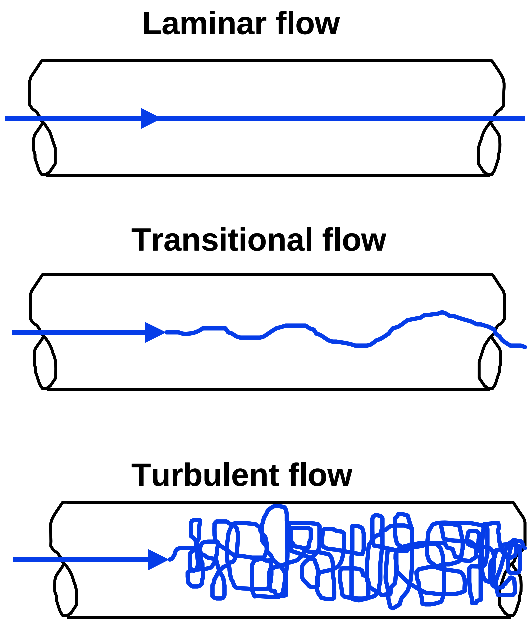


Figure 1.7. Transition from laminar through to turbulent flow.

Since the flow velocity is almost constant in all of the pipe cross section, the velocity profile for turbulent flow is flatter than for laminar flow and thus closer approximates the 'ideal' or 'one dimensional' flow (Figure 1.8).

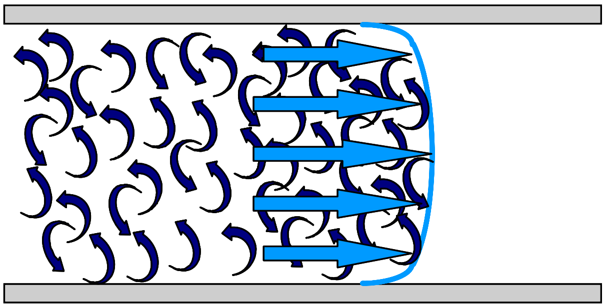


Figure 1.8. A turbulent velocity profile.

1.4 Reynolds number

▶ The onset of turbulence is often abrupt and to be able to predict the type of flow present in a pipe, for any application, use is made of the Reynolds number, Re — a dimensionless number given by:

$$\text{Re} = \frac{\rho \cdot v \cdot d}{\mu}$$

where:

ρ = density of fluid (kg/m^3)
μ = viscosity of fluid (Pa.s)
v = mean flow velocity (m/s)
d = diameter of pipe (m).

Irrespective of the pipe diameter, type of fluid, or velocity, Reynolds showed that the flow is:

Laminar: Re < 2000
Transitional: Re = 2000 - 4000
Turbulent: Re > 4000

From the foregoing it is seen that, in addition to viscosity, Re also depends on density. Since most liquids are pretty well incompressible, the density varies only slightly with temperature. However, for gases, the density depends strongly on the temperature and pressure in which (for ideal gas):

$$PV = mRT$$

where:

P	=	pressure (Pa);
V	=	volume of the gas (m^3);
T	=	temperature (K)
m	=	number of moles; and
R	=	universal gas constant (8,315 J/(mol.K))

Since:

$$\rho = m/V = P/RT$$

Most gases may be considered ideal at room temperatures and low pressures. Both, laminar and turbulent flow profiles require time and space to develop. At an entrance to a pipe, the profile may be very flat – even at low Re. And it may stay laminar, for a short time, even at high Re.◀

1.5 Disturbed flow profiles

Obstructions in a pipe, such as bends, elbows, reducers, expanders, strainers, control valves, and T-pieces, can all affect the flow profile in a manner that can severely affect measurement accuracy.
Such disturbed flow, which should not be confused with turbulent flow, gives rise to a number of effects that include:
Swirl — fluid rotation about the pipe axis.
Vortices — areas of swirling motion with high local velocity which are often caused by separation or a sudden enlargement in pipe area.
Asymmetrical profile — see Figure 1.9
Symmetrical profile with high core velocity — caused by a sudden reduction in pipe area.

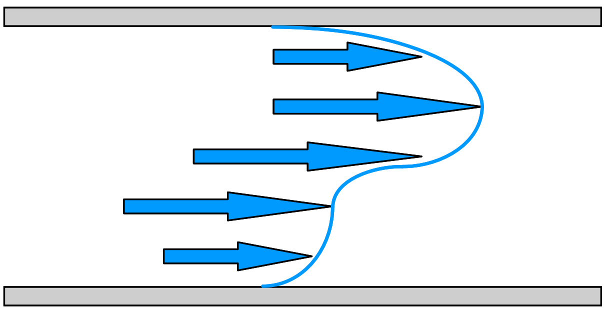


Figure 1.9. Asymmetric flow profile due to disturbed flow.

Ultimately the flow profile will be restored by the natural mixing action of the fluid particles as the fluid moves through the pipe. However, the effect of such disturbances can have an important bearing on accuracy for as much as 40 pipe diameters upstream of the measuring device. Figure 1.10 shows the ongoing disturbance in a pipe following a simple elbow.

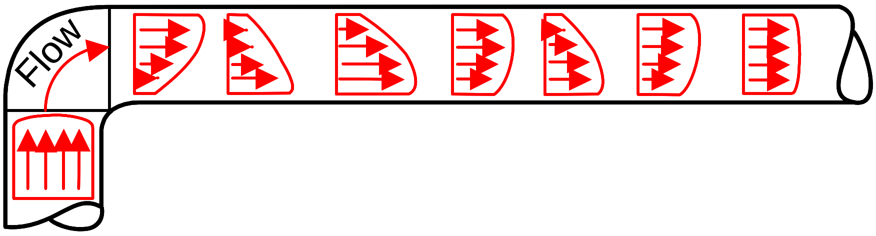


Figure 1.10. Ongoing disturbance in a pipe following a simple elbow.

1.6 Flow measurement

In flow measurement a number of parameters can be used to describe the rate at which a fluid is flowing:

1.6.1 Volumetric flow rate

The volumetric flow rate, Q, represents the total volume of fluid flowing through a pipe per unit of time and is usually expressed in litres per second (ℓ/s) or cubic metres per hour (m^3/h). The measurement of volumetric flow rate is most frequently achieved by measuring the mean velocity of a fluid as it travels through a pipe of known cross sectional area A (Figure 1.11).

$$Q = v \bullet A$$

Thus:

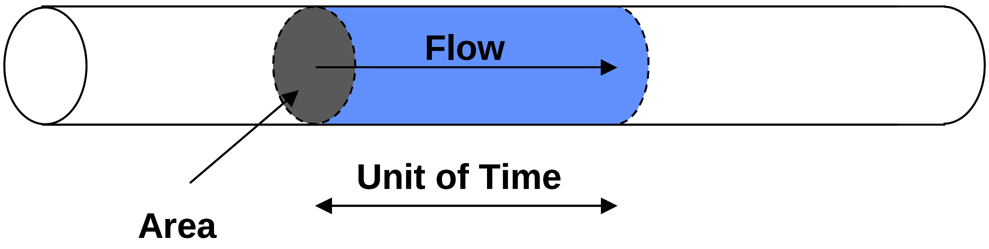


Figure 1.11. The volumetric flow rate, Q, represents the total volume of fluid flowing through a pipe per unit of time.

1.6.2 Velocity

The term velocity is often used very loosely to describe the speed at which the fluid passes a point along the pipe. In reality, most modern flowmeters measure either the point velocity or the mean velocity.

1.6.3 Point velocity

The point velocity is the flow velocity in a localised region or point, in the fluid and is, generally of little use in practice. It is used mainly in research to determine, for example, velocity profiles or flow patterns.

1.6.4 Mean flow velocity

▶ The mean flow velocity, $\bar{v}$, can be obtained by measuring the volumetric flowrate, Q, and dividing it by the cross-sectional area of the pipe, A:

$$\bar{v} = \frac{Q}{A}$$

Alternatively, if the velocity profile is known the mean flow velocity can be obtained by averaging the velocity over the velocity profile, giving equal weight to equal annular regions.

An example of the calculation of the mean velocity of the flow conduit by area-weighting point-velocity measurements is illustrated in Figure 1.12. As shown, a number of velocity bands are scaled across the cross-sectional area of a 320 mm diameter conduit.

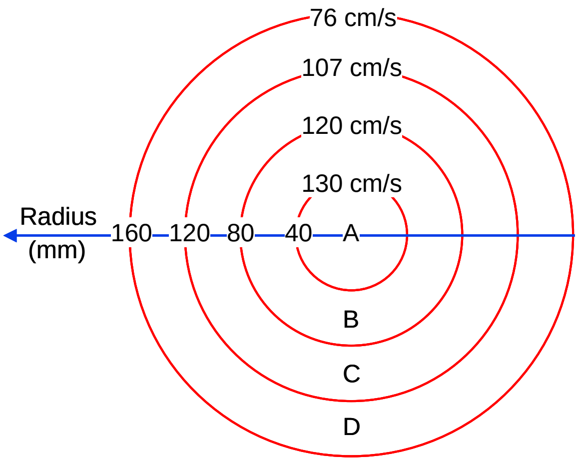


Figure 1.12. Example of area weighted technique for determining the mean velocity of a fluid.

The mean velocity can be determined using standard averaging techniques in which the velocities of each band are summed and then divided by the number of bands:

$$V_{AV} = \frac{V_A + V_B + V_C + V_D}{4} = 108.25$$

In the area-weighted technique, the scaled areas, velocities and products of each area, times its local velocity, are tabulated for each velocity band (Table 1.2). The area-weighted mean velocity is calculated by summing the velocity-area products, and dividing the sum of the cross-sectional area of the flow conduit.

Table 1.2. Calculations for determination of area-weighted mean velocity

Band	**Radius (cm)**	**Velocity (cm/s)**	**Area (cm^2)**	**$V_n . A_n$**
A	4.0	130	50.26	6533
B	8.0	120	150.80	18096
C	12.0	107	251.33	26892
D	16.0	76	351.86	26741
Total			**804.25**	**78262**

$$\overline{V} = \frac{(V_n \cdot A_n)}{Total\, area} = 97.31 cm/s$$

The error thus obtained using the standard averaging technique is:

$$Error = \frac{\left(V_{AV} - \overline{V}\right)}{V_{AV}} = 10.11\%$$

◀

1.7 Mass flow rate

Most chemical reactions are largely based on their mass relationship and, consequently, in order to control the process more accurately, it is often desirable to measure the mass flow of the product. The mass flow rate, W, gives the total mass of fluid flowing at any instant in time. A knowledge of volume flow rate, Q and the fluid density, ρ, determines the mass flow rate from:

$$W = Q.\rho \quad (kg/s)$$

Some flowmeters, such as Coriolis meters, measure the mass flow directly. However, in many cases, mass flow is determined by measuring the volumetric flow and the density and then calculating the mass flow as shown above. Sometimes the density is inferred from the measurement of the pressure and temperature of the fluid. This type of measurement is referred to as the inferred method of measuring mass flow.

1.8 Flow range and rangeability

Whilst there is considerable confusion regarding basis terminology used in the field of instrumentation in general, nowhere is this more evident than in the differences between the terms flow range, turndown ratio, span, and rangeability. Whilst the following terms are those prescribed by the ISA they are by no means adhered to either by different organisations and manufacturers.

1.8.1 Flow range

The ***flow range*** is simply the difference between the maximum and minimum flow rate over which a meter produces acceptable performance within the basic accuracy specification of the meter. This is illustrated in Figure 1.13.

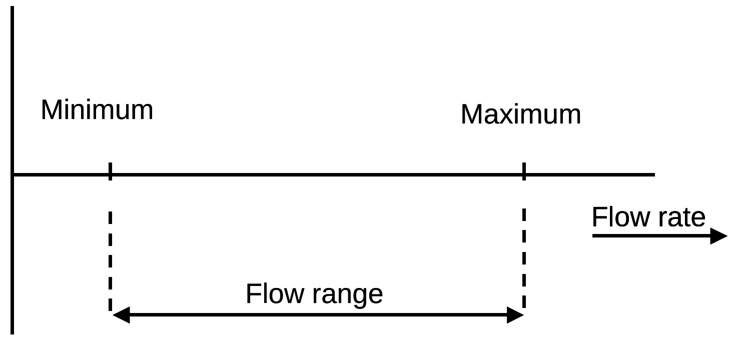


Figure 1.13. The flow range is the difference between the maximum and minimum flow rate over which a meter produces acceptable performance within the basic accuracy specification of the meter.

For flowmeters that exhibit a minimum flowrate, the flow range is thus the interval from the minimum flow rate to the maximum flowrate. If the meter does not exhibit a minimum flow rate, the flow range is the interval from zero flow to maximum flow.

1.8.2 Turn-down ratio

The turn-down ratio is the ratio of the maximum flow rate to the minimum flow rate for a measuring range that is within a stated accuracy. For example, the measuring range of a magnetic flow meter might be 0.3 m/s to 12 m/s within an accuracy of 0.3%. This would thus be stated as having a 40:1 turndown ratio (0.3 %). In addition the measuring range might extend from 0.2 m/s to 12 m/s within an accuracy of 0.5%. In this case the turndown ratio is 60:1 (0.5%). It is, therefore, meaningless to express the turndown ration without a specified accuracy.

1.8.3 Span

The term span relates to the flowmeter output signals and is the difference between the upper and lower range values assigned to the output signal.

For example, for a Coriolis meter having a 4-20 mA analog output the upper and lower range values might be assigned as:

Lower range value: 4 mA = 0 kg/h
Upper range value: 20 mA = 5000 kg/h

The span is thus the difference between the two values, i.e. 5000 - 0 = 5000 kg/h. The minimum span is the lowest flowrate able to produce full-scale output and the maximum span is equal to the maximum range of the sensor.

1.8.4 Rangeability

Rangeability is a measure of how much the flow range of an instrument can be adjusted and is defined as the ratio of the maximum flow range (maximum span) and the minimum span.

The term rangeability is often confused with turndown ratio and users should be careful as to what is actually meant when the terms are uses.

1.8.5 Accuracy

The accuracy of a flowmeter is the maximum deviation between the meter's indication and the true value of the flow rate or of the total flow. Accuracy, also referred to as uncertainty, is the interval within which the true value of the measured quantity can be expected to lie within a stated probability (generally taken to be 95 % unless otherwise specified). Accuracy includes the combined errors due to linearity, hysterisis and repeatability and can be expressed in any one of three ways: as a percentage of span; as a percentage of a rate; or as a percentage of the upper range value.

To illustrate this difference, consider three flowmeters: one with an accuracy of ±1 % of span; one with an accuracy of ± 1 % of a reading; and one with an accuracy of ±1 % of URL (Upper Range Limit). The URL is defined as the highest flowrate that a meter ***can*** be adjusted to measure whilst the Upper Range Value (URV) is defined as the highest flowrate that the meter ***is*** adjusted to measure. Each meter has a URL of 100 ℓ/min, and is calibrated 0 to 50 ℓ/min.

For the percentage of span instrument, the absolute error is determined at the 100 % span reading, and then used to determine the accuracy at lower flow rates. Since the span is 50 ℓ/min the absolute error would be ±1 % of 50, or ±0.5 ℓ/min. The accuracy of the meter at 50 ℓ/min would be 50 ℓ/min ±0.5 ℓ/min, or ±1 %. And at 25 ℓ/min the accuracy at would be 25 ℓ/min ±0.5 ℓ/min, or ±2 % (Figure 1.14).

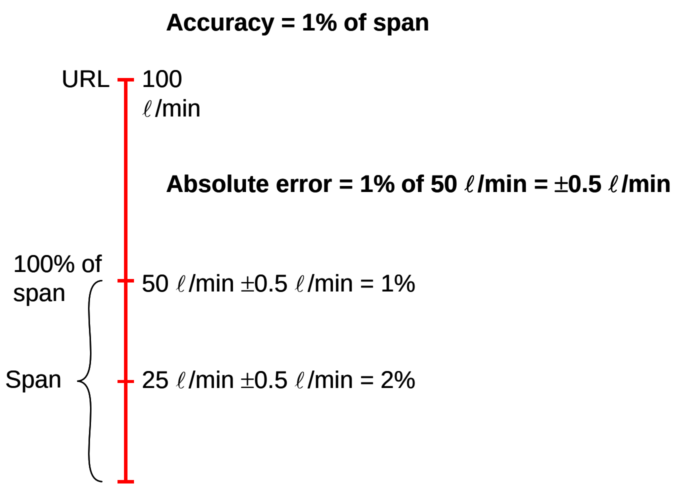


Figure 1.14. In the percentage of span instrument, the absolute error is determined at the 100 % span reading, and then used to determine the accuracy at lower flow rates.

For the percentage of reading instrument, the absolute error is determined at the actual reading, and varies with flow rate. The absolute error at 50 ℓ/min is ±1 % of 50, or ±0.5 ℓ/min. The absolute error at 25 ℓ/min is ±1 % of 25, or ±0.25 ℓ/min. This means the meter has a constant accuracy of ±1 % at all readings (Figure 1.15).

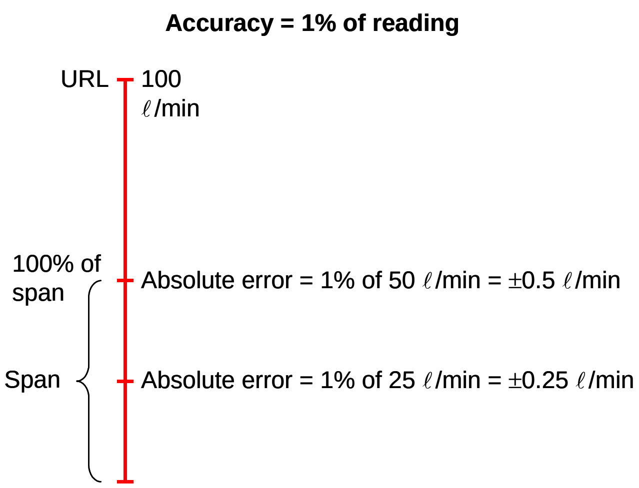


Figure 1.15. In the percentage of reading instrument, the absolute error is determined at the actual reading, and varies with flow rate.

For the percentage of URL instrument, the absolute error is determined at the URL and then used to determine the accuracy at lower flow rates. The absolute error would be ±1 % of 100, or ± 1 ℓ/min. The accuracy of the meter at 50 ℓ/min would be 50 ℓ/min ±1 ℓ/min, or ±2 %. The accuracy at 25 ℓ/min would be 25 ℓ/min at ±1 ℓ/min, or ±4 % (Figure 1.16).

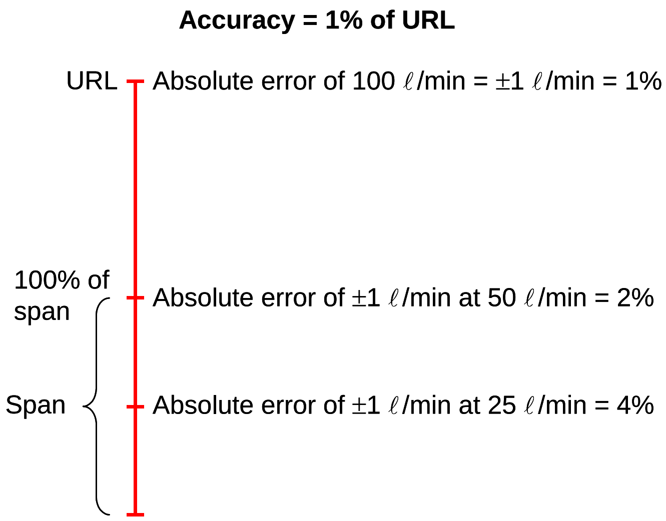


Figure 1.16. In the percentage of URL instrument of, the absolute error is determined at the URL and then used to determine the accuracy at lower flow rates.

In the above example, or three meters would have the same accuracy, ±1 %, when calibrated at the URL, 100 ℓ/min. Percentage of range meters are generally preferred when operating over a wide flowrate range.

1.9 Pipe sizes

Pipes are rated according to their size and pressure ratings.
The size, the normal pipe diameter, is given according to a preferred series – either in inches (ANSI specification) or in mm (DN series) where DN = nominal diameter according to Table 1.3.

Table 1.3. Nominal pipe diameters.

Pipe diameter in inches (ANSI)	**Pipe diameter in mm (DN)**	**Pipe diameter in inches (ANSI)**	**Pipe diameter in mm (DN)**
0.5	15	8	200
0.75	20	10	250
1	25	12	300
1.5	40	14	350
2	50	16	400
3	80	24	600
4	100	36	900
6	150	48	1200

Chapter 2. Positive displacement meters

Industrial Flow Measurement

Chapter 2

Positive Displacement Meters

2.1 Introduction

Positive displacement meters (sometimes referred to as direct volumetric totalisers) all operate on the general principle where defined volumes of the medium are separated from the flow stream and moved from the inlet to the outlet in discrete packages.

Totalising the number of packages provides the total volume passed and the total volume passed in a given time provides the flow rate, for example, litres/min.

Because they pass a known quantity, they are ideal for certain fluid batch, blending and custody transfer applications. They give very accurate information and are generally used for production and accounting purposes.

2.2 Sliding vane

Used extensively in the petroleum industry for gasoline and crude oil metering, the sliding vane meter is one of the highest performance liquid positive displacement meters. In its simplest form it comprises a rotor assembly fitted with four spring-loaded sliding vanes so that they make constant contact with the cylinder wall (Figure 2.1). The rotor is mounted on a shaft that is eccentric to the centre of the meter chamber.

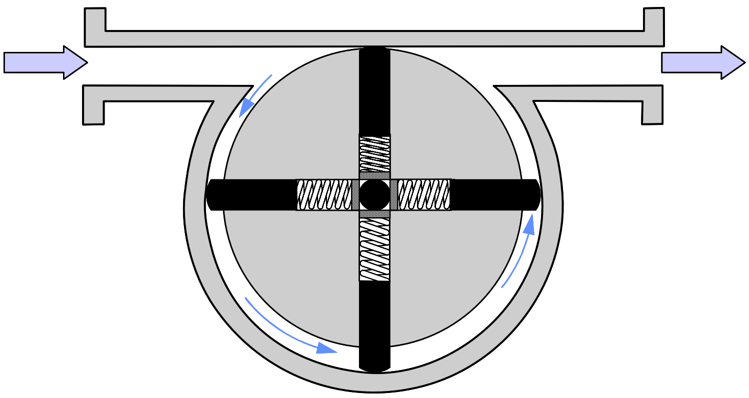


Figure 2.1. Sliding vane positive displacement meter comprising a rotor assembly fitted with four spring-loaded sliding vanes.

As liquid enters the measuring chamber the pressure on the exposed portion of vane 1 causes the rotor to turn. While the rotor turns on its shaft, vane 2 moves to seal off the inlet port — rotating to occupy the position formerly occupied by vane 1.

This process is repeated, without pulsations, as the vanes move around the measuring chamber — with 'packets' of fluid trapped and passed to the outlet manifold as discrete known quantities of fluid.

A mechanical counter register or electronic pulse counter is attached to the shaft of the rotor so that flow volume is directly proportional to shaft rotation.

Close tolerances and carefully machined profiles of the casing ensure the blades are guided smoothly through the measuring crescent to give high performance.

Advantages of the sliding vane meter include:

- suitable for accurately measuring small volumes;
- High accuracy of ± 0.2%;
- high repeatability of ± 0.05%;
- turndown ratio of 20:1;
- suitable for high temperature service, up to 180°C;
- pressures up to 7 Mpa; and
- not affected by viscosity.

Disadvantages of the sliding vane meter include:

- suitable for clean liquids only;
- limitations due to leakage; and
- high unrecoverable pressure loss.

2.3 Oval gear meters

Oval gear flow meters comprise two identical precision moulded oval rotors which mesh together by means of gear teeth around the gear perimeter. The rotors rotate on stationary shafts which are fixed within the measuring chamber (Figure 2.2).

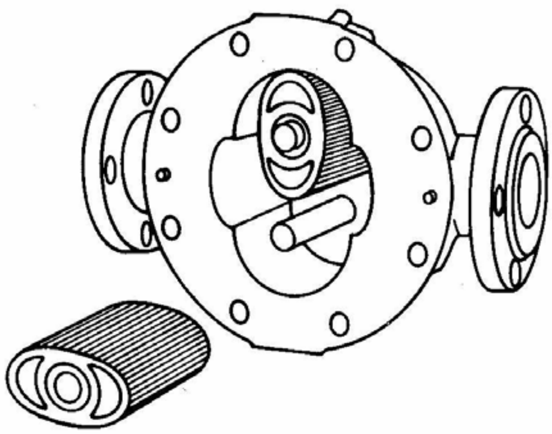


Figure 2.2. Construction of the oval gear meter (courtesy Emerson).

The meshed gears seal the inlet from the outlet flow, developing a slight pressure differential across the meter that results in movement of the oval rotors.

When in the position shown in Figure 2.3(a), Gear A receives torque from the pressure difference while the net torque on Gear B is zero. (b) Gear A drives Gear B. (c) As Gear B continues to rotate, it traps a defined quantity of fluid until, in this position, the net torque on Gear A is zero and Gear B receives torque from the pressure difference. (d) Gear B drives

Gear A and a defined quantity of fluid is passed to the outlet. This alternate driving action provides a smooth rotation of almost constant torque without dead spots.

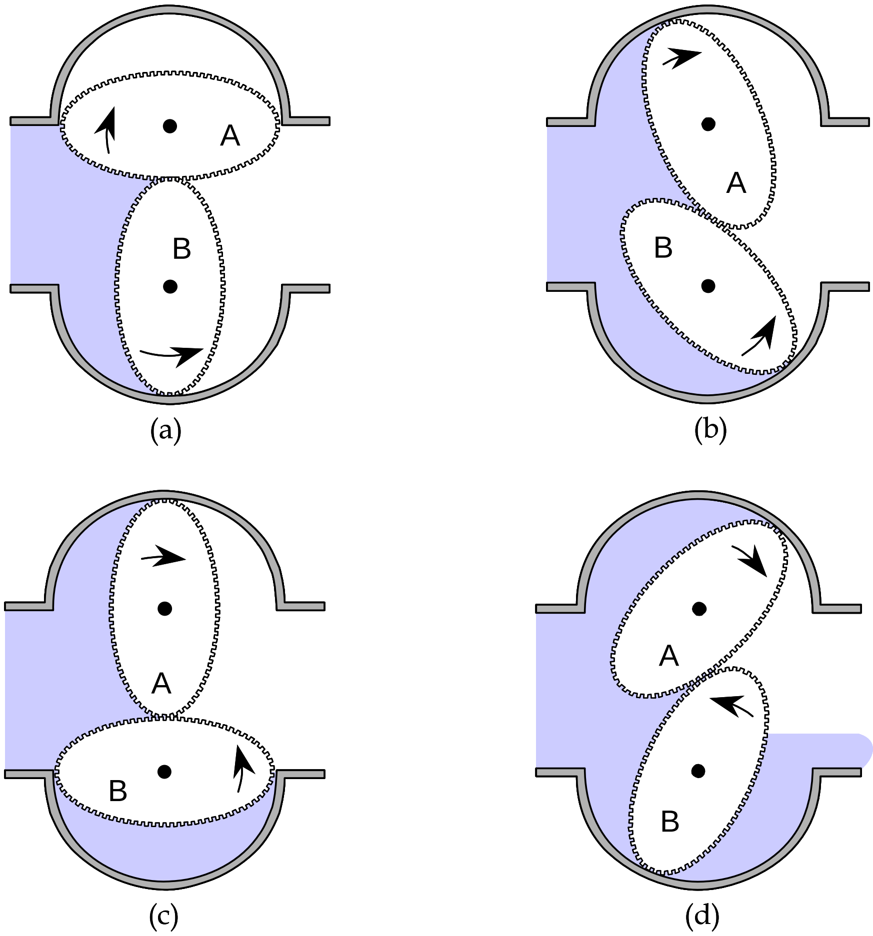


Figure 2.3. Principle of the oval gear meter: (a) Gear A receives torque from the pressure difference while the net torque on Gear B is zero. (b) Gear A drives Gear B. (c) As Gear B continues to rotate it traps a defined quantity of fluid until in this position, the net torque on Gear A is zero and Gear B receives torque from the pressure difference. (d) Gear B drives Gear A and a defined quantity of fluid is passed to the outlet.

With flow through the meter, the gears rotate and trap precise quantities of liquid in the crescent shaped measuring chambers. The total quantity of flow for one rotation of the pair of oval gears is four times that of the crescent shaped gap and the rate of flow is proportional to the rotational speed of the gears.

Because the amount of slippage between the oval gears and the measuring chamber wall is minimal, the meter is essentially unaffected by changes in viscosity and lubricity of the liquids.

An output shaft is rotated in direct proportion to the oval gears by means of a powerful magnetic coupling. Oval gear meters find widespread use in the measurement of solvents, with close tolerances ensuring that leakage is minimised.

The major disadvantage of this meter is that the alternate driving action is not constant and, as a result, the meter introduces pulsations into the flow.

Further, the viscosity of the fluid can affect the leakage or slip flow. If the meter is calibrated on a particular fluid, it will read marginally higher should the viscosity increase.
Newer designs of this type of meter use servomotors to drive the gears. These eliminate the pressure drop across the meter and the force required to drive the gear. This appliesmainly to smaller sized meters and significantly increases the accuracy at low flows.

Advantages of the oval gear meter include:

- high accuracy of ± 0.25%;
- high repeatability of ± 0,05%;
- low pressure drop of less than 20 kPa;
- high operating pressures, up to 10 MPa;
- high temperatures, up to 300 °C; and
- wide range of materials of construction.

Disadvantages of the oval gear meter include:

- pulsations caused by alternate drive action; and
- accuracy dependent on viscosity.

2.4 Lobed impeller

Similar in operation to the Oval meter, the lobed impeller type meter (Figure 2.4) is a non-contact meter comprising two high precision lobed impellers which are geared externally and which rotate in opposite directions within the enclosure. For each revolution four measured ‘cups’ of the fluid are transferred through the meter with an accuracy of up to 0,2% under controlled conditions. The lobed impeller meter is suitable for a wide range of fluids ranging from LPG through to tar in the ranges from 4 litres to 200 kilo-litres/hr, process temperatures up to 300 °C, and pressures up to 10 MPa.

The main disadvantages include:

- Poor accuracy at low flow rates.
- Temperature of process medium limited to about 60°C
- Bulky and heavy.
- Expensive.
- Pulsations caused by alternate drive action
- Accuracy dependent on viscosity

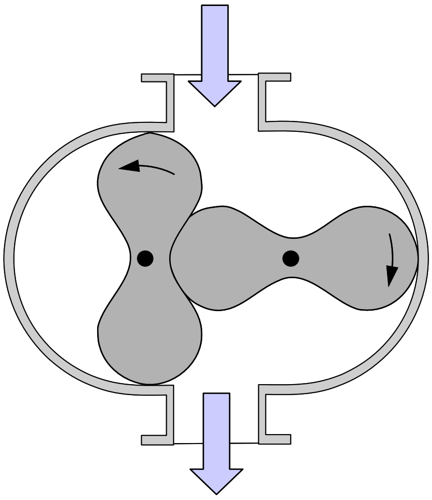


Figure 2.4. Lobed impeller meter (courtesy Tokico Ltd).

2.5 Oscillating piston

The oscillating or rotating piston meter consists of a stainless steel housing and a rotating piston as shown in Figure 2.5. The only moving part in the measuring chamber is the oscillation piston which moves in a circular motion.

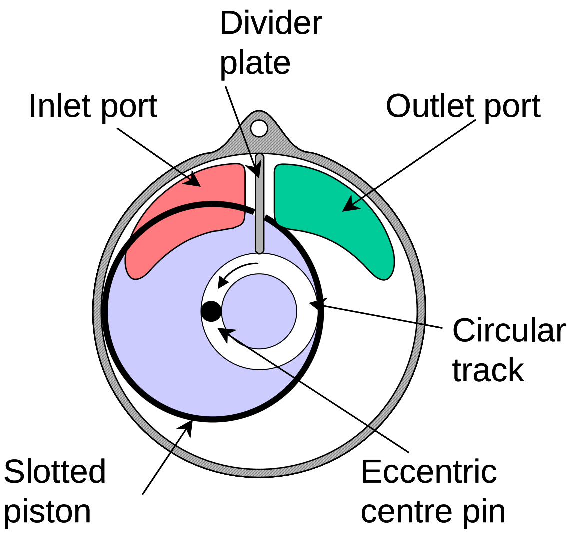


Figure 2.5. Basic layout of oscillating or rotating piston meter.

To obtain an oscillating motion, movement of the piston is restricted in two ways. First, the piston is slotted vertically to accommodate a partition plate which is fixed to the chamber. This plate prevents the piston from spinning around its central axis and also acts as a seal between the inlet and outlet ports of the chamber. Secondly, the piston has a centre vertical pin which confines the piston's movement to a circular track which is part of the chamber.

Differential pressure across the meter causes the piston to sweep the chamber wall in the direction of flow — displacing liquid from the inlet to the outlet port in a continuous stream.

The openings for filling and discharging are located in its base and thus in Figure 2.6 (a), areas 1 and 3 are both receiving liquid from the inlet port (A) and area 2 is discharging through the outlet port (B).

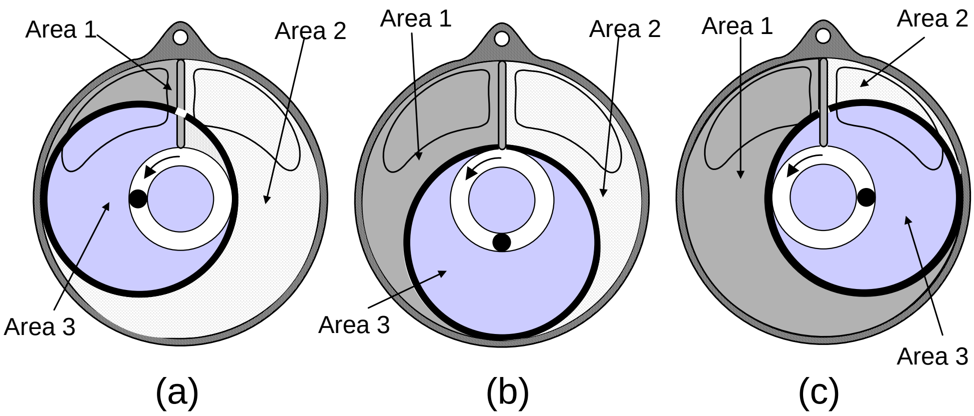


Figure 2.6. Oscillating or rotating piston meter showing principle of operation.

In Figure 2.6 (b), the piston has advanced and area 1, which is connected to the inlet port, has enlarged; and area 2, which is connected to the outlet port, has decreased, while area 4, is about to move into position to discharge through the outlet port.

In Figure 2.6(c), area 1 is still admitting liquid from the inlet port, while areas 2 and 3 are discharging through the outlet port. In this manner known discrete quantities of the medium have been swept from the inlet port to the outlet port.

The rotating piston meter is particularly suitable for accurately measuring small volumes and its main advantages are:

- accuracy of ± 0.5%; and
- performance largely unaffected by viscosity (from heating oil to paste).

The main disadvantages of the oscillating piston meter are:

- leakage and maximum permissible pressure loss.

2.6 Nutating disc

The term nutation is derived from the action of a spinning top whose axis starts to wobble and describe a circular path as the top slows down.

In a nutating disc type meter the displacement element is a disc that is pivoted in the centre of a circular measuring chamber (Figure 2. 7). The lower face of the disc is always in contact with the bottom of the chamber on one side, and the upper face of the disc is always in contact with the top of the chamber on the opposite side. The chamber is therefore divided into separate compartments of known volume.

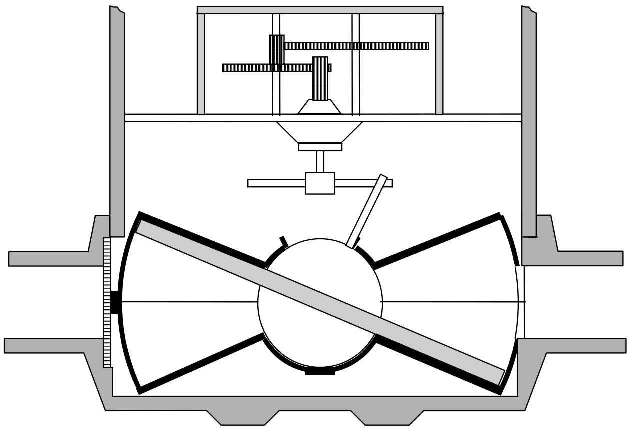


Figure 2.7. Nutating disc meter in which the displacement element is a disc pivoted in the centre of a circular measuring chamber.

Liquid enters through the inlet connection on one side of the meter and leaves through an outlet on the other side — successively filling and emptying the compartments and moving the disc in a nutating motion around a centre pivot. A pin attached to the disc's pivot point drives the counter gear train.

Although there are inherently more leakage paths in this design, the nutating disk meter is also characterised by its simplicity and low-cost.

It tends to be used where longer meter life, rather than high performance, is required, for example, domestic water service. The meter is also suitable for use under high temperatures and pressures.

2.7 Fluted rotor meters

The axial and radial fluted rotor meters work on the same principal.
The axial fluted rotor meter (Figure 2.8) makes use of two aluminium spiral fluted rotors working within the same measuring chamber — with the rotors maintained in a properly timed relationship with one another by helical gears.

The axial fluted rotor meter (Figure 2.8) makes use of two aluminium spiral fluted rotors working within the same measuring chamber — with the rotors maintained in a properly timed relationship with one another by helical gears.

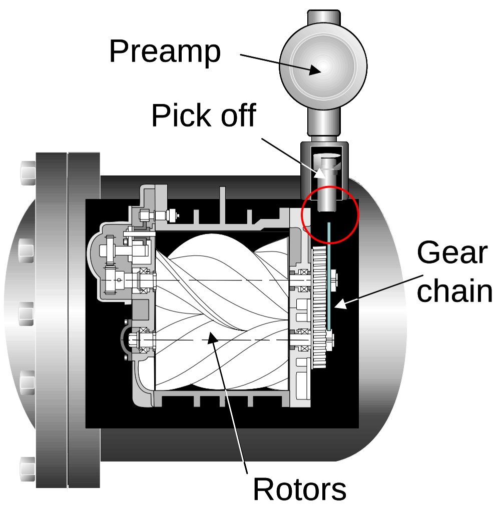


Figure 2.8. Physical construction of the axial radial fluted 'Birotor' meter courtesy Emerson).

As the product enters the intake of the measuring unit chamber, (Figure 2.9) the two rotors divide the volume being measured into segments; momentarily separating each segment from the flowing inlet stream and then returning them to the outlet of the measuring unit chamber.

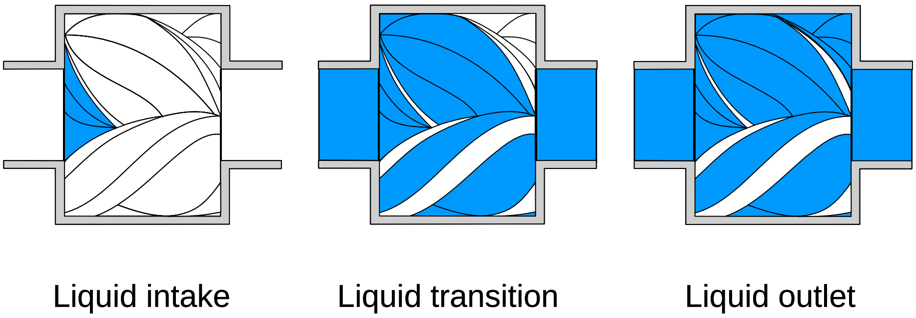


Figure 2.9. Operation of the axial radial fluted 'Birotor' meter (courtesy Emerson).

During this 'liquid transition', the segments of flow are counted and the results are transferred to a totalising counter or other flow recording device by means of a gear train.
In the radial fluted rotor meter, Figure 2.10, two specially shaped hydraulically unbalanced rotors are maintained in a properly timed relationship with one another by helical gears. The rotors are neither in metal-to-metal contact with one another nor with the housing in which they rotate. Again, as shown, as the product enters the intake of the measuring unit chamber the two rotors divide the volume being measured into segments; momentarily separating each segment from the flowing inlet stream and then returning them to the outlet of the measuring unit chamber.

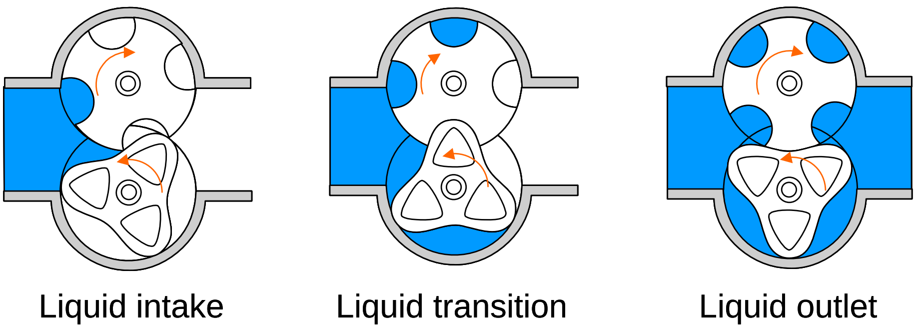


Figure 2.10. Operation of the radial fluted 'Birotor' meter (courtesy Emerson).

2.8 Wet-type gas meters

The wet-type gas meter (Figure 2.11) comprises a gas-tight casing containing a measuring drum, with four separate compartments, mounted on a spindle that is free to revolve. The casing is filled to approximately 60% of its of volume with water or light oil.

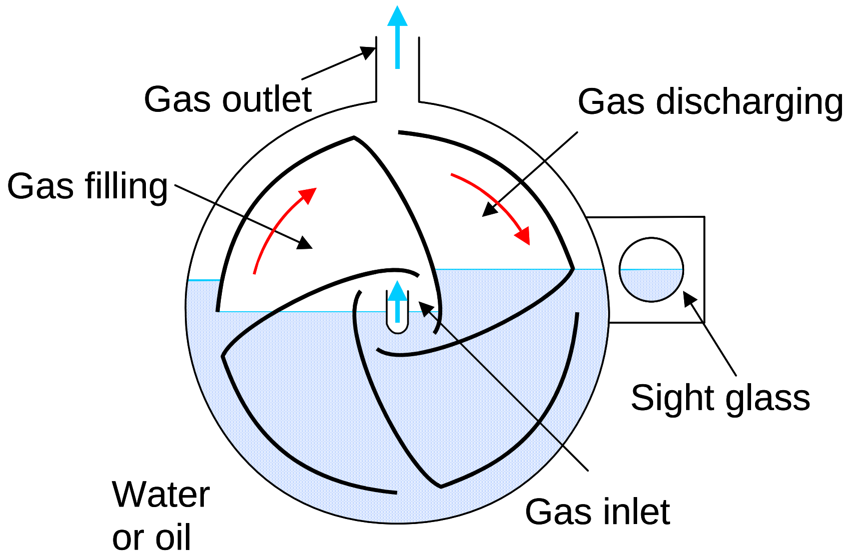


Figure 2.11. The wet-type gas meter (courtesy Alexander Wright division of GH Zeal Ltd)

Under normal operation the gas passes through the measuring drum so that each compartment of the drum must, in turn, be emptied of water and filled with gas — thus forcing the drum to rotate. In an alternative arrangement the gas is introduced into the space above the water in the outer casing and then passes through the drum to the outlet of the meter.

The calibration of the measuring drum (i.e. the quantity of gas passed for each revolution) is determined by the height of the water in the casing. Consequently, the normal calibration point is shown by a water-level indicating point that is visible in the sight box located on the side of the meter casing.

The spindle on which the measuring drum is mounted is connected through gears to record the quantity of gas passing through the meter.

Such meters are available in capacities ranging in size from 0.25 to 100 dm^3 with an accuracy down to ±0.25%.

2.9 General Summary

Because of their high accuracy, positive displacement meters are used extensively in liquid custody transfer applications where duty is applicable on such commodities as petrol, wines, and spirits.

In use, some of the following application limitations should be noted:

- Owing to the mechanical contact between the component parts, wear and tear is a problem. In general, therefore, positive displacement meters are primarily suited for clean, lubricating and non-abrasive applications.
- In some cases, filters (down to 10 µm) may be required to filter debris and clean the fluid before the meter. Such filters require regular maintenance. If regular maintenance is not carried out, the added pressure drop may also need to be considered.
- Their working life also depends on the nature of the fluid being measured, especially in regard to solids build-up and the media temperature.
- Positive displacement meters are an obstruction to the flow path and consequently produce an unrecoverable pressure loss.
- Because many positive displacement meters have the same operating mechanisms as pumps, they may be driven by a motor and used as dosing or metering pumps.
- One of the drawbacks of the positive displacement meter is its high differential pressure loss. This, however may be reduced by measuring the differential pressure across the meter and then driving it with a motor that is controlled by a feedback system.
- Positive displacement meters are limited at both high and low viscosities. Errors can occur due to leakage (slippage) around the gears or pistons. Slippage may be reduced by using viscous fluids which have the ability to seal the small clearances. However if the fluid is too viscous then it can coat the inner chambers of the meter and reduce the volume passed — causing reading errors. Thus, whilst low viscosities limit the use at low flows (due to increased slippage), high viscosities limit the use at high flows due to the high pressure loss.
- If slippage does occur, and is calibrated for, it can change with temperature as the viscosity varies.
- Positive displacement meters can be damaged by over-speeding.
- In certain cases (e.g. the oval gear meter) positive displacement meters give rise to pulsations. This may inhibit the use of this type of meter in certain applications.
- Positive displacement meters are primarily used for low volume applications and are limited when high volume measurement is required.

Chapter 3. Inferential Meters

Industrial Flow Measurement

Chapter 3
Inferential Meters

3.1 Introduction

Inferential meters, loosely referred to as 'turbine meters', are indirect volumetric totalisers, in which packages of the flowing media are separated from the flow stream and moved from the input to the output. However, unlike the positive displacement meter, the enclosed volume is not geometrically defined.

Inferential meters have rotor-mounted blades in the form of a vaned rotor or turbine which is driven by the medium at a speed proportional to the flowrate. The number of rotor revolutions is proportional to the total flow and is monitored by either a gear train or by a magnetic or optical pick-up.

Competing with the positive displacement meter for both accuracy and repeatability, the turbine flowmeter is used extensively in custody transfer applications in the oil and gas industries.

3.2 Turbine meter

Available in sizes from 5 to 600 mm, the turbine meter usually comprises an axially mounted bladed rotor assembly (the turbine) running on bearings and mounted concentrically within the flow stream by means of upstream and downstream support struts (Figure 3.1). The support assembly also often incorporates upstream and downstream straightening sections to condition the flow stream. The rotor is driven by the medium (gas or liquid) impinging on the blades.

The simplest method of measuring the rotor speed is by means of a magnet, fitted within the rotor assembly, that induces a single pulse per revolution in an externally mounted pick-up coil. To improve the resolution, the externally mounted pick-up coil is integrated with a permanent magnet and the rotor blades are made of a magnetically permeable ferrous material. As each blade passes the pick-up coil, it cuts the magnetic field produced by the magnet and induces a voltage pulse in the coil.

To improve the resolution even further, especially in large turbine meters (200 mm and above) where the rotor operates at much lower angular velocities, small magnetic bars are inserted in a non-magnetic rim that is fitted around the blades. This modification can improve the pulse resolution by as much as ten times.

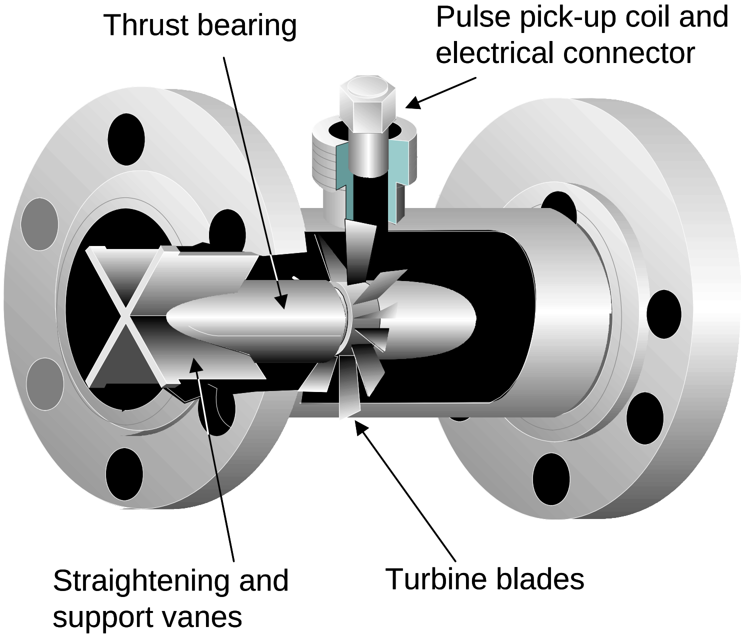


Figure 3.1. Turbine meter consists of a bladed rotor suspended in the flow stream. Upper and lower straightening vanes are normally included. (Courtesy Rosemount).

3.2.1 K-factor

The number of pulses produced per unit volume is termed the K-factor.

Ideally, the meter would exhibit a linear relationship between the meter output and the flow rate – a constant K-factor. In reality, however, the driving torque of the fluid on the rotor is balanced by the influence of viscous, frictional and magnetic drag effects.

Since these vary with the flow rate, the shape of the K-factor curve (Figure 3.2) depends on viscosity, flow rate, bearing design, blade edge sharpness, blade roughness and the nature of the flow profile at the rotor leading edge. In practice, all these influences have differing effects on the meter linearity and thus all turbine meters, even from the same manufacturing batch, should be individually calibrated.

The linear relationship of the K-factor is confined to a flow range of about 10:1 – sometimes extending up to 20:1.

At low flows, the poor response of the meter is due to bearing friction, the effect of fluid viscosity and magnetic drag on the rotor due to the use of a magnetic pick-off. It is possible to extend the lower limit of the meter's response by using, for example, a radio pick-off coupled with the use of high quality rotor bearings. The humping section of the curve flattens as the viscosity decreases – with resultant increase in accuracy.

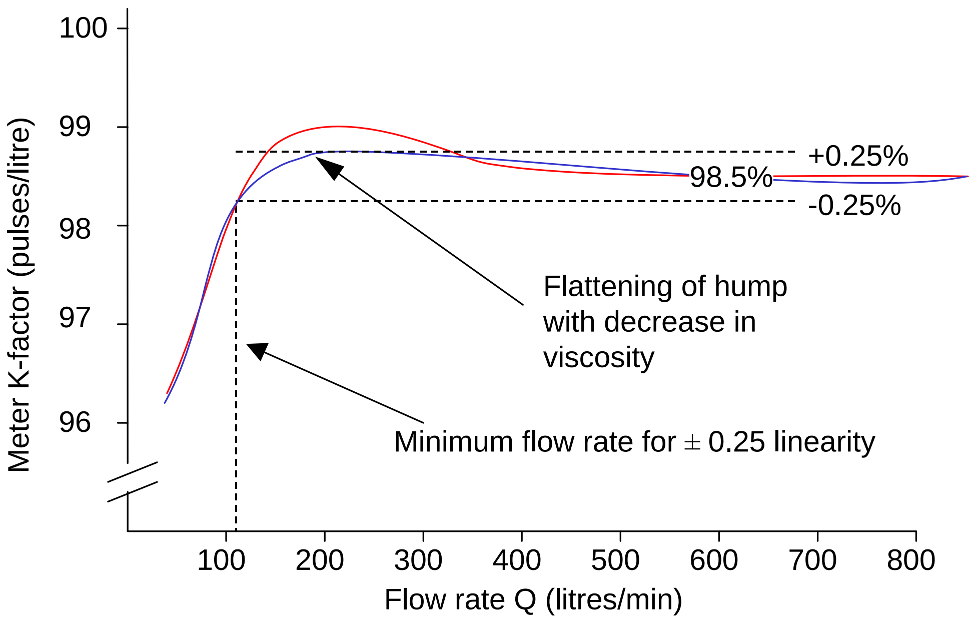


Figure 3.2. K-factor (the meter 'constant') should, ideally, be flat. The actual plot exhibits a drop off at low flow rates and a viscosity hump.

At low flows, the poor response of the meter is due to bearing friction, the effect of fluid viscosity and magnetic drag on the rotor due to the use of a magnetic pick-off. It is possible to extend the lower limit of the meter's response by using, for example, a radio pick-off coupled with the use of high quality rotor bearings. The humping section of the curve flattens as the viscosity decreases – with resultant increase in accuracy.

3.2.2 Selection and Sizing

Although turbine meters are sized by volumetric flow rate, the main factor that affects the meter is viscosity.

Typically, larger meters are less affected by viscosity than smaller meters. This may indicate that larger meters would be preferred; in fact the opposite is true. By using a smaller meter, operation is more likely to occur towards the maximum permitted flowrate, and away from the non-linear 'hump' response at low flows.

Turbine meters are specified with minimum and maximum linear flow rates that ensure the response is linear and the other specifications are met. For good rangeability, it is recommended that the meter be sized such that the maximum flow rate of the application be about 70 to 80% of that of the meter.

3.2.3 Application limitations

In liquids, the maximum flow rate is usually limited by the effect of cavitation that occurs when the system pressure falls to a point at which the liquid itself and/or the dissolved gases in the liquid 'boil off' at critical points in the meter where hydrodynamic forces cause a low pressure region. Cavitation can be avoided by retaining a sufficiently high back pressure and by keeping the pressure loss through the meter at a minimum.

Because the rotor, stator, measuring pipe and bearings all come in contact with the medium, the meter's resistance to aggressive fluids is dependent on the materials from which it is constructed. Generally the measuring pipe, rotor and stator are fabricated from stainless steel, whilst the bearings are made of ceramic materials such as aluminium oxide, or PTFE used in conjunction with metal or other materials.

Density changes have little effect on the meters' calibration.

Because turbine meters rely on the flow impinging on the rotor blades, they absorb some pressure. As a result, the pressure drop is typically around 20 to 30 kPa at the maximum flow rate and varies depending on the flow rate.

3.2.4 Advantages

Because the rotation of the turbine is measured by non-contact methods, no tapping points are required in the pipe. The result is that, depending on pipe diameter and materials of construction, pressures of up to 64 MPa can be applied.

When properly installed and maintained, turbine meters are capable of high accuracy (± 0.5 % of flow) over a 10:1 range as well as excellent repeatability (± 0.05 %). Turbine meters also exhibit a wide flow capacity range (from 4 litres/min – 800 klitres/min)

Temperature limitations are only imposed by the limitations of the materials of construction and turbine flowmeters are capable of operation with very high process media temperatures (up to 600 °C) as well as for use at very low temperatures (cryogenic fluids) down to -220 °C.

- Suitable for pressures of up to 64 MPa.
- High accuracy (up to ± 0.2 % of flow)
- Excellent repeatability (± 0.05 %).
- Wide rangeability up to 20:1
- Wide range of temperature applications from -220 to 600 °C
- Measurement of non-conductive liquids.
- Capability of heating measuring device.
- Suitable for very low flow rates.

3.2.5 Disadvantages

The main limitation of a turbine meter is that because it has a moving part (the rotor), it is subject to wear. Consequently, it is unsuited to dirty fluids and requires regular maintenance and calibration to maintain its accuracy. Another disadvantage is that because the K-factor is dependent on the viscosity, the viscosity of the liquid must be known and each meter must be calibrated for its application – especially at low flow rates.

Turbine meters are not suitable for use with high viscosity fluids since the high friction of the fluid causes excessive losses – leading to excessive non-recoverable pressure losses.

- Not suitable for high viscous fluids.
- Viscosity must be known.
- 10 diameter upstream and 5 diameters downstream of straight pipe is required.
- Not effective with swirling fluids.
- Only suitable for clean liquids and gases.
- Pipe system must not vibrate.
- Specifications critical for measuring range and viscosity.
- Subject to erosion and damage.
- Relatively expensive.

3.3 Woltman meter

The Woltman meter, used primarily as a water meter, is very similar in basic design to the turbine meter. The essential difference is that the measurement of rotation is carried out mechanically using a low friction gear train connecting the axle to the totalizer.

The Woltman meter is available in two basic designs – one with a horizontal turbine (Figure 3.3) and one with a vertical turbine (Figure 3.4). The vertical design offers the advantage of minimal bearing friction and therefore a higher sensitivity resulting in a larger flow range. Whilst the pressure drop of the vertical turbine meter is appreciably higher, because of the shape of the flow passage, it is widely used as a domestic water consumption meter.

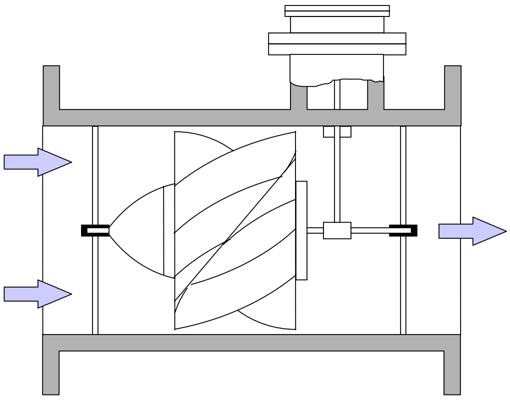


Figure 3.3. Horizontal turbine Woltman meter.

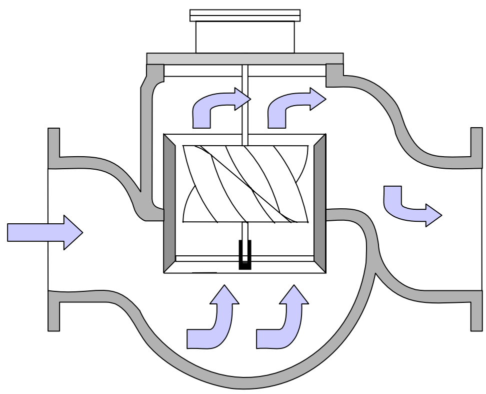


Figure 3.4. Vertical turbine Woltman meter.

In many designs, an adjustable regulating vane is used to control the amount of deflection and thus adjust the meter linearity.

3.4 Propeller type

In the propeller type flowmeter (Figure 3.5) the body of the meter is positioned above the flow path and only the propeller is in the flow line.

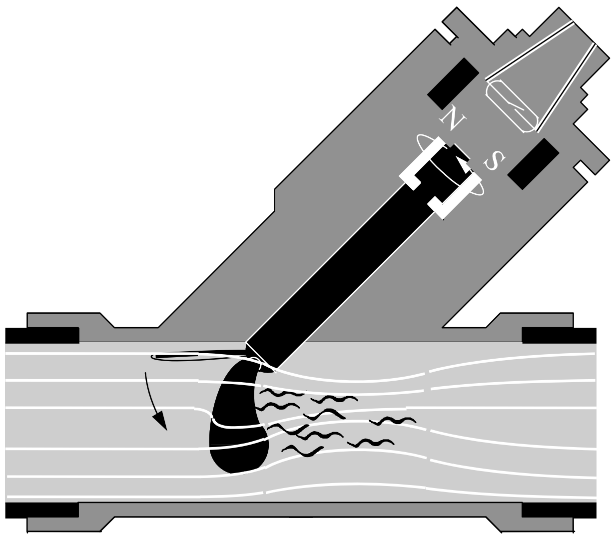


Figure 3.5. Propeller type flowmeter with the meter body positioned above the flow path and only the propeller in the flow line (Courtesy Rhodes & Son).

With the bearings outside of the main flow, the effects of contamination flom dirty liquids are eliminated or reduced to a minimum. The use of a three-bladed propeller with large clearances between each blade, enables particles in suspension to pass with ease and, in addition, the transmitter and all working parts can be removed and replaced in a few minutes, without breaking the pipeline. Another advantage of this type of meter is that manufacturing costs are significantly reduced.

On the negative side performance is correspondingly lower with the linearity typically ±2% and repeatability typically ±1% of full scale.

3.5 Impeller meters

As opposed to the vane-axial blades of turbine-type models, the rotating blades of impeller-type sensors are perpendicular to the flow-making them inherently less accurate than turbine sensors. However, their typical 1% accuracy and excellent repeatability makes them ideal for many applications.

Impeller sensors are especially suitable for measuring flow rates of low-viscosity liquids that are low in suspended solids over line velocities of between 0.15 and 10 m/s (Figure 3.6).

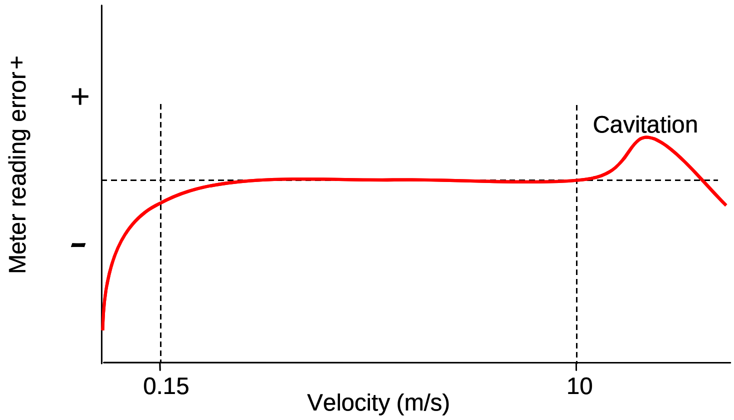


Figure 3.6. Reading vs. velocity for a typical impeller type meter.

At lower flow rates, the fluid cannot maintain the force needed to overcome bearing friction, impeller mass inertia, and fluid drag. And at flow rates above 10 m/s, cavitation can occur and cause readings to increase more than the increase in flow velocity. As velocity continues to increase under cavitation conditions, the reading eventually decreases with respect to true velocity.

The most common form of impeller-type meter is the in-line insertion format in which the main bearing is located out of the main flow stream and thus provides only a minimal pressure drop. Figure 3.7 illustrates a Tee-mount flow sensor suitable for pipe sizes ranging from 10 to 100 mm.

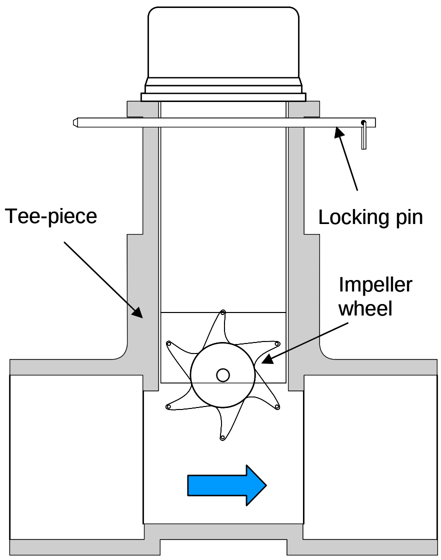


Figure 3.7. A Tee-mount flow sensor suitable for pipe sizes ranging from 10 to 100 mm (courtesy GLI International).

Other versions are available for use with welded-on pipe threads that allow the same meter to be used on pipe sizes ranging from 75 mm to 2.5 m diameter. This technique also allows its use in a 'hot tap' mode whereby it may be removed and replaced on high pressure lines without the need for a shutdown.

Another form of the impeller type meter, the Pelton wheel turbine (Figure 3.8), is able to measure extremely low flow rates down to 0.02 litres/min, coupled with a turn-down ratio of up to 50:1.

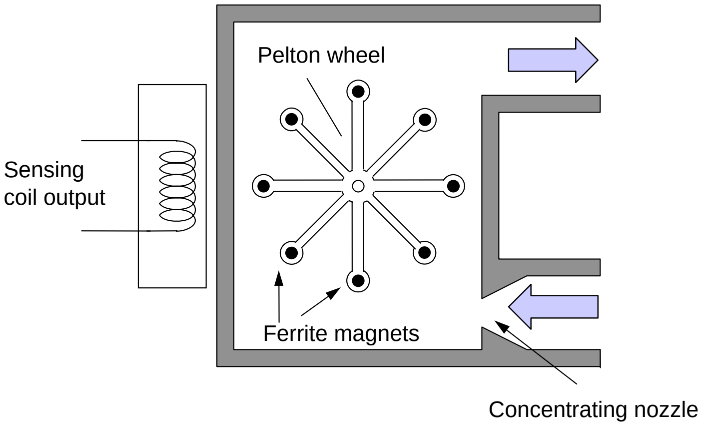


Figure 3.8. Cross-section of Pelton wheel system.

The incoming low velocity fluid is concentrated into a jet that is directed onto a lightweight rotor suspended on jewel bearings. The rotational speed is linear to flow rate and is detected by means of ferrite magnets, located in the rotor tips, which induce voltage pulses in a sensing coil. One drawback is that the nozzle can cause a rather large pressure drop.

3.5.1 Application limitations

As with turbine meters, most such sensors employ multiple blades with a permanent magnet embedded in each blade. A pick-up coil in the sensor acts as a generator stator – generating an electrical pulse each time the blade passes near it.

The use of such a magnetic pick-up, however, has some serious drawbacks. Firstly, the signal is susceptible to interference by extraneous magnetic fields in the vicinity of the coil. In addition, ferrous contamination, present in many industrial applications, causes particles to be attracted to the magnets in each blade. This not only affects sensor accuracy, but can impede or stop the impeller from rotating. Further, at low flows, the magnetic attraction between each rotating blade and the pick-up coil increases the force required to turn the impeller – resulting in poor linearity.

One method of overcoming this problem is shown in Figure 3.9 in which permanent magnets embedded in the impeller blades pass close to a Hall-effect transducer.

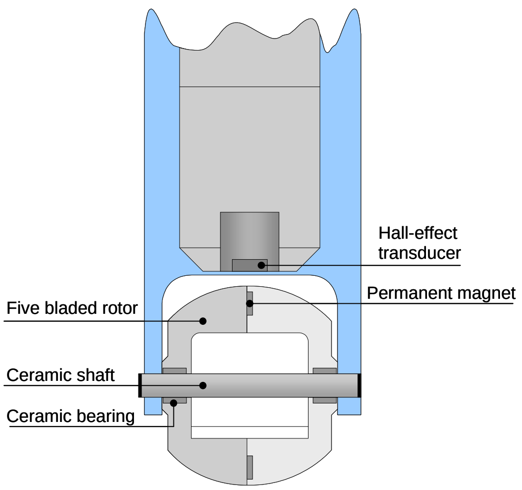


Figure 3.9. The problem of magnetic drag may be overcome through the use of a Hall-effect transducer that picks up the signal from magnets embedded in the impeller blades (courtesy FTE).

Another method of overcoming this problem is through the use of a non-magnetic ferrite rods embedded in the impeller blades. Although the ferrites are not magnetic, they form a low permeable path for a magnetic field.

As shown in Figure 3.10 the pickup comprises a composite transmitting and sensing coil. In the absence of a ferrite rod the magnetic coupling is loose and the signal produced by the receiving coil is small. However, in the presence of a ferrite rod, the magnetic coupling is strong – resulting in a much larger output signal.

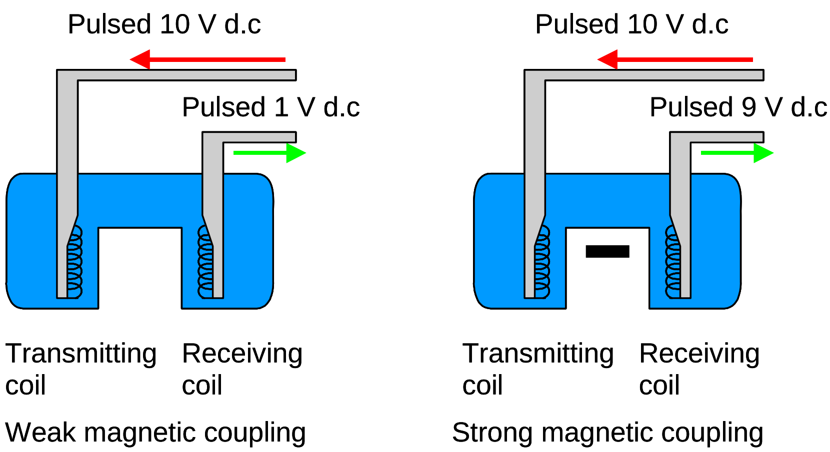


Figure 3.10. In the absence of a ferrite rod the magnetic coupling is loose and the signal produced by the receiving coil is small. When a ferrite rod is present, the magnetic coupling is strong resulting in a much larger output signal (courtesy GLI International).

Because permanent magnets are not used, there is no magnetic drag and no accumulation of magnetic particles to degrade the accuracy or cause clogging.

3.6 Installation recommendations

In order to reap the benefits of high accuracy the following installation practices should be observed:

- At least 10 pipe diameters of straight approach and 5 pipe diameters of straight outlet piping are required.
- Turbines should never be subjected to a swirling flow
- Flow must not contain any solids – especially fibre.
- Do not exceed the measuring range.
- A turbine for liquids should never be subjected to gas flow (danger of over-speeding)
- Never clean with compressed air.

Chapter 4. Oscillatory Flow Meters

Industrial Flow Measurement

Chapter 4

Oscillatory Flow Meters

4.1 Introduction

Oscillatory flow measurement systems involve three primary metering principles: vortex, vortex swirl (precession) and Coanda effect. In all three, the primary device generates an oscillatory motion of the fluid whose frequency is detected by a secondary measuring device to produce an output signal that is proportional to fluid velocity.

4.2 Vortex flowmeters

Vortex flowmeters for industrial flow measurement were first introduced in the mid-1970s but the technology was poorly applied by several suppliers. As a result, the technology developed a bad reputation and several manufacturers dropped the technology. However, since the mid-1980s many of the original limitations have been overcome and vortex flowmetering has become a fast growing flow technology.

Vortex meters are based on the phenomenon known as vortex shedding that takes place when a fluid (gas, steam or liquid) meets a non-streamlined obstacle – termed a bluff body. Because the flow is unable to follow the defined contours of the obstacle, the peripheral layers of the fluid separate from its surfaces to form vortices in the low pressure area behind the body (Figure 4.1). These vortices are swept downstream to form a so-called Karman Vortex Street. Vortices are shed alternately from either side of the bluff body at a frequency that, within a given Reynolds number range, is proportional to the mean flow velocity in the pipe.

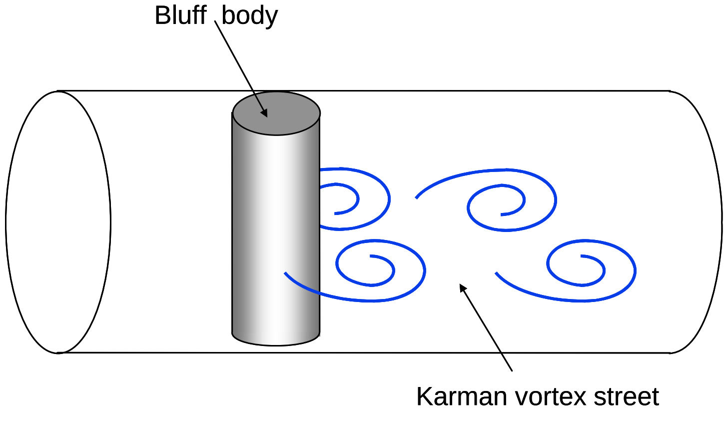


Figure 4.1. The Karman vortex street – with vortices formed on alternate sides in the low pressure area of bluff body.

In vortex meters, the differential pressure changes that occur as the vortices are formed and shed, are used to actuate the sealed sensor at a frequency proportional to the vortex shedding.

4.2.1 Formation of vortices

At very low velocities – the laminar flow region (Figure 4.2(a)) – the fluid flows evenly around the body without producing turbulence. As the fluid velocity increases the fluid tends to shoot past the body, leaving a low pressure region behind it (Figure 4.2(b)). As the fluid velocity increases even further, this low pressure region begins to create a flow pattern as shown in Figure 4.2(c) – the beginning of the turbulent flow region. This action momentarily relieves the pressure void on one side of the low pressure region and the fluid forms into a vortex. The interaction of the vortex with the main stream fluid releases it from the surface of the body and it travels downstream. Once released, the low pressure region shifts towards the other rear side of the body to form another vortex. This process is repeated, resulting in the release of vortices from alternate sides of the bluff body as illustrated in Figure 4.1.

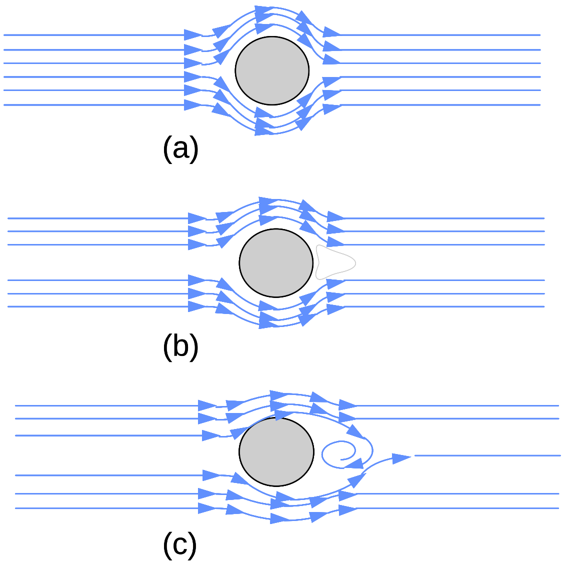


Figure 4.2. Formation of vortices: (a) laminar flow region with fluid flowing evenly around the body; (b) at higher velocities a low pressure region starts to form behind the bluff body; and (c) beginning of turbulent flow region and formation of vortex.

Vortex shedding occurs naturally throughout nature and can be observed in the whistling tone that the wind produces through telephone wires or in a flag waving from a flagpole. Because the flagpole acts as a bluff body, vortex shedding occurs. As the wind speed increases the rate of vortex shedding increases and causes the flag to wave faster.

4.2.2 Strouhal factor

▶ In 1878 Strouhal observed that the frequency of oscillation of a wire, set in motion by a stream of air, is proportional to the flow velocity. He showed that:

$$f = \frac{St \cdot v}{d}$$

where:

f = vortex frequency (Hz)
d = diameter of the bluff body (m)
v = velocity of liquid(m/s)
St = Strouhal factor (dimensionless)

Unlike other flow sensing systems, because the vortex shedding frequency is directly proportional to flow velocity, drift is not a problem as long as the system does not leave its operating range. Further, the frequency is unaffected by the medium's density, viscosity, temperature, pressure, and conductivity, as long as the Reynolds number (Re) stays within defined limits. Consequently, irrespective of whether the meter is used for measuring steam, gas or liquids, it will have virtually the same calibration characteristic and the same meter factor – although not necessarily over the same volumetric flow velocity ranges.

In reality, the Strouhal factor is not a constant but, as illustrated in Figure 4.3, varies with the shape of the bluff body and the Reynolds number. The ideal vortex flowmeter would, therefore, have a bluff body shape that features a constant Strouhal number over as wide a measuring range as possible. ◀

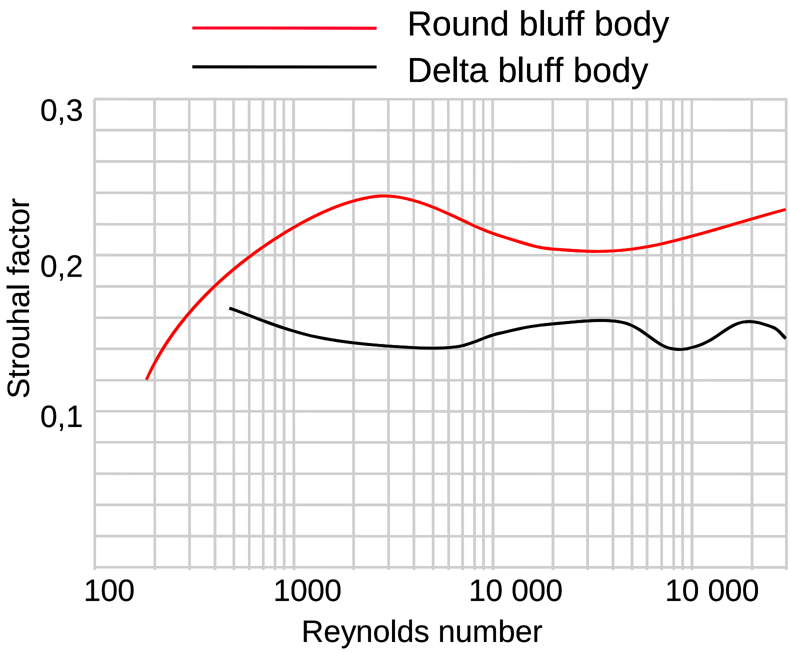


Figure 4.3. Relationship between Strouhal factor and Reynolds number for both a round and a delta bluff body (courtesy Endress + Hauser).

Meters based on this relationship are shown to have a linearity of better than ±0.5 % over a wide flow range of as high as 50: 1 for liquids and 100:1 for gases. The limits are determined at the low-end by viscosity effects and at the upper end by cavitation or compressibility.

Another major advantage of the vortex meter is that it has a constant, long-term calibration that does not involve any in-service adjustment or tuning. For a given size and shape of the bluff body, the vortex shedding frequency is directly proportional to flow rate.

4.2.3 Shedder design

Meters differ only in the shape of the bluff body and in the sensing methods used – with each manufacturer claiming specific advantages. Some of the bluff body shapes are shown in Figure 4.4.

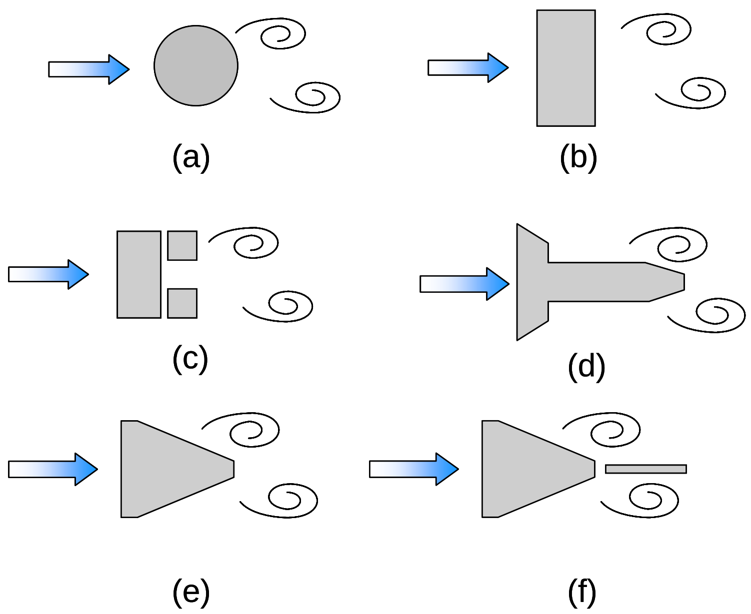


Figure 4.4. Various bluff body shapes: (a) round; (b) rectangular; and (c) two-part rectangular; (d) Tee-bar; (e) delta-shaped (courtesy Endress + Hauser).

Tests have shown that changes in the dimensions of the bluff body have a negligible effect on calibration. For example, tests with a rectangular bluff body indicate that with a body-to-meter bore ratio of 0.3, the body width can vary by as much as ±10 % to produce a change in the meter factor of < 0.4 %. Similarly, radiussing the edges of the bluff body by as much as 4 mm will not cause the calibration to deviate outside the standard accuracy band.

(Compare this with an orifice plate where radiussing the sharp edge of the orifice by as little as 0.4 mm produces a reading inaccuracy of approximately 4%.) The major benefit of this insensitivity to dimensional changes of the bluff body is that the vortex meter is virtually unaffected by erosion or deposits.

4.2.3.1 *Cylindrical*

Early bluff bodies were cylindrical. However, as the boundary layer changes from laminar to turbulent, the vortex release point fluctuates backwards and forwards, depending on the flow velocity, and the frequency is, subsequently, not exactly proportional to velocity.
As a result, use is made of bluff bodies having a sharp edge that defines the vortex shedding point.

4.2.3.2 *Rectangular bodies*

Following the cylindrical body, the rectangular body was used for many years. However, current research indicates that this body shape produces considerable fluctuation in linearity in varying process densities.

4.2.3.3 *Rectangular two-part bodies*

In this configuration, the first body is used to generate the vortices and the second body to measure them.

The two-part body generates a strong vortex (hydraulic amplification) that requires the use of less complicated sensors and amplifiers. On the negative side, the pressure loss is almost doubled.

4.2.3.4 *Delta-shaped bodies*
The delta-shaped shedder has a clearly defined vortex shedding edge and tests (including those carried out by NASA) indicate that the delta shape provides excellent linearity. Accuracy is not affected by pressure, viscosity or other fluid conditions. Many variations of the Delta shape exist and are in operation.

4.2.3.5 *Delta-shaped two-part bodies*
Claimed to combine the best features of modern technology, here, the delta-shaped bluff body generates the vortices and the second body is used to measure them.

4.2.3.6 *Tee-shaped bar*
Also claimed to combine the best features of the delta-shaped body with a high hydraulic amplification.

4.2.4 Sensors
▶ Since the shedder bar is excited by kinetic energy, the amplitude of the vortex signal depends on the dynamic pressure of the fluid:

$$p_d = \tfrac{1}{2} \cdot \rho \cdot v^2$$

where:

p_d	=	dynamic pressure
ρ	=	fluid density
v	=	velocity

As shown, the sensor amplitude is thus proportional to the fluid density and to the square of the velocity (Figure 4.5).

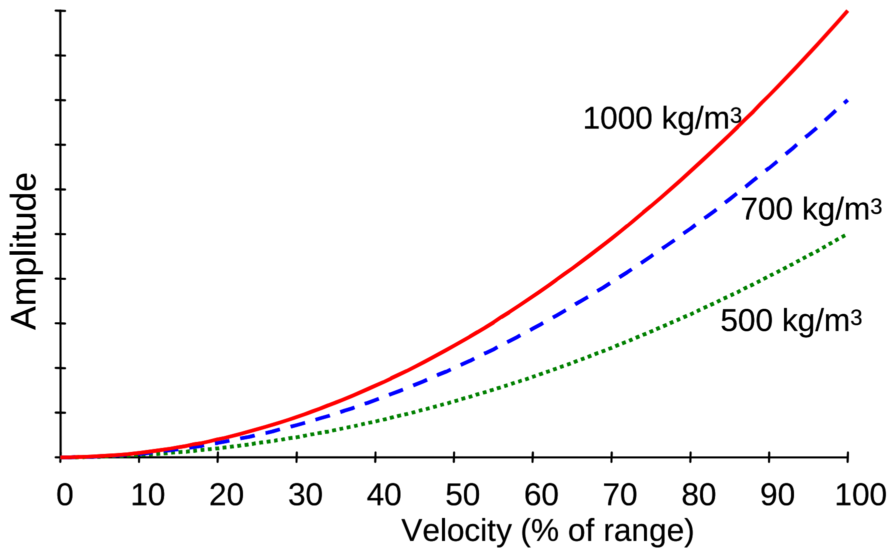
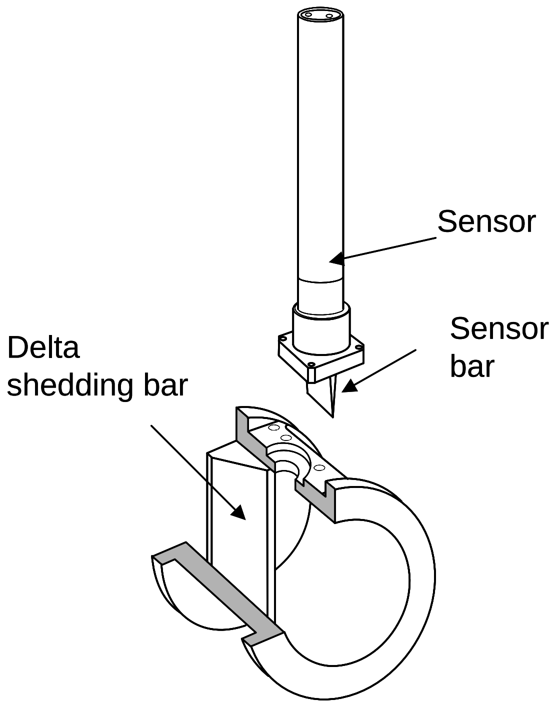


Figure 4.5. Amplitude as a function of velocity and process density.

Consequently, the dynamic sensitivity range of the vortex sensor needs to be quite large. For a turn-down ratio of 1:50 in flow velocity, the magnitude of the vortex signal would vary by 1:2500. This leads to very small signal levels at the low end of the measuring range.

While the vortex shedding frequency decreases as the size of the bluff body or meter increases, the signal strength falls off as the size decreases – thus, generally, limiting the meter size to within the range 15 to 200 mm bore. While there are several methods available for measuring the vortex frequency, there is no sensor currently available that will suit all operating conditions. ◀



Many vortex meters use non-wetted, external sensors connected to internal parts that move or twist due to vortex shedding. Formerly, this technology was plagued by sensitivity to pipeline vibration that produces a similar motion to vortex shedding when there is no flow in the pipe and can cause an erroneous output at zero flow. However, modern instruments have largely overcome this problem and systems as illustrated in Figure 4.6 are insensitive to vibrations in each axis up to at least 1 *g* covering the frequency range up to 500 Hz.

Figure 4.6. Use of separate mechanically balanced sensor positioned behind the bluff body (courtesy Endress + Hauser).

4.2.4.1 *Thermal sensing*

Thermal sensors (Figure 4.7) make use of electrically heated thermistors (heat-sensitive semi-conductor resistors) with a high temperature coefficient and a rapid time response. As the vortices are shed, on alternate sides of the fluff body, heat is convected away from the preheated elements – resulting in a change in resistance that is in phase with the shedding frequency.

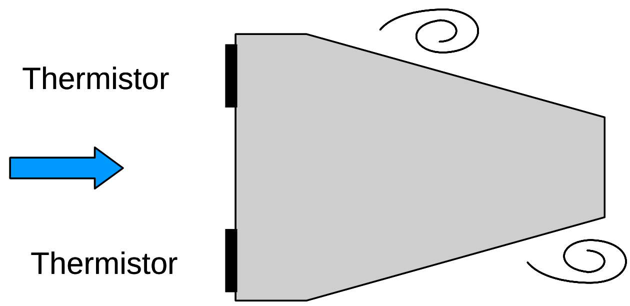


Figure 4.7. Basic configuration of thermal sensor (courtesy Endress + Hauser).

Depending on their location, the thermistors are sensitive to dirt and are generally incapable of withstanding temperature shocks. In addition, the upper frequency limit 500 Hz precludes their use with small diameter pipes (e.g. 25 mm) particularly with gas where vortex frequencies of 3300 Hz or more can be encountered.

4.2.4.2 *Mechanical sensors*

Sometimes called a shuttle ball sensor, a magnetic ball or disc moves from side to side, under the influence of the vortices, along a lateral bore that connects both sides of the bluff body (Figure 4.8). This movement is detected by a magnetic pick-up.

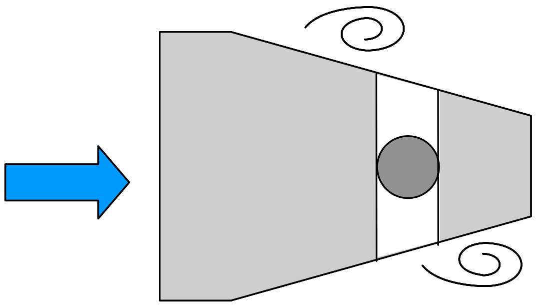


Figure 4.8. Shuttle ball or disc sensor (courtesy Endress + Hauser).

The main problems with this sensor are that it is easily blocked by dirt and in saturated steam the movement of the ball or disc can be slowed by condensation. Further, condensed water can cause the ball or disc to adhere to one side or other.

4.2.4.3 *Capacitive sensors*

In the form illustrated in Figure 4.9, stainless steel diaphragms are welded onto the sides of the bluff body and the assembly filled with oil and sealed. Since the oil is incompressible it fully supports the diaphragms against high static pressure. However, under the influence of an asymmetric differential pressure, as occurs during vortex shedding, the diaphragms deflect and the oil transfers through the internal port from one side to the other. When the diaphragms deflect there is a change in the capacitance between the diaphragms and the electrodes — one side increasing and the other side decreasing..

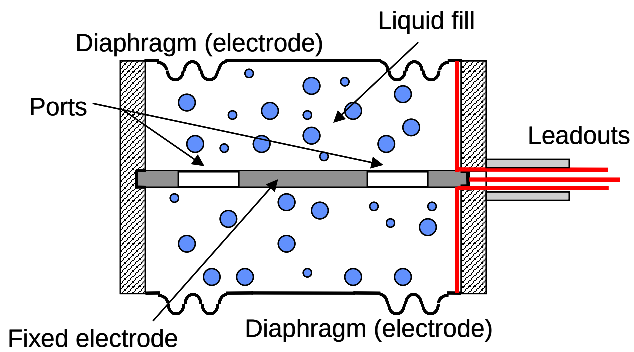


Figure 4.9. The vortices act on two diaphragms. As the diaphragms deflect the oil transfers through the internal ports from one side to the other — changing the capacitance between the diaphragms and the electrodes (courtesy Endress + Hauser).

Since the capacitance is inversely proportional to the distance between the electrodes and directly proportional to the plate area, pressure differences can be used to vary the plate overlap area or the electrode distance. Modern capacitive sensors are available for use with superheated steam for temperatures up to 427°C.

4.2.4.4 *Piezoelectric sensor*

Like the capacitive sensor, the alternating vortices, shed on each side of the shedder, act on two diaphragms mounted on each side of the sensor. In this case, (Figure 4.10) the flexing motion is coupled to a piezoelectric sensor, outside the flow line, which senses the alternating forces and converts them to an alternating signal.

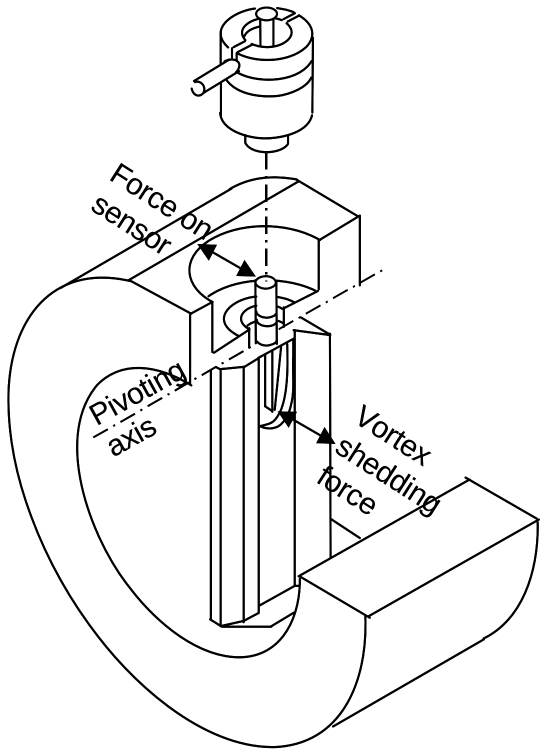


Figure 4. 10. Use of piezoelectric sensor positioned outside the flow line (courtesy Emerson).

The piezo elements produce a voltage output that is proportional to the applied pressure. Whilst piezo-ceramic materials produce a high output for a given pressure (a high ‘coupling factor’) they have a limited operating temperature range (about 250 °C).

The piezoelectric material Lithium Niobate ($LiNbO_3$) offers only medium coupling factors but can be operated at temperatures above 300 °C.

Generally, piezoelectric materials are unsuitable for temperatures below -40 °C since below this point, the piezoelectric effect becomes too small.

Because the piezoelectric element produces an output that is affected by movement or acceleration, it is also sensitive to external pipe vibration. This problem can be overcome by using a second piezoelectric element to measure the vibration and use it in a compensating circuit to ensure that only the clean vortex shedding frequency is obtained.

4.2.4.5 *Strain gauge sensors*

The vortices created by the bluff body cause the body itself to be mechanically displaced by small amounts – of the order of 10 μm. This elastic movement can be detected using strain gauges attached directly or indirectly to the bluff body. Movement of the body produces a change in resistance of the strain gauges.

The main drawbacks of this technology are the upper temperature limitation of the strain gauges (about 120°C) and the fact that diameters above 150 mm are sensitive to vibration.

4.2.4.6 *Ultrasonic sensing*

An ultrasonic detector system (Figure 4.11) makes use of an ultrasonic transmitter and receiver placed behind the bluff body. The vortices modulate the ultrasonic beam and the resultant output is the vortex signal.

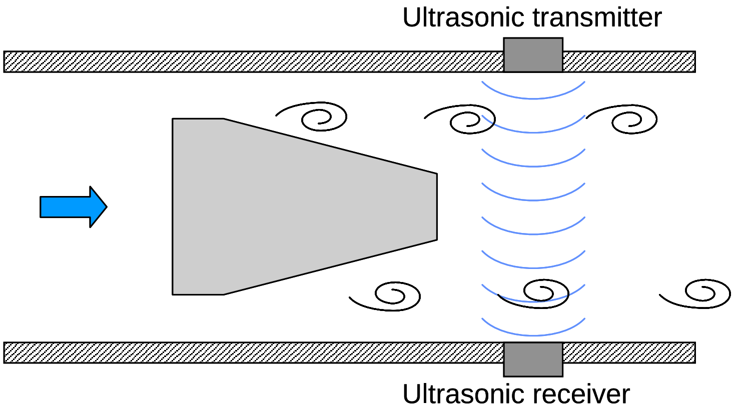


Figure 4.11. General configuration of the ultrasonic sensor (courtesy Endress + Hauser).

This sensor system has a good turn-down ratio and, since there is no mass associated with the sensor that would experience a force under vibration, the sensor is virtually vibration insensitive.

The main problem associated with this technique is that extraneous sound sources can affect measurements.

4.2.5 APPLICATION GUIDELINES FOR VORTEX FLOWMETERING*

**** These application guidelines have been compiled from a series of notes supplied by Krohne***

In general, a vortex shedding flowmeter works well on relatively clean low viscosity liquids, gases and steam to obtain specified accuracy.

4.2.5.1 Viscosity

The pipe Reynolds number should be above 30 000 minimum. This means vortex meters can only be used on low viscosity liquids. Highly viscous fluids (>3 Pa.s (30 cP)) and slurries are not recommended applications. As a rule of thumb, the viscosity should be 0.8 Pa.s (8 cP) or less (a viscosity of 0.8 Pa.s would correspond to cooking oil). Higher viscosity fluids can be metered, but at the expense of rangeability and head loss.

4.2.5.2 Low flow

The vortex meter cannot measure flow down to zero flow since, at low flow rates, vortex shedding becomes highly irregular and the meter is totally inaccurate. This generally corresponds to a Reynolds number between 5 000 and 10 000 and therefore depends on the pipe diameter and the fluid viscosity. For water, typical minimum velocity flow rate values would vary from about 2.4 m/s for a 15 DN pipe to 0.5 m/s for a 300 DN pipe.

Whilst the minimum Reynolds number requirement imposes a limitation on the usability of the vortex meter, this is not a serious limitation for many applications. For example, water flow in line sizes 25 DN and higher generally corresponds to Reynolds numbers in the tens of thousands to hundreds of thousands. Gas and steam applications generally correspond to Reynolds numbers in the low hundreds of thousands to the millions.

Most vortex meters include a low flow cut-in point, below which the meter output is automatically clamped at zero (for example, 4 mA for analog output).

For many applications the low flow cut-off point does not pose a problem. However, it can be a serious drawback for applications that see low flows during start-up and shutdown operations (i.e., flows much lower than normal conditions, often by a factor of 10 or more). While users may not want to measure flow accurately during such times, they may want to get some indication of flow. The vortex meter is not a good choice for such an application.

4.2.5.3 Batching operations

Vortex meters may or may not be suitable for typical batching applications involving intermittent (on/off) flow — especially if the pipe does not remain full at zero flow. The vortex meter will not register flow as the fluid accelerates from zero to the low flow cut-in value, and again when the flow decelerates from the low flow cut-in value to zero. This lost flow may or may not create a significant error depending on the dynamics of the system, and the size of the batch being measured. In addition, the vortex meter can only measure flow in one direction. Any back flow through the meter (for example, the result of turning a pump off) will not be measured and will not be deducted from the registered batch total. One way to minimise errors on intermittent flows is to install check valves with the vortex meter on horizontal lines to keep the line full during zero flow conditions.

4.2.5.4 Measuring range

Note that in vortex meters, the measuring range is fixed for a given application and meter size. Although it depends on the specific application it is generally > 20:1 on gases and steam, and >10:1 on liquids.

A 50 mm vortex meter has, typically, a flow range over the range of 1 to 15 ℓ/s on water (15: 1 rangeability). If we need to measure over the range 0.5 to 3 ℓ/s there is nothing that can be done to the 50 DN meter to allow it to measure a lower range and it would be necessary to use a 25 DN meter. For this reason, vortex meters are sized to the desired flow range, rather than to the nominal pipe diameter. To get the proper measuring range (Figure 4.12), it is often necessary to use a smaller diameter meter than the nominal diameter of the pipe.

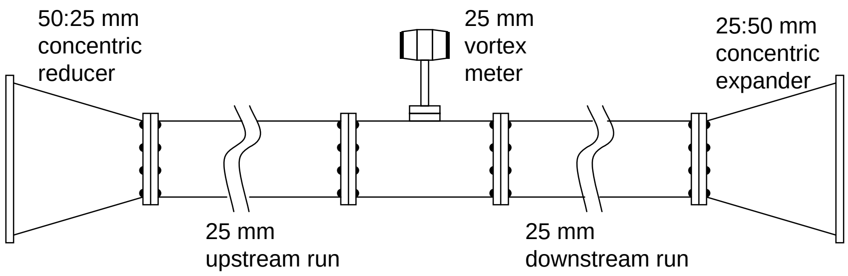


Figure 4.12. Use of reducer and expander to obtain the correct measuring range (courtesy Krohne).

When buying a flow meter, the instrument engineer often does not know the exact flow range and has to make an educated guess. Since vortex meter rangeability is fixed for a given line size by the process conditions, a meter sized on an educated guess may not meet the process conditions.

Consequently if the user does not have a good 'ball park' figure in regard to rangeability it is often better to opt for a more forgiving technology such a magnetic flowmeter.

4.2.5.5 Process noise

Process noise from pumps, compressors, steam traps, valves, etc., may cause the meter to read high, by triggering a higher than expected frequency output from the sensor, or by indicating a false flow rate when the system is at zero flow. Process noise is generally not a problem on liquids because the sensor's signal-to-noise ratio is at a maximum. However, gases and steam produce a much weaker sensor signal, which may not be as easily discernible from process noise at low flow.

Process noise cannot be quantified before the meter is installed and, therefore, it should always be assumed that some process noise exists. It can be eliminated using built-in noise filtering circuitry. However, this raises the threshold value of the low flow cut off. Thus, the more filtering used to eliminate process noise, the less the net rangeability of the meter. To avoid this, vortex flowmeters need to be sized properly to ensure the desired rangeability . There are two general sizing guidelines that should be followed:

1. The user Upper Range Value (URV) must not be less than 20% of the meter Upper Range Limit (URL).

Note. URL is the highest flow rate that a meter can be adjusted to measure whilst the URV is the highest flowrate that a meter is adjusted to measure. The URV will always be equal to or lower than the URL.

2. The minimum desired flow rate must be > 2 times the value of the meter's low flow cut-in rate

4.2.5.6 Accuracy

Vortex meter accuracy is based on the known value of the meter factor (K-factor), determined from a water calibration at the factory. Accuracy for liquids is typically stated as ± 0.5% of flowrate for Reynolds numbers above 30 000.

Water calibration data cannot precisely predict K-factor values for gases and steam, which can flow at Reynolds numbers well outside the test data range. For this reason, gas and steam accuracy is typically stated as ±1.0% of flowrate for Reynolds numbers above 30 000.

Long term accuracy depends on the stability of the internal dimensions of the flow-tube and shedder body. Only significant changes in these dimensions (due to corrosion, erosion, coatings, etc.) can affect accuracy with time. Whilst vortex meter K-factors can only be determined by wet calibration, the dimensions of the flow-tube inside diameter and bluff body thickness can be used as a 'flag' to determine if recalibration is necessary. Prior to installation, inspect the flow-tube and carefully measure and record the two reference dimensions. After a period of time in service, the meter can be removed, cleaned, and re-measured. The meter does not require recalibration if there has been no significant change in the two reference dimensions.

4.2.5.7 Effects of erosion

Although vortex shedding flowmeters are primarily designed for measuring the flow of clean liquids and gases, they can still be used if small amounts of foreign matter are present. Since there are no moving parts, or ports with active flow, there is little concern for erosion, physical damage or clogging. The effect of erosion on the salient edges of the bluff body is small and often poses no significant accuracy degradation.

4.2.5.8 Low density gases

Measuring gas flows can be a problem when the process pressure is low (i.e. low density gases) because a vortex produced under such conditions does not have a strong enough pressure pulse to enable a sensor to distinguish it from flow noise. For such applications, minimum measurable flow becomes a function of the strength of the pressure pulse (a function of the product of fluid density and the square of fluid velocity) rather than Reynolds number. Low-density gases can be measured with a vortex meter; however, minimum measurable flow may correspond to a high fluid velocity, and rangeability may be significantly less than 20:1.

4.2.5.9 Orientation

Vortex meters can be installed vertically, horizontally or at an angle. However, for liquid measurements the meter must be full at all times. The meter should also be installed to avoid formation of secondary phases (liquid, gas or solid) in the internal sensor chambers.

4.2.5.10 Pressure drop

If the inside meter diameter is the same as the nominal diameter of the process piping (i.e. a 50 DN meter is used in a 50 DN line), then the pressure drop will normally be less than 40 kPa on liquid flow at the URL (usually in the 14 to 20 kPa range at the user's URV). However, when downsizing the vortex meter to achieve a desired rangeability, the unrecoverable pressure loss through the meter is increased.

It must be ensured that this increased pressure loss is not enough to cause a liquid to flash or cavitate within the pipe. Flashing and cavitation have an adverse effect on meter accuracy, and can cause damage to the meter itself.

4.2.5.11 Multi-phase flow

Measurement of two- or three-phase flow (for example, water with sand and air, or 'wet' steam with vapour and liquid) is difficult and if multi-phase flow is present the vortex meter will not be as accurate.

Because the vortex meter is a volumetric device, it cannot distinguish which portions of the flow are liquid and which portions of the flow are gas or vapour. Consequently, the meter will report all the flow as gas, or all the flow as liquid, depending on the original configuration of the device. Thus, for example, if the meter is configured to measure water in litres, and the actual water has some entrained air and sand mixed in, a litre registered by the meter will include the water, air and sand that is present. Therefore if the area of interest were the amount of water, the reading from the meter would be consistently high, based on the proportions of air and sand present. A user would, consequently, need to separate the phases prior to metering or live with this inherent error.

4.2.5.12 Material build-up

Fluids that tend to form coatings are bad applications for vortex meters. Coating build-up on the bluff body will change its dimensions, and therefore, the value of the K-factor.

4.2.5.13 Piping effects

The specification for vortex meter accuracy is based on a well developed and symmetrical fluid velocity profile, free from distortion or swirl, existing in the pipe. The most common way to prevent errors is to provide sufficient lengths of straight, unobstructed pipe, upstream and downstream of the meter, to create a stable profile at the meter site.

Generally, vortex meters require similar amounts of upstream and downstream pipe runs to orifice plates, turbine meters and ultrasonic meters. Vortex meters are not usually recommended for 'tight' piping situations, with limited runs of straight pipe, unless repeatability is more important than accuracy. Typical manufacturers' recommendations are shown in Figure 4.13, when flow conditioners are not being used.

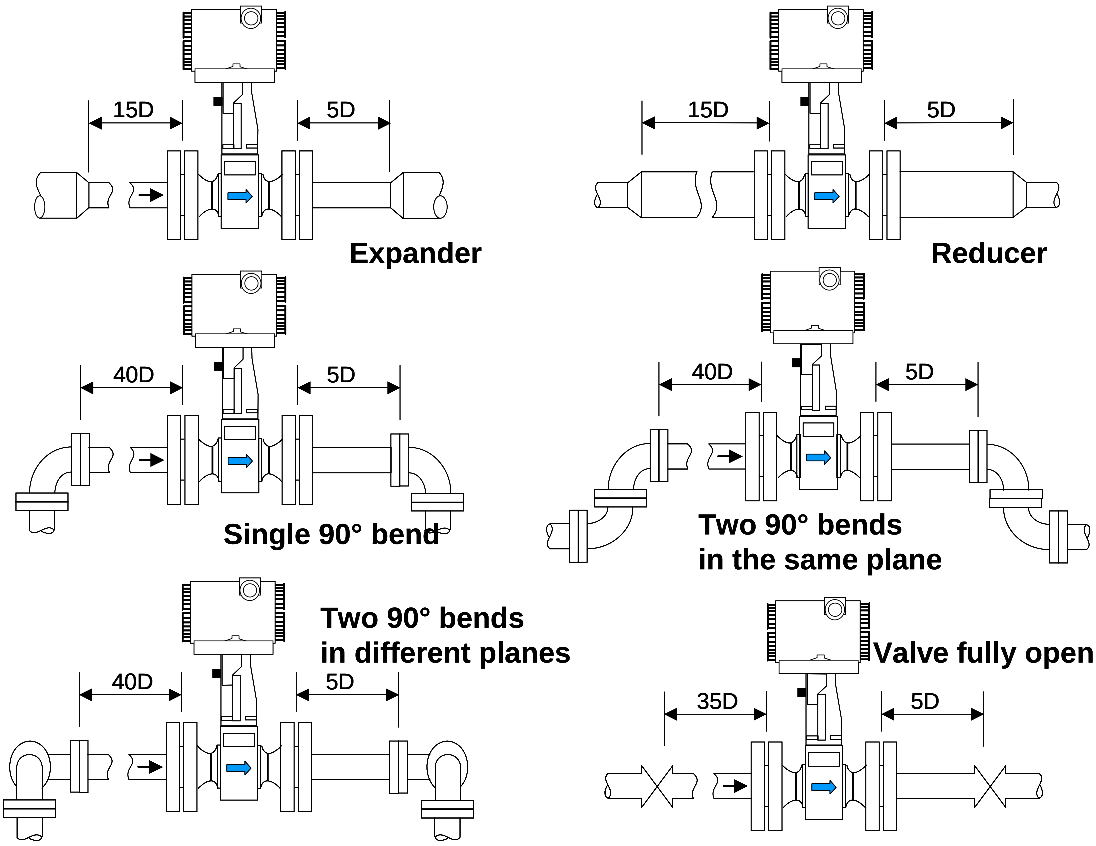


Figure 4.13. Typical manufacturers' recommendations for straight pipe lengths (courtesy Emerson).

Most performance specifications are based on using schedule 40 process piping. This pipe should have an internal surface free from mill scale, pits, holes, reaming scores, bumps, or other irregularities for a distance of 4 diameters upstream, and 2 diameters downstream of the vortex meter. The bores of the adjacent piping, the meter, and the mating gaskets must be carefully aligned to prevent measurement errors.

For liquid control applications, it is recommended that the vortex meter be located upstream of the control valve for a minimum of 5 diameters. For gas or steam control applications, it is recommended that the vortex meter be located a minimum of 30 diameters downstream of the valve. The only exception to this rule is for butterfly valves. In this instance the recommended distances are increased to 10 diameters for liquids, and 40 to 60 diameters for gases and steam.

4.2.5.14 Mass measurement

Pressure and/or temperature measurements are generally used in conjunction with a vortex meter measurement when the user wants an output in mass.

- Pressure taps should be located 3.5 to 4.5 diameters downstream of the meter.
- The temperature tap should be located 5 to 6 diameters downstream of the meter, and the smallest possible probe is recommended to reduce the chances of flow disturbance.

4.2.5.15 Avoiding problems

The following guidelines will help prevent application and measurement problems with a vortex meter and ensure premium performance:

- improper configuration;
- improper sizing;
- insufficient upstream/downstream relaxation piping;
- improper meter orientation;
- partially full piping;
- accumulation of secondary phase (gas, liquid or solid) inside the meter;
- improper temperature/pressure taps;
- flows below Reynolds numbers of 30000;
- flows below the low flow cut-in;
- process noise (at low flows or zero flow); and
- presence of multiple phases.

4.3 Vortex precession

The 'Swirlmeter', a patented technology with manufacturing rights ceded to Bailey-Fischer & Porter, is based on the principle known as vortex precession.

The inlet of the Swirlmeter (Figure 4.14) uses guide vanes, whose shape is similar to a turbine rotor, to force the fluid entering the meter to spin about the centreline. This swirling flow then passes through a venturi, where it is accelerated and then expanded in an expansion chamber.

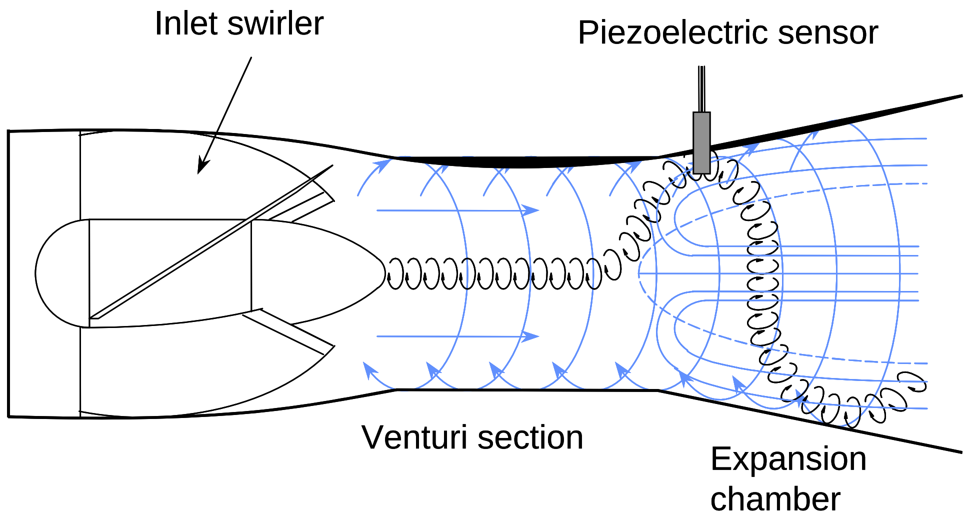


Figure 4.14. Basic principle of a vortex precession Swirlmeter (courtesy Bailey Fischer & Porter).

The expansion changes the direction of the axis about which the swirl is spinning – moving the axis from a straight to a helical path. This spiralling vortex is called vortex precession. A flow straightener is used at the outlet from the meter. This isolates the meter from any downstream piping effects that may affect the development of the vortex.

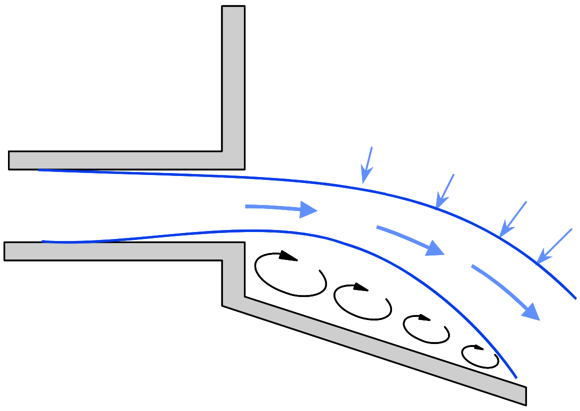
Above a given Reynolds number, the vortex precession frequency, which lies between 10 and 1500 Hz and is measured with a piezoelectric sensor, is directly proportional to the flow rate.

Although the Swirlmeter can be used with both gases or liquids, it finds its main application as a gas flowmeter.
A major advantage of the vortex precession technique over that of vortex shedding is that it has a much lower susceptibility to the flow profile and hence only three diameters of straight line are required upstream of the meter. In addition, the Swirlmeter features: linear flow measurement; rangeability between 1:10 and 1:30; no moving parts; and installation at any angle in the pipeline.

Because of the higher tolerance in manufacture of this type of meter, it is more expensive than comparative meters.

4.4 Fluidic flowmeter

The fluidic flowmeter is based on the wall attachment or 'Coanda' effect. Wall attachment occurs when a boundary wall is placed in proximity to a fluid jet – causing the jet to bend and adhere to the wall.



This effect is caused by the differential pressure across the jet, deflecting it towards the boundary (Figure 4.15). Here it forms a stable attachment to the wall, which is little affected by any downstream disturbances.

Figure 4.15. Explanation of the Coanda effect – resulting in stable attachment of the flow stream to the wall.

In the fluidic meter (Figures 4.16 and 4.17), the flow stream attaches itself to one of the walls – with a small portion of the flow fed back through a passage to a control port (Figure 4.16).

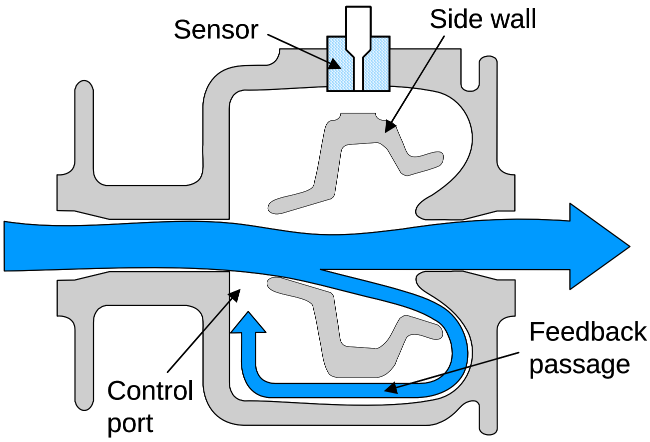


Figure 4.16. Once attached to one side of the wall a feedback passage diverts a portion of stream back onto the main flow (courtesy Moore Products).

This feedback, diverts the main flow to the opposite side wall where the same feedback action is repeated (Figure 4.17).

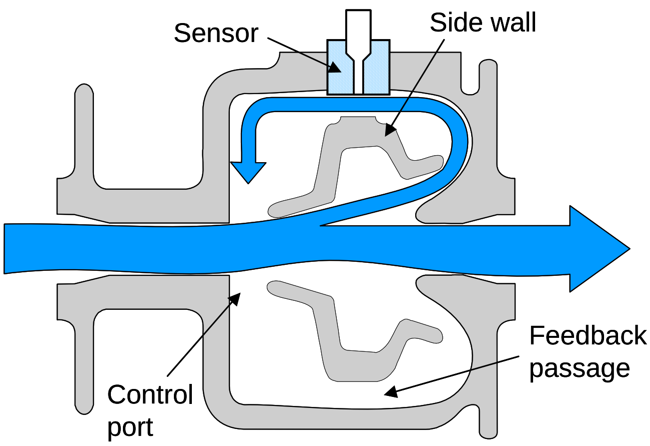


Figure 4.17. Main stream is diverted to the other wall by the feedback control action, and the procedure is then repeated (courtesy Moore Products).

The result is a continuous oscillation of the flow between the sidewalls of the meter body whose frequency is linearly related to the fluid velocity. Flow in the feedback passage cycles between zero and maximum which is detected by a built-in thermistor sensor.

The main benefit offered by the fluidic meter is that feedback occurs at much lower Reynolds numbers and it may thus be used with fairly viscous media. In addition, since a fluidic oscillator has no moving parts to wear with time, there is no need for recalibration during its expected lifetime. Other benefits include:

- rugged construction;
- high immunity to shock and pipe vibration; and
- high turndown ratio.

The main drawback of the fluidic oscillator is its relatively high pressure loss and its poor performance at low flow rates.

Chapter 5. Differential Pressure Meters

Chapter 5

Differential Pressure Meters

5.1 Introduction

Differential pressure flow meters encompass a wide variety of meter types that includes: orifice plates, venturi tubes, nozzles, Dall tubes, target meters, pitot tubes and variable area meters. Indeed, the measurement of flow using differential pressure is still the most widely used technology.

One of the features of the differential flow meter, sometimes referred to as a 'head' or 'head loss' meter, is that flow can be accurately determined from: the differential pressure; accurately measurable dimensions of the primary device; and properties of the fluid. Thus, an important advantage of differential type meters over other instruments is that they do not always require direct flow calibration. In addition, they offer excellent reliability, reasonable performance and modest cost.

Another advantage of orifice plates in particular, is that they can be used on liquid or gas applications with little change.

5.2 Basic theory

Differential pressure flow rate meters are based on a physical phenomenon in which a restriction in the flow line creates a pressure drop that bears a relationship to the flow rate.

▶ This physical phenomenon is based on two well-known equations: the equation of continuity and Bernoulli's equation.

5.2.1 Equation of continuity

Consider the pipe in Figure 5.1 that rapidly converges from its nominal size to a smaller size followed by a short parallel sided throat before slowly expanding to its full size again. Further, assume that a fluid of density ρ flowing in the pipe of area A_1, has a mean velocity v_1 at a line pressure P_1. It then flows through the restriction of area A_2, where the mean velocity increases to v_2 and the pressure falls to P_2.

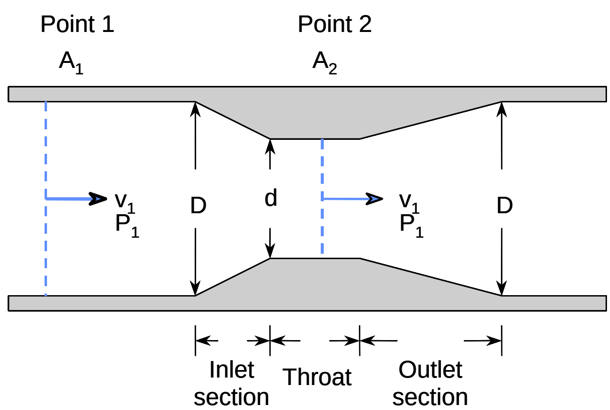


Figure 5.1. Basic definition of terms.

The ratio of the diameters of the restriction (d) to the ID (inside diameter) (D) of the pipe is called the **beta ratio** (β), i.e.

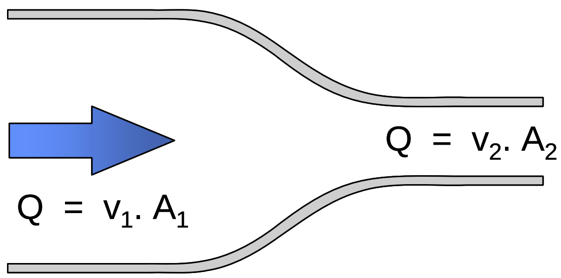
$$\frac{d}{D} = \beta \quad \text{……………………………………………………………….(5.1)}$$

The equation of continuity states that for an incompressible fluid the volume flow rate, Q, must be constant. Very simply, this indicates that when a liquid flows through a restriction, then in order to allow the same amount of liquid to pass (to achieve a constant flow rate) the velocity must increase (Figure 5.2).

Mathematically:

$$Q = v_1A_1 = v_2A_2 \quad \text{……………………………………………….(5.2)}$$

where: v_1 and v_2 and A_1 and A_2 are the velocities and cross-sectional areas of the pipe at points 1 and 2 respectively.



i.e. $Q = v_1A_1 = v_2A_2$

Figure 5.2. To allow the same amount of liquid to pass the velocity must increase

5.2.2 Bernoulli's equation

In its simplest form, Bernoulli's equation states that under steady flow conditions, the total energy (kinetic +pressure + gravitational) per unit mass of an ideal incompressible fluid (i.e. one having a constant density and zero viscosity) remains constant along a flow line.

$$\frac{v^2}{2} + \frac{P}{\rho} + gz = k \quad \text{……………………………………………….(3)}$$

where:

v = the velocity at a point in the streamline
P = the pressure at that point
ρ = the fluid density
g = the acceleration due to gravity
z = the level of the point above some arbitrary horizontal reference plane with the positive *z*-direction in the direction opposite to the gravitational acceleration,
k = constant

In the restricted section of the flow stream, the kinetic energy (dynamic pressure) increases due to the increase in velocity and the potential energy (static pressure) decreases.

Relating this to the conservation of energy at two points in the fluid flow then:

$$\frac{v_1^2}{2}+\frac{P_1}{\rho}=\frac{v_2^2}{2}+\frac{P_2}{\rho} \quad \ldots\ldots(5.4)$$

Multiplying through by ρ gives:

$$\frac{1}{2}\cdot\rho\cdot v_1^2+P_1=\frac{1}{2}\cdot\rho\cdot v_2^2+P_2 \quad \ldots\ldots(5.5)$$

or:

$$P_1-P_2=\frac{1}{2}\cdot\rho\cdot v_2^2-\frac{1}{2}\cdot\rho\cdot v_1^2 \quad \ldots\ldots(5.6)$$

or:

$$\Delta P=\frac{1}{2}\cdot\rho\cdot v_2^2-\frac{1}{2}\cdot\rho\cdot v_1^2 \quad \ldots\ldots(5.7)$$

where:

$$\Delta P=P_1-P_2 \quad \ldots\ldots(5.8)$$

Now from the continuity equation (2) we can derive:

$$v_1=\frac{Q}{A_1} \quad \ldots\ldots(5.7)$$

and:

$$v_2=\frac{Q}{A_2} \quad \ldots\ldots(5.8)$$

substituting in (6):

$$\Delta P=\frac{1}{2}\cdot\rho\cdot\left(\frac{Q}{A_2}\right)^2-\frac{1}{2}\cdot\rho\cdot\left(\frac{Q}{A_1}\right)^2 \quad \ldots\ldots(5.9)$$

Solving for Q:

$$Q=A_2\sqrt{\frac{\frac{2\cdot\Delta P}{\rho}}{1-\left(\frac{A_2}{A_1}\right)^2}} \quad \ldots\ldots(5.10)$$

Since it is more convenient to work in terms of the diameters of the restriction (d) and the ID (inside diameter) (D) of the pipe we can substitute for:

$$A_1=\frac{\pi\cdot D^2}{4} \quad \ldots\ldots(5.11)$$

and:

$$A_2=\frac{\pi\cdot d^2}{4} \quad \ldots\ldots(5.12)$$

$$Q = \frac{\pi \cdot d^2}{4}\sqrt{\frac{\frac{2\cdot\Delta P}{\rho}}{1-\left(\frac{d}{D}\right)^2}} \qquad \text{……………………………………(5.13)}$$

The term:

$$\sqrt{\frac{1}{1-\left(\frac{d}{D}\right)^2}} \qquad \text{……………………………………(5.14)}$$

is called the 'Velocity of Approach Factor' (E_v) and by substituting from (1):

$$E_v = \sqrt{\frac{1}{1-(\beta)^2}} \qquad \text{……………………………………(5.15)}$$

Now, substituting in (13) we have:

$$Q = E_v \cdot d^2 \sqrt{\frac{2\cdot\Delta P}{\rho}} \qquad \text{…………………………………(5.16)}$$

Unfortunately, equation (16) only applies to perfectly laminar, inviscid flows. In order to take into account the effects of viscosity and turbulence a term called the '**discharge coefficient**' (C_d) is introduced that marginally reduces the flow rate (Q).

The full equation for an incomprehensible fluid thus becomes:

$$Q = C_d \cdot E_v \cdot d^2 \sqrt{\frac{2\cdot\Delta P}{\rho}} \qquad \text{…………………………………(5.17)} \blacktriangleleft$$

In practice use is often made of a simplified formula that relates the difference between the upstream static pressure and the pressure at or immediately downstream of the restriction, to flow, with the following expression:

$$Q = kC_d \sqrt{\frac{2\Delta P}{\rho}} \qquad \text{…………………………………(5.18)}$$

where k is a lumped constant.

▶ The discharge coefficient C_d is a function of the diameter ratio, the Reynolds number Re, the design of the restriction, the location of the pressure taps and the friction due to pipe roughness. Generally, for most orifices the discharge coefficient ranges from 0.6 to 0.9. Reference texts and standards are available that list typical values and tolerances for C_d under certain flows in standard installations.

The discharge coefficient may also be calculated using the following (ISO) equation:

$$C_d = 0.5961 + 0.0261\beta^2 - 0.216\beta^3 + 0.000521\left(\frac{10^6\beta}{\text{Re}}\right)^{0.7} + \left(0.0188 + 0.0063\left(\frac{19000\beta}{\text{Re}}\right)^{0.8}\right)\left(\frac{10^6}{\text{Re}}\right)^{0.3}\beta^{3.5} +$$

$$\left(0.043 + 0.08\varepsilon^{-10L_1} - 0.123\varepsilon^{-7L_1}\right)\left(1 - 0.11\left(\frac{19000\beta}{\text{Re}}\right)^{0.8}\right)\frac{\beta^4}{1-\beta^4} - 0.031\left(\frac{2L_2}{1-\beta} - 0.8\left(\frac{2L_2}{1-\beta}\right)^{1.1}\right)\beta^{1.3}$$

……………………………..…….(5.19)

where:

β = diameter relation d/D
Re = Reynolds number
L_1 and L_2 are functions of the tap type where:
$L_1 = L_2 = 0$ for corner taps
$L_1 = 1$ and $L_2 = 0.47$ for D and D/2 taps
$L_1 = L_2 = 0.0254/D$ D (m) for 2.54 mm taps ◀

The foregoing formulae highlight two major limitations that are applicable to all differential pressure systems:

- the square root relationship between differential pressure (ΔP) and flow (Q) severely limits the turn-down ratio of such techniques to a maximum of 5:1 or less; and
- if density (ρ) is not constant, it must be known or measured. In practice the effect of density changes is not significant in the majority of liquid flow applications and needs only to be taken into account in the measurement of gas flow.

A third limitation of meters based on differential pressure measurement is that, as shown in Figure 5.3, they create a permanent pressure loss. This 'head' loss depends on the type of meter and on the square of the volume flow (Figure 5.4).

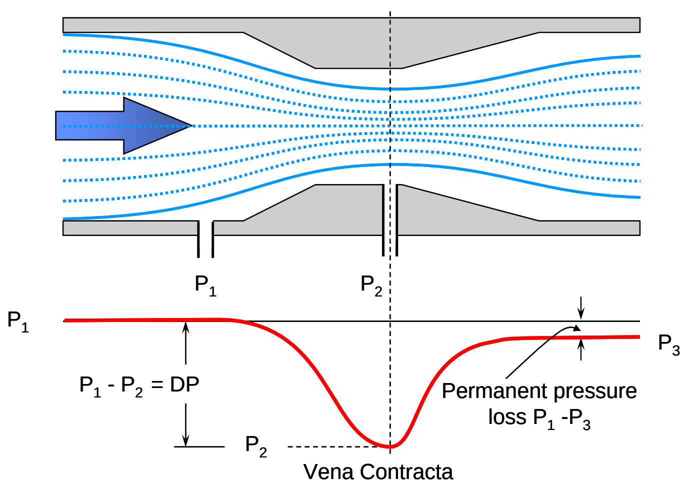


Figure 5.3. Defining the 'head' loss.

The point at which the minimum cross sectional area of the flow stream reaches a minimum is known as the '**vena contracta**' and occurs at, or just downstream of, the narrowest point of the venturi. The 'vena contracta' (L., literally, contracted vein) is characterized by high velocity, laminar flow.

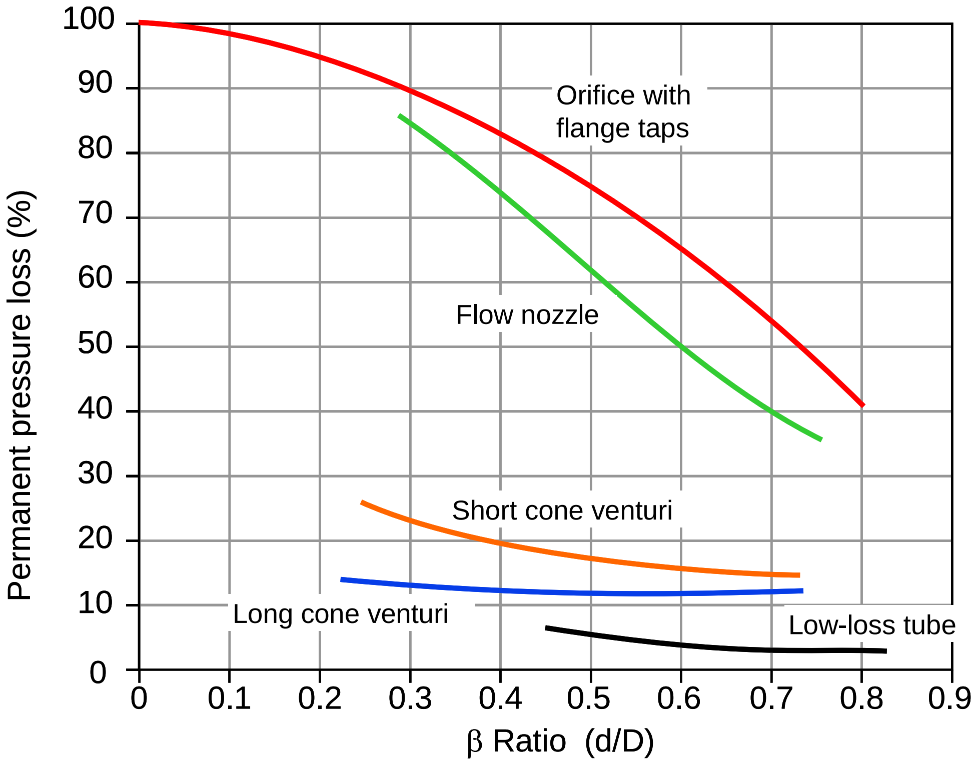


Figure 5.4. The permanent 'head' loss for various measurement techniques. The orifice plate produces the most drop whilst the Low-loss tube causes the least (courtesy Emerson).

5.2.3 Gas flow

► Vapour or gas flow through a restriction differs from liquid flow in that the pressure decrease in the throat is accompanied by a decrease in density. Thus, for the mass flow to remain constant, the velocity must increase to compensate for the lower density. The result is that the formula for gas flow is slightly modified by the addition of the term Y_1 **gas expansion factor** (= 1 for liquid);

$$Q = C_d \cdot E_v \cdot Y_1 \cdot d^2 \sqrt{\frac{2 \cdot \Delta P}{\rho}} \quad \text{.......................................(5.20)}$$

The gas expansion factor is based on the determination of density at the upstream of the restriction. Tables and graphs are available for the expansion factor as a function of the pressure ratio across the restriction and the specific heat of the gas (BS 1042). Alternatively, the expansion factor may be calculated by standard equations listed in BS 1042. The mass flow rate for both liquids and gases is found by multiplying the theoretical mass flow equation by the expansion factor and the appropriate discharge coefficient. ◄

5.3 Orifice plate

The orifice plate is the simplest and most widely used differential pressure flow measuring element and generally comprises a metal plate with a concentric round hole (orifice) through which the liquid flows (Figure 5.5). An integral metal tab facilitates installation and carries details of the plate size, thickness, serial number, etc. The plate, usually manufactured from stainless steel, Monel, or phosphor bronze, should be of sufficient thickness to withstand buckling (3 - 6 mm). The orifice features a sharp square upstream edge and, unless a thin plate is used, a bevelled downstream edge.

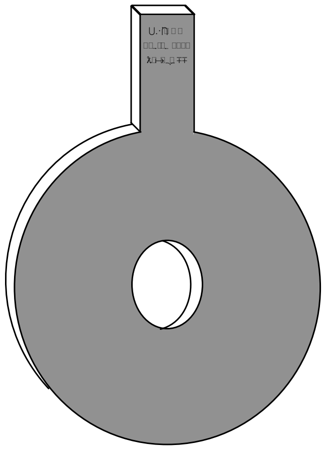


Figure 5.5. Concentric orifice plate with integral metal tab.

A major advantage of the orifice plate is that it is easily fitted between adjacent flanges that allow it to be easily changed or inspected (Figure 5.6).

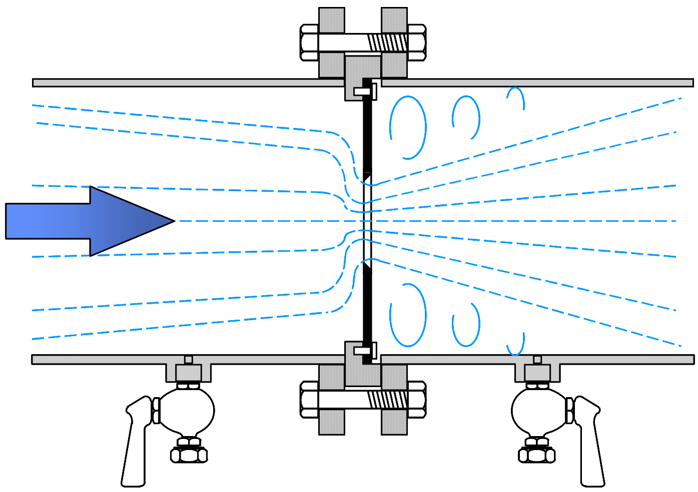


Figure 5.6. Orifice plate fitted between adjacent flanges.

It is commonly assumed that, since the orifice is essentially fixed, its performance does not change with time. In reality the orifice dimensions are extremely critical and although the uncertainty may be as low as 0.6% for a new plate, this measurement accuracy is rapidly impaired should the edge of the orifice bore become worn, burred or corroded.

Indeed, damaged, coated or worn plates that have not been examined for some time can lead to dramatic measurement uncertainties as shown in Figure 5.7. Even radiussing the sharp edge of the orifice by as little as 0.4 mm produces a reading inaccuracy of approximately 4%.

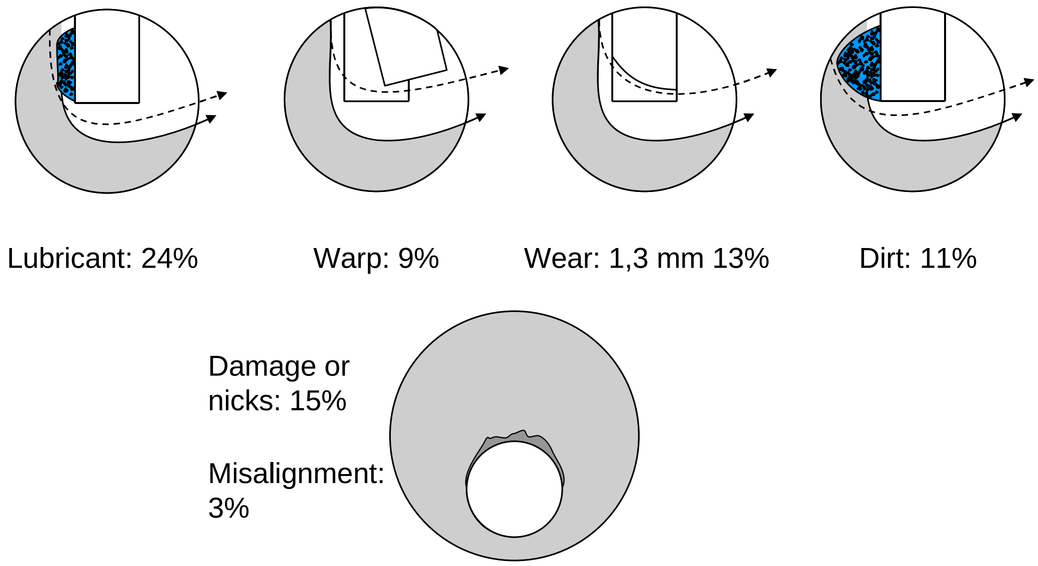


Figure 5.7. Errors incurred as a result of wear and contamination on the orifice plate. Independent tests carried out by Florida Gas Transmission Co. (courtesy Dieterich Standard).

Although a correctly installed new plate may have an uncertainty of 0.6%, the vast majority of orifice meters measure flow only to an accuracy of about ± 2 to 3%. This uncertainty is due mainly to errors in temperature and pressure measurement, variations in ambient and process conditions and the effects of upstream pipework.

An adaptation of the sharp, square edge is the quadrant edge orifice plate (also called quarter circle and round edge). As shown in Figure 5.8 this has a concentric opening with a rounded upstream edge that produces a coefficient of discharge that is practically constant for Reynolds numbers from 300 to 25 000, and is therefore useful for use with high viscosity fluids or at low flow rates.

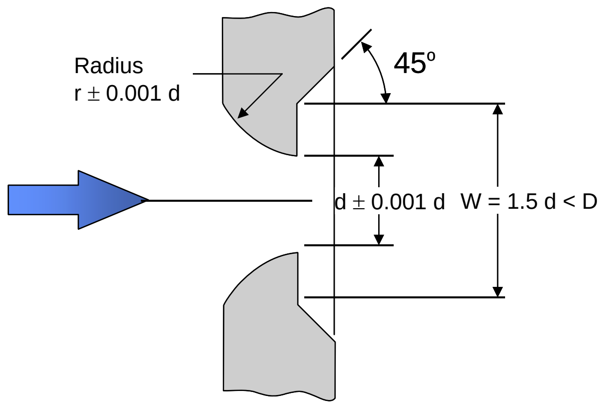


Figure 5.8. The quadrant edge orifice plate with a rounded upstream edge.

The radius of the edge is a function of the diameters of both the pipe and the orifice. In a specific installation this radius may be so small as to be impractical to manufacture or it can be so large that it practically becomes a flow nozzle. As a result, on some installations it may be necessary to change maximum differentials or even pipe sizes to obtain a workable solution for the plate thickness and its radius.

5.3.1 Orifice plate configurations

Although the concentric orifice (Figure 5.9 (a)) is the most frequently used, other plate configurations are used:

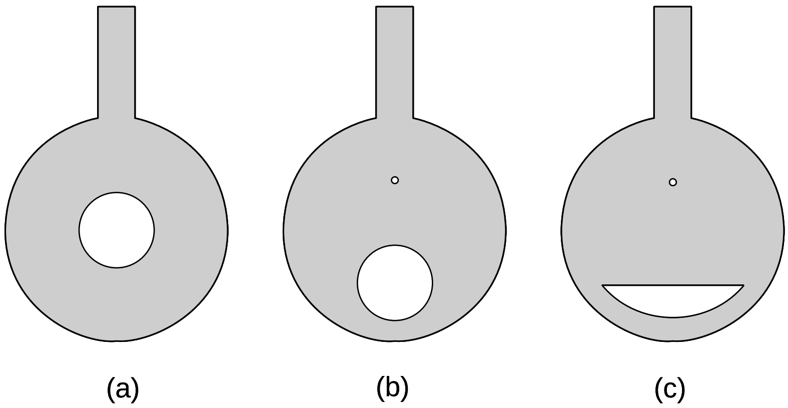


Figure 5.9. Various types of orifice plate configurations: (a) concentric; (b) eccentric; and (c) segmental.

Eccentric

In the eccentric bore orifice plate (Figure 5.9 (b)), the orifice is offset from the centre and is usually set at the bottom of the pipe bore. This configuration is mainly used in applications where the fluid contains heavy solids that might become trapped and accumulate on the back of the plate. With the orifice set at the bottom, these solids are allowed to pass. A small vent hole is usually drilled in the top of the plate to allow gas, which is often associated with liquid flow, to pass.

It should be noted, however, that the vent hole adds an unknown flow error and runs the risk of plugging.

Eccentric plates are also used to measure the flow of vapours or gases that carry small amounts of liquids (condensed vapours), since the liquids will carry through the opening at the bottom of the pipe.

The coefficients for eccentric plates are not as reproducible as those for concentric plates, and in general, the error can be 3 to 5 times greater than on concentric plates.

Segmental orifice plates

The opening in a segmental orifice plate (Figure 5.9 (c)) is a circular segment – comparable to a partially opened gate valve. This plate is generally employed for measuring liquids or gases that carry non-abrasive impurities, which are normally heavier than the flowing media such as light slurries, or exceptionally dirty gases.

5.3.2 Tapping points

The measurement of differential pressure requires that the pipe is ‘tapped’ at suitable upstream (high pressure) and downstream (low pressure) points. The exact positioning of these taps is largely determined by the application and desired accuracy.

Vena contracta tapping
Because of the fluid inertia, its cross-sectional area continues to decrease after the fluid has passed through the orifice. Thus its maximum velocity (and lowest pressure) is at some point downstream of the orifice – at the vena contracta. On standard concentric orifice plates these taps are designed to obtain the maximum differential pressure and are normally located one pipe diameter upstream and at the vena contracta – about ½-pipe diameter downstream (Figure 5.10).

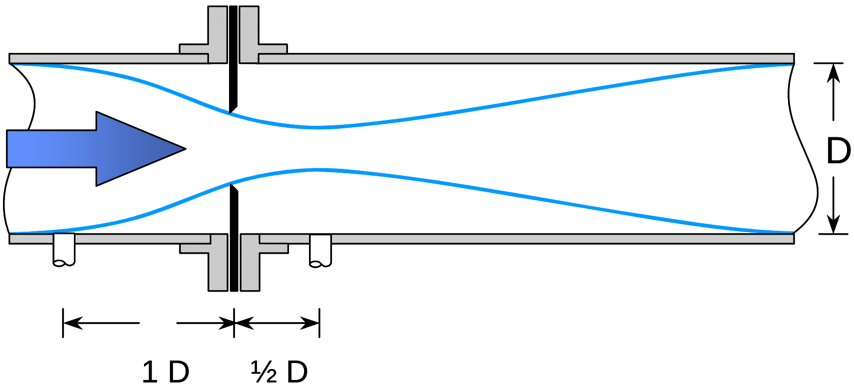


Figure 5.10. For maximum differential pressure the high pressure tap is located one pipe diameter upstream and the low pressure tap at the vena contracta – about ½-pipe diameter downstream.

The main disadvantage of using the vena contracta tapping point is that the exact location depends on the flow rate and on the orifice size – an expensive undertaking if the orifice plate size has to be changed.

Vena contracta taps should not be used for pipe sizes under 150 mm diameter because of interference between the flange and the downstream tap.

Pipe taps
Pipe taps (Figure 5.11) are a compromise solution and are located 2½ pipe diameters upstream and 8 pipe diameters downstream. Whilst not producing the maximum available differential pressure, pipe taps are far less dependent on flow rate and orifice size.

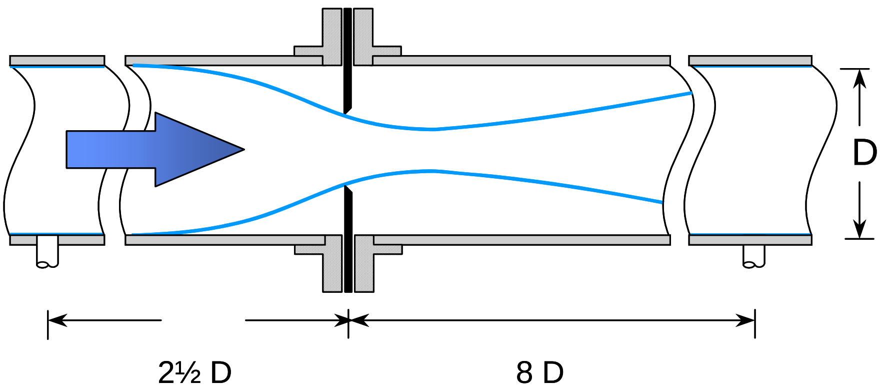
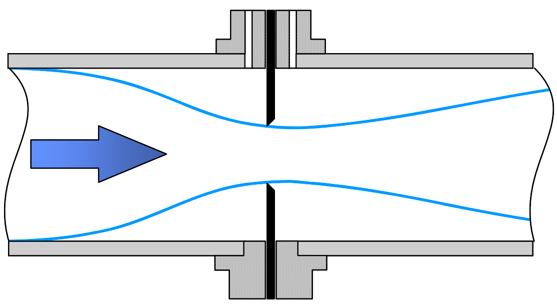


Figure 5.11. Pipe taps are far less dependent on flow rate and orifice size and are located 2½ pipe diameters upstream and 8 x pipe diameters downstream.

Pipe taps are used typically in existing installations, where radius and vena contracta taps cannot be used. They are also used in applications of greatly varying flow since the measurement is not affected by flowrate or orifice size. Since pipe taps do not measure the maximum available pressure, accuracy is reduced.

Flange taps

Flange taps are used when it is undesirable or inconvenient to drill and tap the pipe for pressure connections. Flange taps are quite common and are generally used for pipe sizes of 50mm and greater. They are, typically, located 25 mm either side of the orifice plate (Figure 5.12).



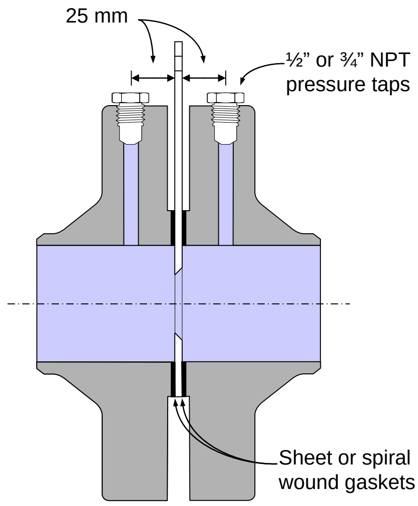


Figure 5.12. Flange taps are located 25 mm either side of the orifice plate.

Flange taps are not used for pipe diameters less than 50 mm, as the vena contracta starts to become close to and, possibly, forward of the downstream tapping point.

Usually, the flanges, incorporating the drilled pressure tappings, are supplied by the manufacturer. With the taps thus accurately placed by the manufacturer the need to recalculate the tapping point, when the plate is changed, is eliminated.

Corner taps

Suitable for pipe diameters less than 50 mm, corner taps are an adaptation of the flange tap (Figure 5.13) in which the tappings are made to each face of the orifice plate. The taps are located in the corner formed by the pipe wall and the orifice plate on both the upstream and downstream sides and require the use of special flanges or orifice holding rings.

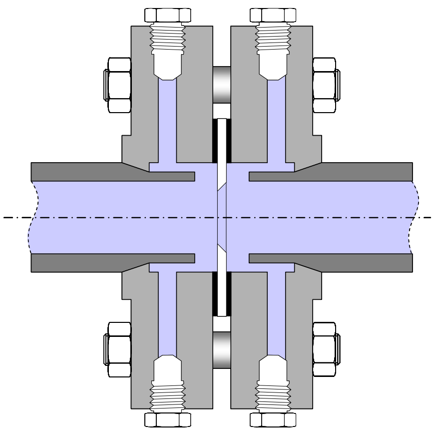


Figure 5.13. Corner tap is made to each face of the orifice plate.

5.3.3 Orifice plate sizing

Whilst use can be made of the formulae detailed in the equations to 17, 19 and 20 the modern practice is to make use of any one of a number of software sizing programs that are available from a number of sources. Several, are detailed below:

http://www.flowcalcs.com/

http://www.osti.gov/energycitations/prod...

http://www.farrisengineering.com/Product...

http://www.efunda.com/formulae/fluids/calc_orifice_flowmeter.cfm

http://www.flowmeterdirectory.com/flowmeter_orifice_calc.html

5.3.4 Orifice plates – general

At the beginning of this chapter it was stated that an important feature of differential type meters is that flow can be determined directly – without the need for calibration. This is particularly true for the orifice plate where there is a comprehensive range of standard designs that require no calibration.

5.3.4.1 Advantages

- Simple construction.
- Inexpensive.
- Robust
- Easily fitted between flanges.
- No moving parts.
- Large range of sizes and opening ratios.
- Suitable for most gases and liquids as well as steam.
- Price does not increase dramatically with size.
- Well understood and proven.

The advantages listed above would normally be listed in most textbooks on the subject of orifice plates. However, few observations regarding some of these 'advantages' are in order.

'Expensive' and 'inexpensive' are, of course, relative terms. Certainly the primary element, the orifice plate itself, is relatively inexpensive compared with other flow measuring systems. However, as shown in Figure 5.14 the orifice plate is only one part of a number of ancillary components that includes: the flange plate assembly, the isolation valves, the impulse tubing, the valve manifold, and the differential pressure transmitter.

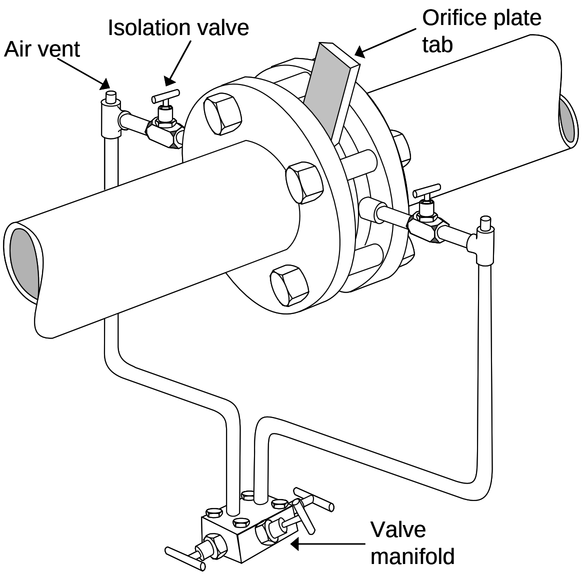


Figure 5.14. The orifice plate is only one of a number of ancillary components that includes the flange plate assembly, the isolation valves, the impulse tubing, the valve manifold, and the differential pressure transmitter (not shown).

Designing, purchasing, installing, and commissioning an orifice plate based flow measuring system can thus be a far more expensive proposal than first envisaged. In

Well understood and proven often has a negative connotation in that many technically challenged instrumentation personnel would rather follow well-established instrumentation solutions even if, as is often the case, they are extremely outdated.

5.3.4.2 Disadvantages

- Permanent pressure loss of head is quite high.
- Inaccuracy, typically 2 to 3%.
- Low turndown ratio, typically from 3 to 4:1.
- Accuracy is affected by density, pressure and viscosity fluctuations.
- Erosion and physical damage to the restriction affects measurement accuracy.
- Viscosity limits measuring range.
- Requires straight pipe runs to ensure accuracy is maintained.
- Pipeline must be full (typically for liquids).
- Output is not linearly related to flowrate.
- Multiple potential leakage points

5.3.4.2.1 Straight pipe run requirements

The inaccuracy with orifice type measurement is due mainly to process conditions and temperature and pressure variations. Ambient conditions and upstream and downstream piping also affect the accuracy because of changes to the pressure and continuity of flow.

The comparatively low turndown ratio is as a direct result for the need for square root extraction which severely limits the range over which the instrument can operate.

Standard concentric orifice plate devices should not be used for slurries and dirty fluids, or in applications where there is a high probability of solids accumulating near the plate. Half-circle or eccentric bores can be used for these applications. With modern differential pressure transducers, the rangeability can be substantially improved.

The need for straight runs of piping both before and after the orifice plate flow element is rarely met – often through ignorance; often through a 'we'll probably get away with it' attitude; but, more often, because of the piping layout was designed well ahead of the instrumentation requirements.

Without flow-straightening, a typical installation requires from 25 to 40 pipe diameters of straight run piping before the element and about 4 or 5 pipe diameters downstream of the element. These requirements vary quite considerably according to the upstream (and downstream) discontinuities and the beta ratio. Typically:

β ratio of 0.5: 25 pipe diameters upstream and (25 D) and 4 pipe diameters downstream (4D).
β ratio of 0.7: 40 D upstream and 5 D downstream

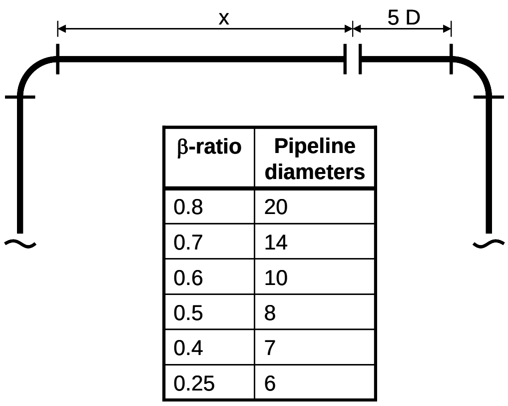
The requirements for custody transfer applications are considerably more onerous:

The **ASME** (MFC 3M) requires up to 54 D upstream and 5 D downstream

AGA (Report Number 3) specifies up to 95 D upstream and 4.2 D downstream;

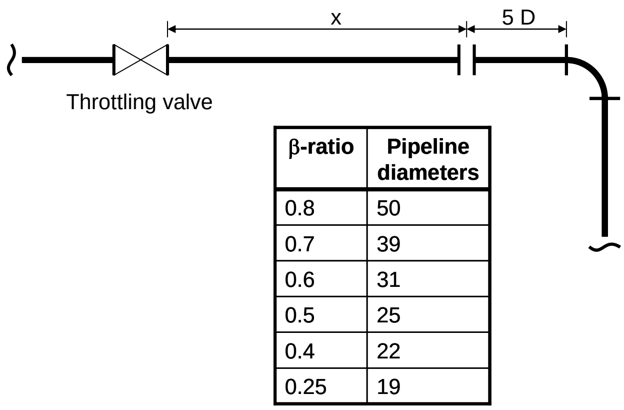
ISO 5167 specifies up to 60 D upstream and 7 D downstream.

The requirements for the **API (RP550**) are no less rigorous and specify the type of upstream and downstream disturbance (e.g. valve, elbow, double elbow, etc.) as illustrated in Figures 5.15 and 5.16.



β-ratio	Pipeline diameters
0.8	20
0.7	14
0.6	10
0.5	8
0.4	7
0.25	6

Figures 5.15. API (RP550) straight-pipe run lengths for a single upstream and downstream elbow, for differing beta ratios.



β-ratio	Pipeline diameters
0.8	50
0.7	39
0.6	31
0.5	25
0.4	22
0.25	19

Figures 5.16. API (RP550) straight-pipe run lengths for an upstream valve and a single downstream elbow.

5.3.4.2.2 Multiple leakage points

Figure 5.17 clearly illustrates the potential for multiple leakage points. Whilst many of these can be eliminated using continuous welded impulse tubing, the risks associated with blockages are increased.

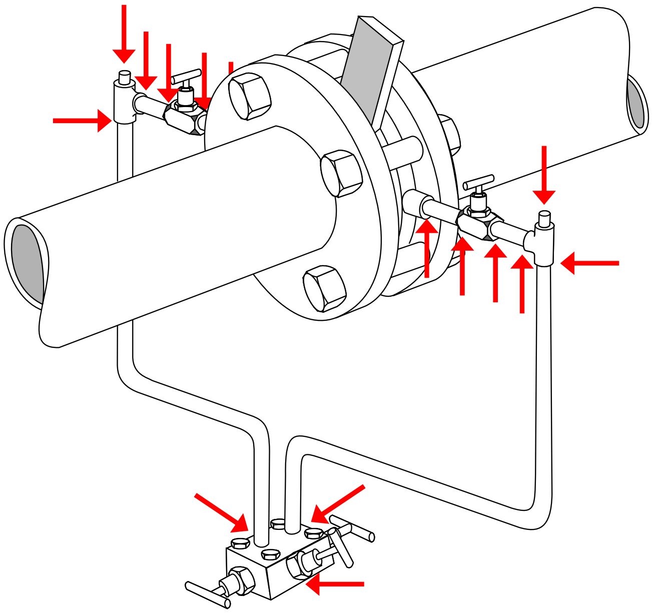


Figure 5.17. Potential for multiple leakage points.

5.3.4.2.3 Orifice plate thickness

As the differential pressure across the orifice increases, the plate tends to deform elastically and, beyond a certain point, the deformation results in a shift in the meter characteristics and an increase in the measurement uncertainty.

The thickness of an orifice plate should thus be sufficient to ensure that the deflection does not exceed certain limits. The thickness is generally determined according to the guidelines given by ISO-5167; ISA-RP-3.2; API-2530; and ASME-MFC-3M.
Theses are shown in Table 5.1.

Line size (DN)	Thickness in mm
< 150	3.18
> 200 < 400	6.125
> 450	9.53

Table 5.1. Orifice plate thickness according to pipeline size.

In addition the AGA -3 Appendix- 2-F provides guidelines for using high differential for measurement of natural gas. This maximum limit is dependent upon the thickness, diameter and beta ratio. For a given line size, there is always a maximum allowable differential pressure on the plate e.g. for 50 DN pipe, the maximum allowable ΔP is 1000 MPa in 2.5 bar with minimum thickness of 3.2 mm.

5.4 Conditioning orifice plate

The 'Conditioning Orifice Plate' introduced several years ago by Emerson overcomes the problem of upstream disturbances that cause swirl in a pipe and create an irregular flow profile. In a conventional concentric orifice plate (Figure 5.18) these effects are amplified, allowing the disturbance to impact measurement.

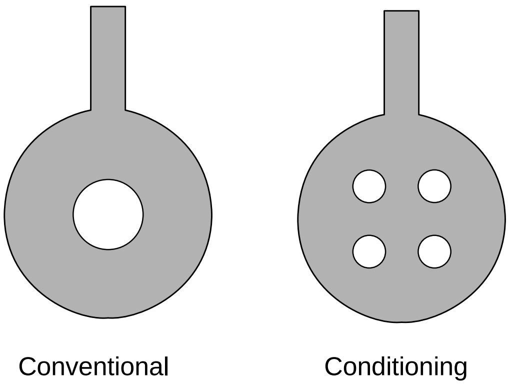


Figure 5.18 (a)conventional concentric orifice plate and (b) 'Conditioning Orifice Plate (courtesy Emerson).

The 'Conditioning Orifice Plate' is a differential pressure producer that differs from the conventional orifice plate in using four equally spaced holes (Figure 5.18) that are arranged in such a fashion as to leave a metal section of the plate in the center of the pipe. This causes the flow to condition itself as it is forced through the four holes – thus eliminating swirl and irregular flow profiles and removing the requirement for a flow conditioner.

The consequence of this arrangement is that the straight-run requirements are reduced to only 2 upstream and 2 downstream pipe diameters. Furthermore, the discharge coefficient (C_d) is reduced to ± 0.5%. A further benefit is that the four-hole design minimizes liquid hold-up, as compared with a standard orifice plate, without the need for an accuracy-reducing and plugging-prone vent hole.

The sum of the area of the four bores is equivalent to the area of a bore 'd' in the standard equation:

$$\beta = d/D \qquad (5.21)$$

for a schedule standard pipe.

The Conditioning Orifice Plate is designed with 2 standard bore sizes, one for high flow rates and one for low flow rates having bores equal to betas of 0.4 and 0.65.

5.5 Segmental wedge meter

The segmental wedge element has a V-shaped restriction cast or welded into a flanged meter body that creates a differential pressure. The restriction is characterized by the h/D ratio (Figure 5.19), corresponding to the β ratio of an orifice plate, where (h) is the height of the opening below the restriction (the only critical dimension) and (D) is the inside diameter of the pipe.

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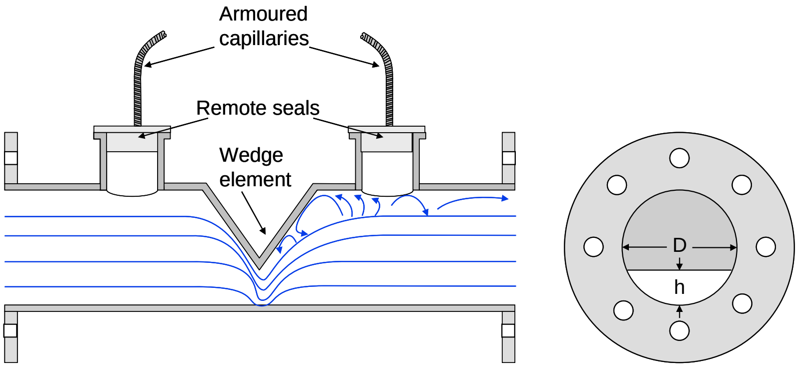


Figure 5.19. The segmental wedge element has a V-shaped restriction cast or welded into a flanged meter body that creates a differential pressure.

The slanting upstream face of the wedge element is insensitive to wear and creates a sweeping action that has a scouring effect that helps to keep it clean and free of build-up. Further, because of the wedge does not restrict the bottom of the pipe, it can be used for a variety of corrosive, erosive, and highly viscous fluids and slurries. The discharge coefficient (C_d) is a stable for Reynolds numbers of less than 500 – allowing it to be used down to laminar flow regimes. Further , because the discharge coefficient is highly insensitive to velocity profile distortion and swirl, only 5 pipe diameters of relaxation piping is required upstream of the meter for most common combinations of fittings and valves. An uncalibrated element has a C_d uncertainty of 2 to 5% whilst for a calibrated system is 0.5%. The largest source of measurement error is generally due to the variations in the density which, if not measured, is taken as an assumed 'normal' value.

A typical segmental wedge meter is provided as a complete assembly combining the wedge element and the pressure taps into a one-piece unit (Figure 5.20). The upstream and downstream pressure taps are usually in the form of remote diaphragm seals – eliminating the need for lead lines.

Figure 5.20. A typical segmental wedge meter is provided as a complete assembly combining the wedge element and the pressure taps into a one-piece unit (courtesy PFS Inc.).

Because of its as symmetrical design the primary segmental wedge can be used to measure bidirectional flow, but would require two differential pressure transmitters.

5.6 V-Cone meter

The V-Cone Flowmeter from McCrometer is a patented technology that features a centrally-located cone inside the flow tube that interacts with the fluid and creates a region of lower pressure immediately downstream of the cone.

The pressure difference is measured between the upstream static line pressure tap, placed slightly upstream of the cone, and the downstream low pressure tap located in the downstream face of the cone (Figure 5.21).

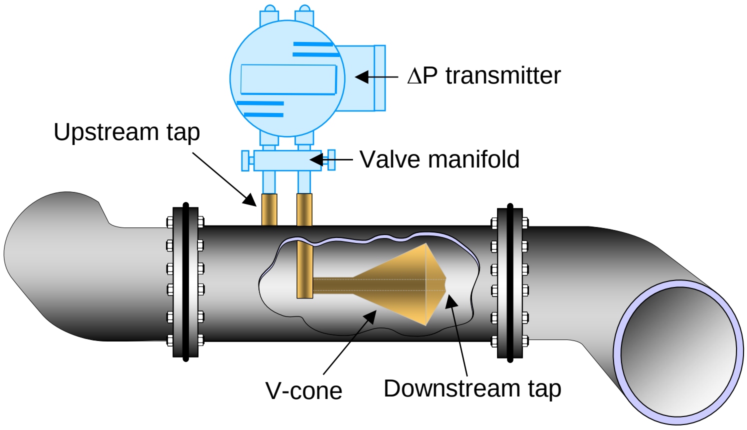


Figure 5.21. The pressure difference is measured between the upstream static line pressure tap, placed slightly upstream of the cone, and the downstream low pressure tap located in the downstream face of the cone (courtesy McCrometer).

Because the cone is suspended in the center of the pipe, it interacts directly with the "high velocity core" of the flow – forcing it to mix with the lower velocity flows closer to the pipe walls. As a consequence, the flow profile is flattened toward the shape of a well-developed profile – even under extreme conditions, such as single or double elbows out-of-plane positioned closely upstream of the meter. (Figure 5.22). The V-Cone's contour shaped cone also directs the flow without impacting it against an abrupt surface. As a result, the beta edge of the cone is not subject to wear by dirty fluids.

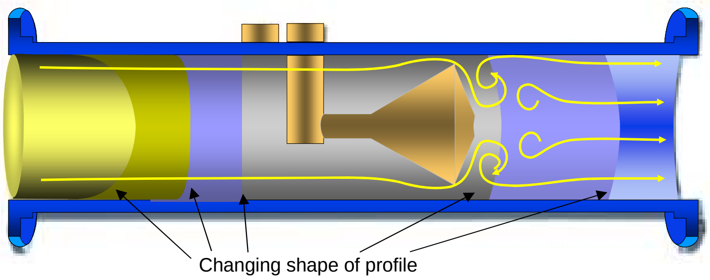


Figure 5.22. The flow profile is flattened toward the shape of a well-developed profile – even under extreme conditions, such as single or double elbows out-of-plane positioned closely upstream of the meter (courtesy McCrometer).

Other major features of the V-Cone Flowmeter include:

- 0 to 3 diameters straight run piping upstream and 0 to 1 diameters downstream.
- primary element accuracy of ±0.5% of reading with a repeatability of ±0.1% or better.
- turndown ratio 10:1 with Reynolds numbers as low as 8000.
- Suitable for use with dirty fluids

5.7 Venturi tube meter

The venturi tube (Figure 5.23) has tapered inlet and outlet sections with a central parallel section, called the throat, where the low pressure tapping is located.

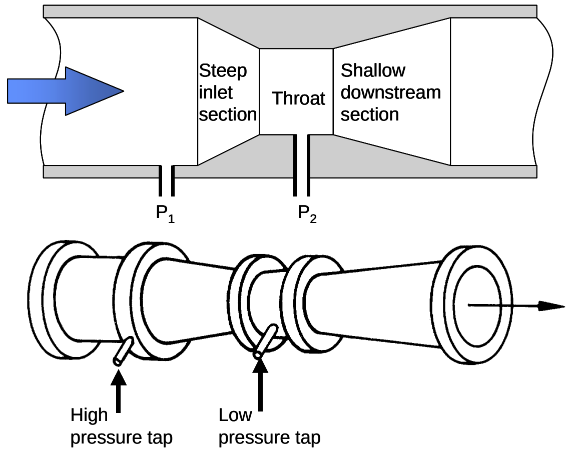


Figure 5.23. The venturi tube has tapered inlet and outlet sections with a central parallel section (courtesy Emerson).

Generally, the inlet section, which provides a smooth approach to the throat, has a steeper angle than the downstream section. The shallower angle of the downstream section reduces the overall permanent pressure loss by decelerating the flow smoothly and thus minimising turbulence. Consequently, one of the main advantages of the venturi tube meter over other differential pressure measuring methods is that its permanent pressure loss is only about 10 % of the differential pressure (Figure 5.4). At the same time, its relatively stream-lined form allows it to handle about 60 % more flow than, for example, that of an orifice plate.

The venturi tube also has relatively high accuracy: better than ± 0.75 % over the orifice ratios (d/D) of 0.3 to 0.75. This order of accuracy, however, can only be obtained as long as the dimensional accuracy is maintained. Consequently, although the venturi tube can also be used with fluids carrying a relatively high percentage of entrained solids, it is not well suited for abrasive media.

Although generally regarded as the best choice of a differential type meter for bores over 1000 mm, the major disadvantage of the venturi type meter is its high cost – about 20 times more expensive than an orifice plate. In addition, its large and awkward size makes it difficult to install since a 1 m bore venturi is 4 - 5 m in length.
Although it is possible to shorten the length of the divergent outlet section by up to 35%, thus reducing the high manufacturing cost without greatly affecting the characteristics, this is at the expense of an increased pressure loss.

Advantages

- Less significant pressure drop across restriction.
- Less unrecoverable pressure loss.
- Requires less straight pipe up and downstream.

Disadvantages

- More expensive.
- Bulky – requires large section for installation.

5.8 Venturi nozzle meters

The venturi nozzle is an adaptation of the standard venturi that makes use of a 'nozzle' shaped inlet (Figure 5.24), a short throat and a flared downstream expansion section. Whilst increasing the permanent pressure loss to around 25 % of the measured differential pressure of the standard venturi, the venturi nozzle is cheaper, requires less space for installation, and yet still retains the benefits of high accuracy (± 0.75%) and high velocity flow.

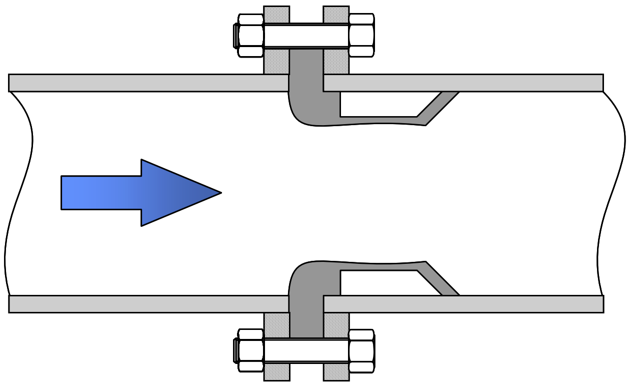


Figure 5.24. The venturi nozzle is an adaptation of the standard venturi using a 'nozzle' shaped inlet.

5.9 Flow nozzle meters

The flow nozzle (Figure 5.25) is used mainly in high velocity applications or where fluids are being discharged into the atmosphere. It differs from the nozzle venturi in that it retains the 'nozzle' inlet but has no exit section.

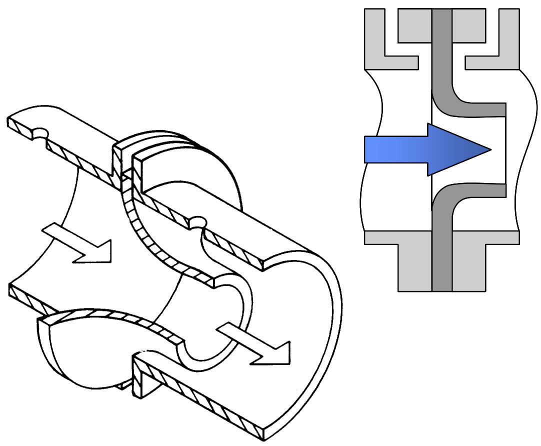


Figure 5.25. The flow nozzle is used mainly in high velocity applications (courtesy Emerson).

The main disadvantage of the flow nozzle is that the permanent pressure loss is increased to between 30 to 80% of the measured differential pressure – depending on its design.

Offsetting this disadvantage, however, accuracy is only slightly less than for the venturi tube (± 1 to 1.5 %) and it is usually only half the cost of the standard venturi. In addition it requires far less space for installation and, because the nozzle can be mounted between flanges or in a carrier, installation and maintenance are much easier than for the venturi.

5.10 The Dall tube

Although many variations of low-loss meters have appeared on the market, the best-known and most commercially successful is the Dall tube (Figure 5.26).

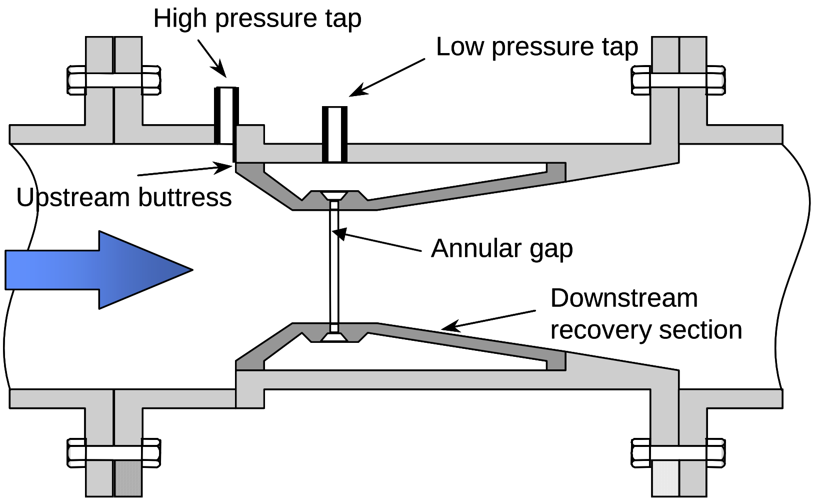


Figure 5 .26. The Dall tube low-loss meter.

The Dall tube is virtually throatless and has a short steep converging cone that starts at a stepped buttress whose diameter is somewhat less than the pipe diameter. Following an annular space at the 'throat', there is a diverging cone that again finishes at a step.

A major feature of the Dall tube is the annular space between the 'liner' and tube into which the flowing media passes to provide an average 'throat' pressure.

With a conventional venturi, upstream and throat tappings are taken at points of parallel flow where the pressures across a cross section are constant. If the streamlines were curved the pressure would not be constant over the cross section but would be greater at the convex surface and less at the concave surface.

In the Dall tube, the upstream tapping is taken immediately before the buttress formed by the start of the converging cone, where the convex curvature of the streamlines is at a maximum. At the 'throat', where there is an immediate change from the converging to diverging section, the 'throat' tapping is thus taken at the point of maximum concave curvature. This means that a streamlined curvature head is added to the upstream pressure and subtracted from the 'throat' pressure and the differential pressure is considerably increased. Thus, for a given differential head the throat can be larger – reducing the head loss.

Because of the annular gap, no breakaway of the liquid from the wall occurs at the throat and the flow leaves the 'throat' as a diverging jet. Since this jet follows the walls of the diverging cone, eddy losses are practically eliminated, while friction losses are small because of the short length of the inlet and outlet sections. The main disadvantages are: high sensitivity to both Reynolds number and cavitation and manufacturing complexity.

5.11 Target meter

The target flowmeter is, in effect, an 'inside out' orifice plate used to sense fluid momentum. Sometimes called a drag disc or drag plate, the target meter usually takes the form of a disc mounted within the line of flowing fluid (Figure 5.27). The flow creates a differential pressure force across the target and the resultant deflection is transmitted to a flexure tube – with strain gauge elements mounted external to the flowing medium indicating the degree of movement.

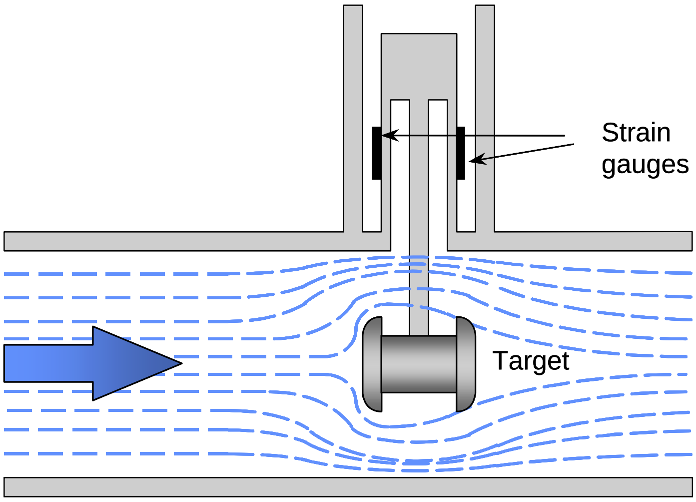


Figure 5.27. The target flowmeter – an 'inside out' orifice plate.

The major advantages of the target meter include: ability to cope with highly viscous fluids at high temperatures (hot tarry and sediment-bearing fluids); free passage of particles or bubbles; and no pressure tap or lead line problems.

Disadvantages include: limited size availability; limited flow range; and high head loss.

5.12 Pitot tube

The Pitot tube is one of the oldest devices for measuring velocity and is frequently used to determine the velocity profile in a pipe by measuring the velocity at various points.

In its simplest form the Pitot tube (Figure 5.28) comprises a small tube inserted into a pipe with the head bent so that the mouth of the tube faces into the flow. As a result, a small sample of the flowing medium impinges on the open end of the tube and is brought to rest. Thus, the kinetic energy of the fluid is transformed into potential energy in the form of a head pressure (also called stagnation pressure).

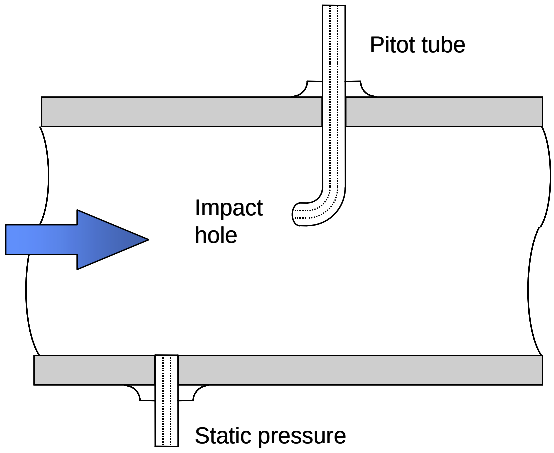


Figure 5.28. Basic Pitot tube illustrating principle of operation.

▶ Mathematically this can be expressed by applying Bernoulli's equation to a point in the small tube and a point in the free flow region. From Bernoulli's general equation:

$$P_1 + ½\rho v_1^2 + \rho g h_1 = P_2 + ½\rho v_2^2 + \rho g h_2 \quad \text{……………………………………….(5.22)}$$

we can write:

$$P_h/\rho + 0 + gh_1 = P_s/\rho + v^2/2 + gh_2 \quad \text{…………………………………….(5.23)}$$

where:

P_s = static pressure
P_h = stagnation pressure
v = liquid velocity
g = acceleration due to gravity
h_1 and h_2 = heads of the liquid at the static and stagnation pressure measuring points respectively

If $h_1 = h_2$ then:

$$v = \sqrt{\frac{2\left(P_h - P_s\right)}{\rho}} \quad \text{…………………………………….(5.24)}$$

Because the Pitot tube is an intrusive device and some of the flow is deflected around the mouth, a compensatory flow coefficient K_p is required. Thus :

$$v = K_p \sqrt{\frac{2\ \Delta P}{\rho}} \qquad \text{......................................(5.25)}$$

For compressible fluids at high velocities (for example, > 100 m/s in air) a modified equation should be used. ◀

By measuring the static pressure with a convenient tapping, the flow velocity can be determined from the difference between the head pressure and the static pressure. This difference, measured by a differential pressure cell, provides a measurement of flow that, like a conventional differential pressure measurement, obeys a square root relationship to pressure. Low flow measurement at the bottom end of the scale is thus difficult to achieve accurately.

A problem with this basic configuration is that the flow coefficient K_p depends on the tube design and the location of the static tap. One means of overcoming this problem is to use a system as shown in Figure 5.29 that makes use of a pair of concentric tubes – the inner tube measuring the full head pressure and the outer tube using static holes to measure the static pressure.

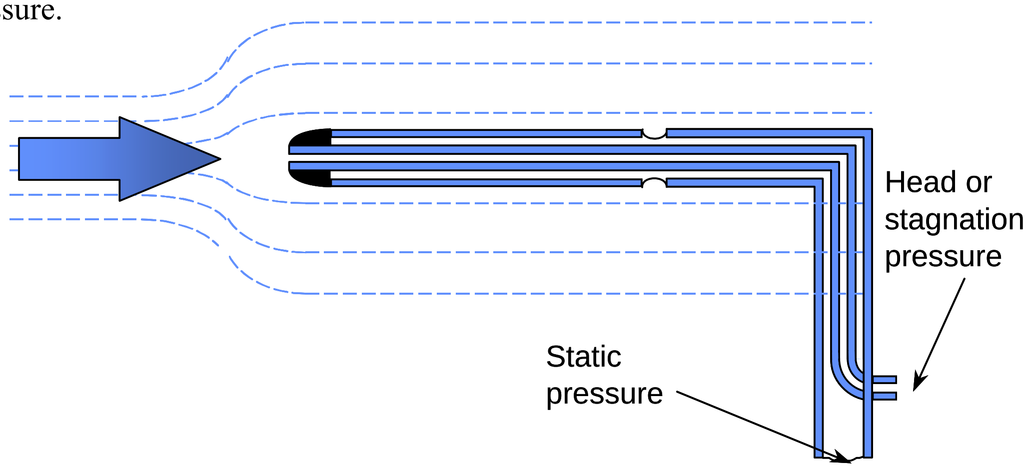


Figure 5.29. Integrated Pitot tube system in which the inner tube measures the head pressure and the outer tube uses static holes to measure the static pressure.

Both these designs of Pitot tube measure the point velocity. However it is possible to calculate the mean velocity by sampling the point velocity at several points within the pipe.

Alternatively, provided a fully developed turbulent profile exists, a rough indication of the average velocity can be obtained by positioning the tube at a point three-quarters of the way between the centreline and the pipe wall.

5.13 Point averaging

Another method of determining the average velocity is with a point averaging Pitot tube system (Figure 5.30).

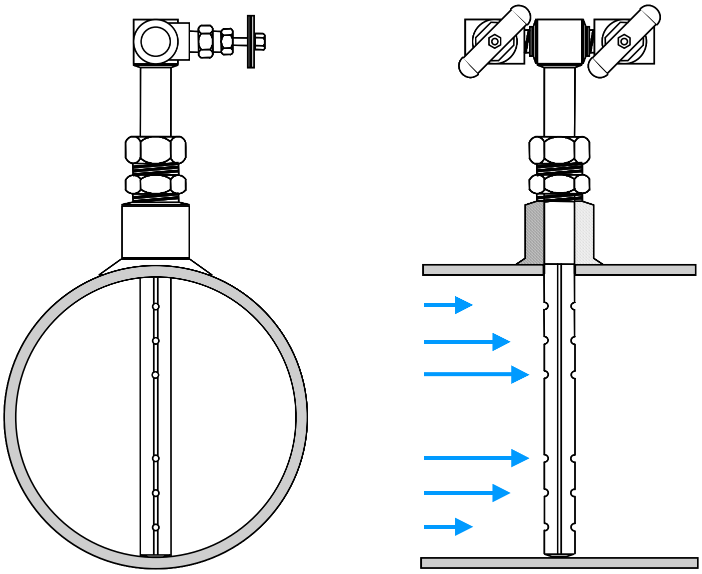


Figure 5.30. Multiport 'Annnubar' Pitot averaging system (courtesy Dieterich Standard).

Essentially, this instrument comprises two back-to-back sensing bars, that span the pipe, in which the up- and down-stream pressures are sensed by a number of critically located holes. The holes in the upstream detection bar are arranged so that the average pressure is equal to the value corresponding to the average of the flow profile.

Because the point at which the fluid separates from the sensor varies according to the flow rate (Figure 5.31) extreme care must be taken in positioning the static pressure sensing holes. One solution is to locate the static pressure point just before the changing separation point.

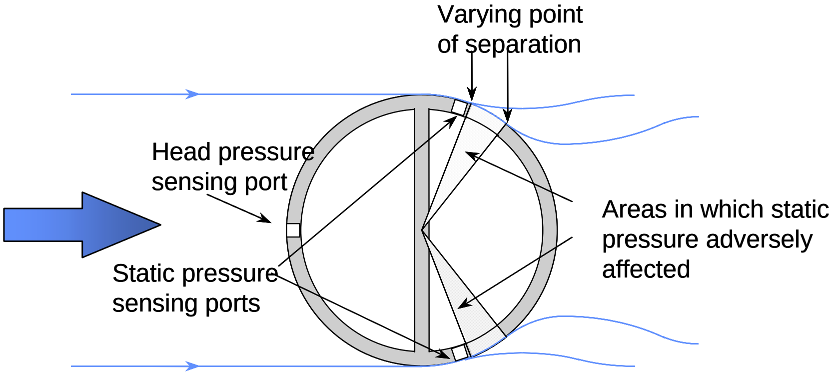


Figure 5.31. Variation in flow velocity can affect point of separation and the downstream static pressure measurement.

Alternatively, a 'shaped' sensor (Figure 5.32) can be used to establish a fixed point where the fluid separates from the sensor.

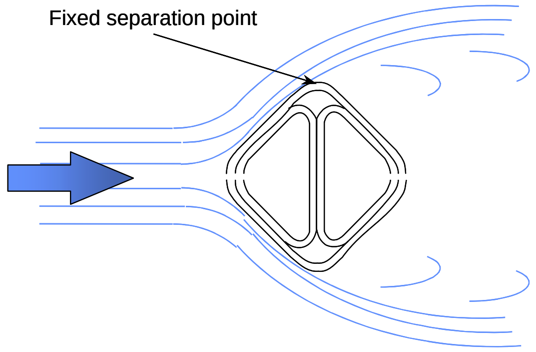


Figure 5.32. 'Shaped' bluff body establishes a fixed separation point (courtesy Dieterich Standard).

These multi-port averaging devices, commonly called 'Annubars' after the first design, are used mainly in metering flows in large bore pipes – particularly water and steam. Properly installed, 'Annubar' type instruments have a repeatability of 0.1% and an accuracy of 1% of actual value.

Although intrusive, averaging Pitot type instruments offer a low pressure drop and application on a wide range of fluids. Because they average the flow profile across the diameter of the pipe bore, they are less sensitive to the flow profile than, for example, an orifice plate and can be used as little as 2½ pipe diameters downstream of a discontinuity. On the negative side, the holes are easily fouled if used on 'dirty' fluids.

On a conventional integrated Pitot tube, the alignment can be critical. Misalignment causes errors in static pressure since a port facing slightly upstream is subject to 'part' of the stagnation or total pressure. A static port facing slightly downstream is subjected to a slightly reduced pressure.

5.14 Elbow

In applications where cost is a factor and additional pressure loss from an orifice plate is not permitted, a pipe elbow can be used as a differential pressure primary device. Elbow taps have an advantage in that most piping systems have elbows that can be used.

If an existing elbow is used then no additional pressure drop occurs and the expense involved is minimal. They can also be produced in-situ from an existing bend, and are typically formed by two tappings drilled at an angle of 45^o through the bend (Figure 5.33). These tappings provide the high and low pressure tapping points respectively. Whilst 45^o tappings are more suited to bi-directional flow measurement, tappings at 22.5^o can provide more stable and reliable readings and are less affected by upstream piping.

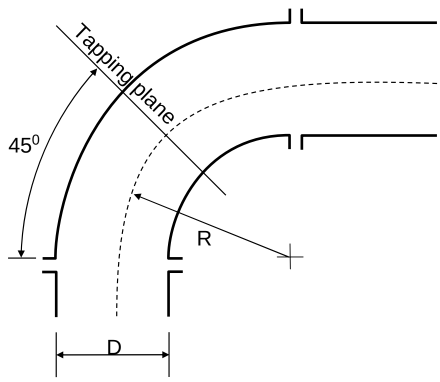


Figure 5.33. Elbow meter geometry

A number of factors contribute to the differential pressure that is produced and, subsequently, it is difficult to predict the exact flow rate accurately. Some of these factors are:

- force of the flow onto the outer tapping;
- turbulence generated due to cross-axial flow at the bend;
- differing velocities between outer and inner radius of flow;
- pipe texture; and
- relationship between elbow radius and pipe diameter.

Generally, the elbow meter is only suitable for higher velocities and cannot produce an accuracy of better than 5% . However, on-site calibration can produce more accurate results, with the added advantage that repeatability is good.

Although the elbow meter is not commonly used, it is underrated since its low cost, together with its application after completion of pipework, can be a major benefit for low accuracy flow metering applications.

Suitable applications would include plant air conditioning, cooling water metering, site flow checkpoints possibly with local indicators and check flow applications, where the cost of magnetic meters is prohibitive.

For installation, it is recommended that the elbow be installed with 25 pipe diameters of straight pipe upstream and at least 10 pipe diameters of straight pipe downstream.

5.15 Troubleshooting

One of the most common inaccuracies induced in differential pressure flowmeters is not allowing enough straight pipe. When the flow material approaches and passes some change in the pipe, small eddies are formed in the flow stream. These eddies are localised regions of high velocity and low pressure and can start to form upstream of the change and dissipate further downstream.

Flowmeter sensors detect these changes in pressure and consequently produce erratic or inaccurate readings for flow rate.

5.16 Variable area meters

The variable area flowmeter is a reverse differential pressure meter used to measure the flow rate of liquids and gases.

5.16.1 Operating principle

The instrument generally comprises a vertical, tapered glass tube and a weighted float whose diameter is approximately the same as the tube base (Figure 5.34).

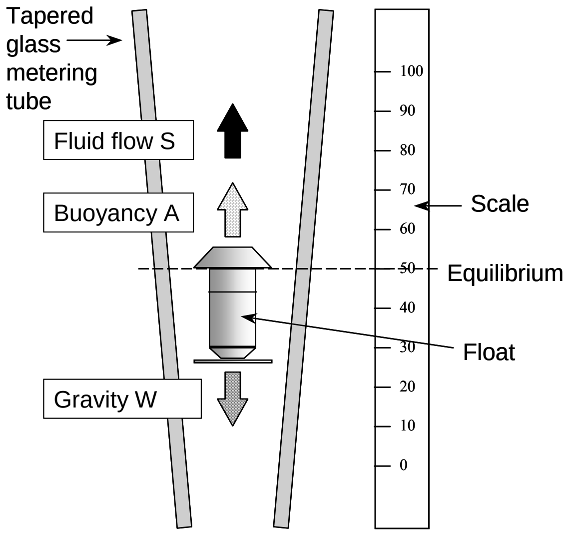


Figure 5.34. Basic configuration of a variable area flowmeter (courtesy Brooks Instrument).

In operation, the fluid or gas flows through the inverted conical tube from the bottom to the top, carrying the float upwards. Since the diameter of the tube increases in the upward direction the float rises to a point where the upward force on the float created by differential pressure across the annular gap, between the float and the tube, equals the weight of the float.

As shown in Figure 5.34, the three forces acting on the float are:

- constant gravitational force W;
- buoyancy A that, according to Archimedes' principle, is constant if the fluid density is constant; and
- force S, the upward force of the fluid flowing past the float.

For a given instrument, when the float is stationary, W and A are constant and S must also be constant. In a position of equilibrium (floating state) the sum of forces S + A is opposite and equal to W and the float position corresponds to a particular flow rate that can be read off a scale. A major advantage of the variable area flowmeter is that the flow rate is directly proportional to the orifice area that, in turn, can be made to be linearly proportional to the vertical displacement of the float. Thus, unlike most differential pressure systems, it is unnecessary to carry out square root extraction.

The taper can be ground to give special desirable characteristics such as an offset of higher resolution at low flows.

▶ In a typical variable area flowmeter, the flow q can be shown to be approximately given by:

$$q = C A \sqrt{\rho} \quad \text{……………………………(5.26)}$$

where:

q	=	flow
C	=	constant that depends mainly on the float
A	=	cross-sectional area available for fluid flow past the float
ρ	=	density of the fluid

Indicated flow, therefore, depends on the density of the fluid which, in the case of gases, varies strongly with the temperature, pressure and composition of the gas.

It is possible to extend the range of variable area flowmeters by combining an orifice plate in parallel with the flow meter.◀

5.16.2 Floats

A wide variety of float materials, weights, and configurations is available to meet specific applications.

The float material is largely determined by the medium and the flow range and includes: stainless steel, titanium, aluminium, black glass, synthetic sapphire, polypropylene, Teflon, PVC, hard rubber, Monel, nickel and Hastelloy C.

5.16.3 Float centring methods

An important requirement for accurate metering is that the float is exactly centred in the metering tube. One of three methods is usually applied:

1. Slots in the float head cause the float to rotate and centre itself and prevent it sticking to the walls of the tube (Figure 5.35). This arrangement led to the term 'Rotameter', a registered trademark of KDG Instruments Ltd, being applied to variable area flow meters. Slots cannot be applied to all float shapes and, further, can cause the indicated flow to become slightly viscosity dependent.

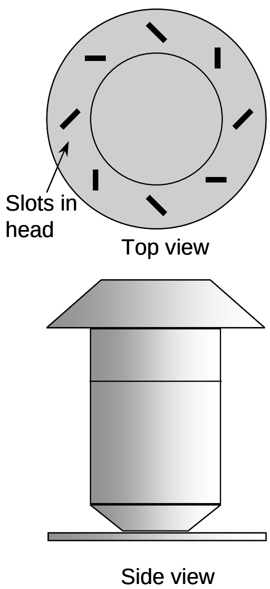


Figure 5.35. Float centring in which a slotted float head rotates and automatically centres itself.

2. Three moulded ribs within the metering tube cone (Figure 5.36), parallel to the tube axis, guide the float and keep it centred. This principle allows a variety of float shapes to be used and the metering edge remains visible even when metering opaque fluids.

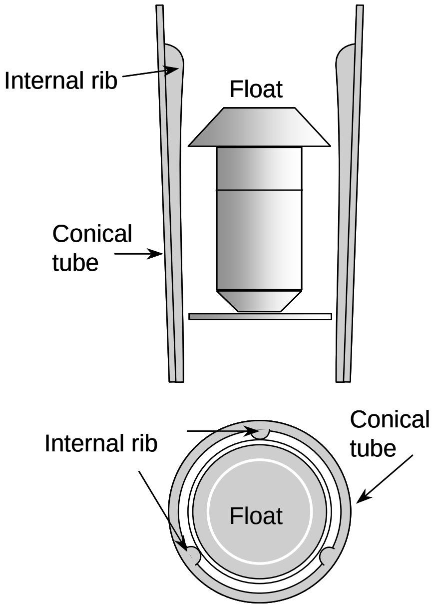


Figure 5.36. Float centring in which the float is centred by three moulded ribs parallel to the tube axis.

3.

A fixed centre guide rod within the metering tube (Figure 5.37 (a)) is used to guide the float and keep it centred. Alternatively, the rod may be attached to the float and moved within fixed guides (Figure 5.37 (b)). The use of guide rods is confined mainly to applications where the fluid stream is subject to pulsations likely to cause the float to 'chatter' and possibly, in extreme cases, break the tube. It is also used extensively in metal metering tubes.

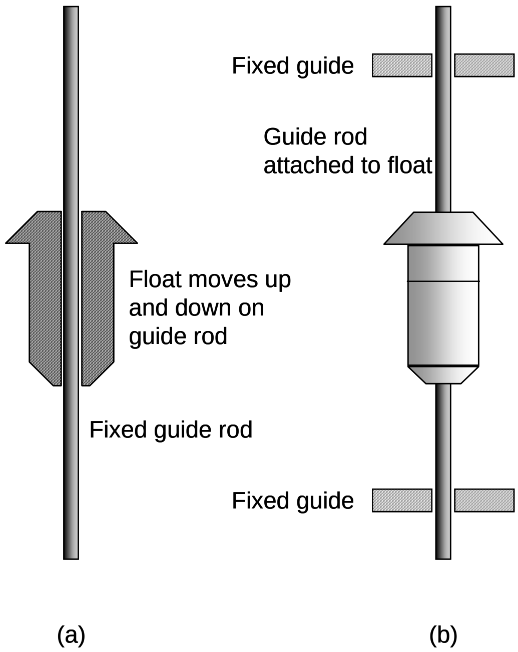


Figure 5.37. Float is centred by (a) fixed centre guide rod; or (b) guide rod attached to the float (courtesy Bailey-Fischer & Porter).

5.16.4 Float shapes

The design of the floats is confined to four basic shapes (Figure 5.38):

- ball float;
- rotating (viscosity non-immune) float;
- viscosity immune float; and
- float for low pressure losses.

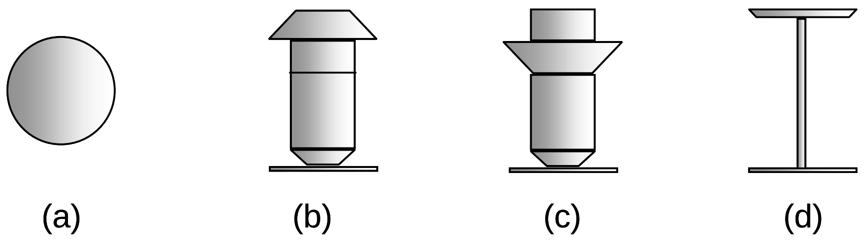


Figure 5.38. (a) ball float; (b) rotating (viscosity non-immune) float; (c) viscosity immune float; and (d) float for low pressure losses (courtesy Bailey-Fischer & Porter).

Ball float

The ball float (Figure 5.38 (a)) is mainly used as a metering element for small flowmeters – with its weight determined by selecting from a variety of materials. Figure 5.39 shows the effect of viscosity on the flow rate indication. Since its shape cannot be changed, the flow coefficient is clearly defined (1) and, as shown, exhibits virtually no linear region. Thus, any change in viscosity, due often to small changes in temperature, results in changes in indication.

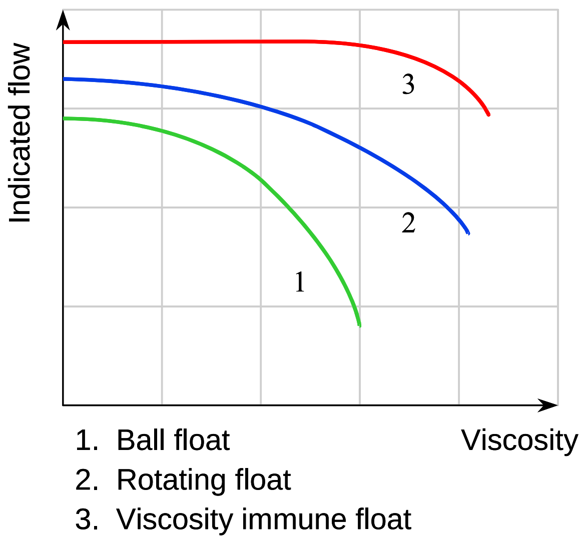


Figure 5.39. Viscosity effect for various float shapes(courtesy Bailey-Fischer & Porter).

Rotating float
Rotating floats (Figure 5.38 (b)) are used in larger sized meters and are characterised by a relatively narrow linear (viscosity-immune) region as shown in Figure 5.39 (2).

Viscosity immune float
The viscosity immune float (Figure 5.38 (c)) is appreciably less sensitive to changes in viscosity and is characterised by a wider linear region as shown in Figure 5.39 (3). Although such an instrument is unaffected by relatively large changes in viscosity, the same size meter has a span 25% smaller than the previously described rotating float.

Low pressure loss float
For gas flow rate metering, light floats (Figure 5.38 (d)) with relatively low pressure drops can be used.

The pressure drop across the instrument is due, primarily, to the float since the energy required to produce the metering effect is derived from the pressure drop of the flowing fluid. This pressure drop is independent of the float height and is constant.

Further pressure drop is due to the meter fittings (connection and mounting devices) and increases with the square of the flow rate. For this reason, the design requires a minimum upstream pressure.

5.16.5 Metering tube
The meter tube is normally manufactured from borosilicate glass that is suitable for metering process medium temperatures up to 200 °C and pressures up to about 2 - 3 MPa.

Because the glass tube is vulnerable to damage from thermal shocks and pressure hammering, it is often necessary to provide a protective shield around the tube.

Variable area meters are inherently self-cleaning since the fluid flow between the tube wall and the float provides a scouring action that discourages the build-up of foreign matter. Nonetheless, if the fluid is dirty, the tube can become coated – affecting calibration and preventing the scale from being read. This effect can be minimised through the use of an in-line filter.

In some applications use can be made of an opaque tube used in conjunction with a float follower. Such tubes can be made from steel, stainless steel, or plastic.

By using a float with a built-in permanent magnet, externally mounted reed-relays can be used to detect upper and lower flow limits and initiate the appropriate action.

The temperature and pressure range may be considerably extended (for example up to 400 °C and 70 MPa) through the use of a stainless steel metering tube. Again, the float can incorporate a built-in permanent magnet that is coupled to an external field sensor that provides a flow reading on a meter.

In cases where the fluid might contain ferromagnetic particles that could adhere to the magnetic float, a magnetic filter should be installed upstream of the flowmeter. Typically (Figure 5.40) such a filter contains bar magnets, coated with PTFE as protection against corrosion, arranged in a helical fashion.

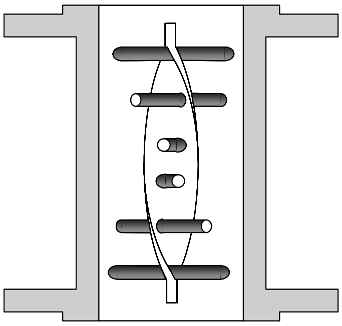


Figure 5.40. Typical magnetic filter (courtesy Krohne).

5.16.6 Conclusion

Generally, variable area flowmeters have uncertainties ranging from 1 to 3% of full scale. Precision instruments are, however, available with uncertainties down to 0.4% of full scale

The variable area meter is an exceptionally practical flow measurement device. Its advantages include:

- wide range of applications;
- linear float response to flow rate change;
- 10 to 1 flow range or tumdown ratio;
- easy sizing or conversion from one particular service to another;
- ease of installation and maintenance;
- simplicity;
- low cost;
- high low-flow accuracy (down to 5 cm^3/ min); and
- easy visualisation of flow

Its disadvantages are:

- limited accuracy;
- susceptibility to changes in temperature, density and viscosity;
- fluid must be clean, no solids content;
- erosion of device (wear and tear);
- can be expensive for large diameters;
- operates in vertical position only; and
- accessories required for data transmission.

5.17 Differential pressure transmitters

In modern process control systems, measurement of differential pressure is normally carried out by a differential pressure transmitter whose role is to measure the differential pressure and convert it to an electrical signal that can be transmitted from the field to the control room or the process controlling system.

As illustrated in Figure 5.41, most industrial differential cells make use of isolation diaphragms that isolate the transmitter. Movement of the isolation diaphragms is transmitted via the isolating fluid (for example, silicon fluid) to the measuring diaphragm whose deflection is a measure of the differential pressure.

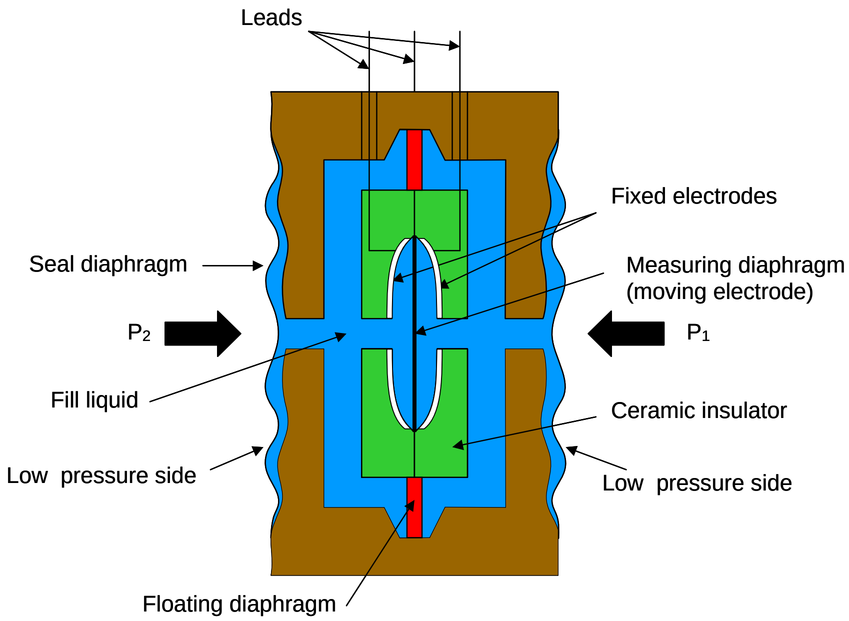


Figure 5.41. Basic construction of a floating cell capacitive differential pressure sensor in which movement of the isolation diaphragms is transmitted via the isolating fluid (for example, silicon fluid) to the measuring diaphragm whose deflection is a measure of the differential pressure (courtesy Fuji Electric).

Measurement of the deflection of the measuring diaphragm may be carried out by a number of methods including inductance, strain gauge, and piezoelectric. However, the most popular method of measuring differential pressure, adopted by a large number of manufacturers, is the variable capacitance transmitter.

As shown, the upstream and downstream pressures are applied to isolation diaphragms on the high and low pressure sides, which are transmitted to the sensing diaphragm, which forms a movable electrode. As the electrode changes its distance from the fixed plate electrodes, this results in a change in capacitance.

Capacitance based transmitters are simple, reliable, accurate (typically 0.1% or better), small in size and weight, and remain stable over a wide temperature range. The main advantage of the capacitive transmitter is that it is extremely sensitive to small changes in pressure – down to 100 Pa pressure.

Other manufacturers (including Honeywell) make extensive use of the piezoresistive element, in which piezoresistors are diffused into the surface of a thin circular wafer of N-type silicon and the diaphragm is formed by chemically etching a circular cavity – with the unetched portion forming a rigid boundary and surface. Such silicon-on-insulator devices are now capable of providing continuous operation at temperatures up to 225 ºC at pressures of up to 7 MPa.

5.17.1 Multivariable transmitters

▶ At the beginning of this chapter it was shown that the differential pressure can be related to flow by the expression:

$$Q = k\,C_d \sqrt{\frac{\Delta P}{\rho}} \qquad \text{....(5.27)}$$

where:

Q = flow rate
k = constant
C_d = discharge coefficient
ΔP = differential pressure (P_1 - P_2)
ρ = density of fluid

In practice this expression is painfully inadequate — especially in applications involving, for example, the mass flow of steam.

The most commonly used expression (AIME) for mass flow of liquids, gases and steam is:

$$Q_m = N\,C_d\,E_v\,Y_1\,d^2\sqrt{\Delta P\,\rho} \qquad \text{....(5.28)}$$

where:

Q_m	=	mass flow rate
N	=	units factor
C_d	=	discharge coefficient
E_v	=	velocity of approach factor
Y_1	=	gas expansion factor (= 1 for liquid);
d	=	bore diameter
DP	=	differential pressure; and
ρ	=	density of fluid.

Using this equation, the traditional approach has been to make use of three separate transmitters to measure differential pressure, static pressure and temperature to infer the mass flow. As shown in Figure 5.42 the density of a gas may be deduced from the ***measurement*** of static pressure and temperature combined with the entry of certain known constants: i.e. the compression factor, gas constant, molecular weight, and fluid constant.◀

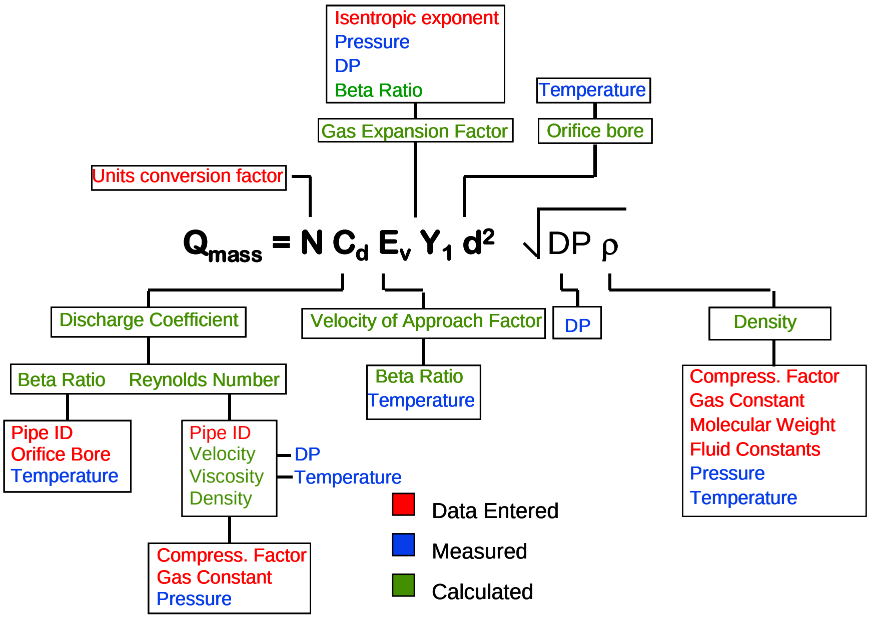


Figure 5.42. Computation of fully compensated mass flow requires the measurement of DP, static pressure and temperature (courtesy Emerson).

In recent years both Honeywell and Emerson have developed a single transmitter solution that makes simultaneous measurement of differential pressure, static pressure and temperature and provides the on-board computation.

Apart from providing tremendous cost savings in purchase price as well as installation, such multivariable transmitters provide accurate mass flow measurements of process gases (combustion air and fuel gases) and steam, whether saturated or superheated. Other applications include: DP measurement across filters and in distillation columns where the user is concerned with the static pressure and temperature measurements to infer composition; and in liquid flowrate applications where density and viscosity compensation is required due to large temperature changes.

5.17.2 Special transmitters

Continued emphasis on safely shut-down systems in the petrochemical industries has lead to the development of a new 'Critical' high availability transmitter from Moore which provides complete hardware and software redundancy; comprehensive self testing and primary and secondary current sources to ensure safe fault indication. These capabilities allow a single 'Critical' transmitter to be installed where two conventional transmitters are usually installed on a critical application or two 'Critical' transmitters to be installed where three conventional transmitters are required in a safety shutdown system.

Chapter 6. Electromagnetic Flowmeters

Chapter 6

Electromagnetic Flowmeters

6.1 Introduction

Electromagnetic flowmeters, also known as ‘Magflows’ or ‘Magmeters’, have now been in widespread use throughout industry for more than 40 years and were the first of modern meters to exhibit no moving parts and zero pressure drop.

6.2 Measuring principle

The principle of the EM flowmeter is based on Faraday's law of induction that states that if a conductor is moved through a magnetic field a voltage will be induced in it that is proportional to the velocity of the conductor.

▶ Referring to Figure 6.1, if the conductor of length (l) is moved through the magnetic field having a magnetic flux density (B) at a velocity (v), then a voltage will be induced where:

$$e = B.l.v \quad \ldots\ldots(6.1)$$

and:

e = induced voltage (V);
B = magnetic flux density (Wb/m^2);
l = length of conductor (m); and
v = velocity of conductor (m/s).

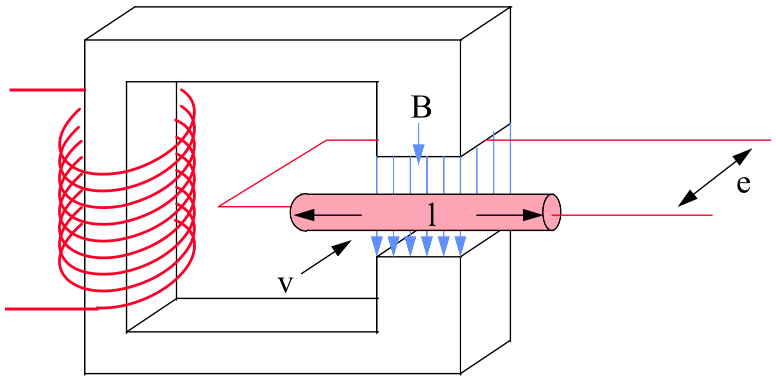


Figure 6.1. Illustration of Faraday’s Law of electromagnetic induction.

In the electromagnetic flowmeter (Figure 6.2) a magnetic field is produced across a cross-section of the pipe – with the conductive liquid forming the conductor (Figure 6.3). Two sensing electrodes, set at right angles to the magnetic field, are used to detect the voltage that is generated across the flowing liquid and which is directly proportional to the flow rate of the media.

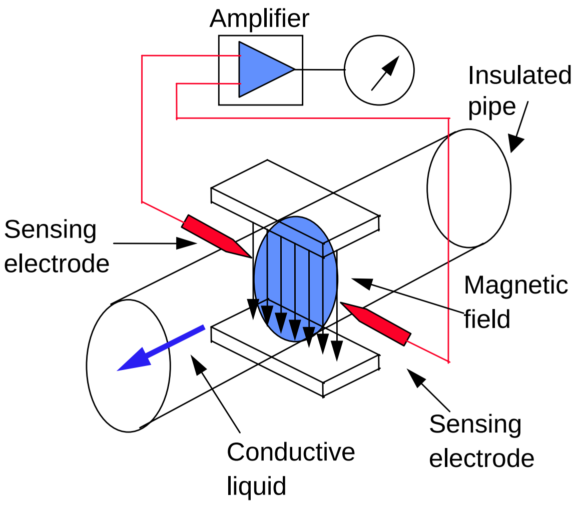


Figure 6.2. Basic principle of electromagnetic flowmeter.

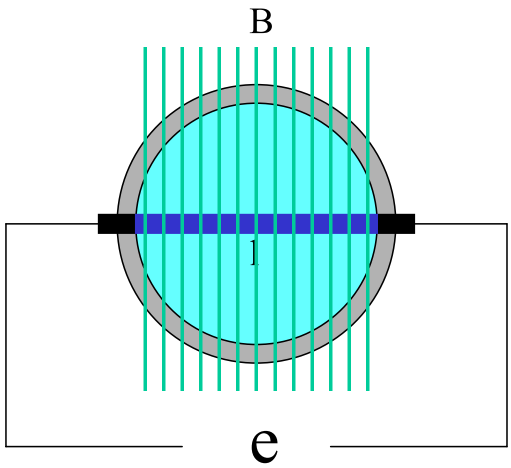


Figure 6.3. The conductive liquid forms the conductor in contact with the electrodes.

▶ It can thus be seen that since v is the flow rate (the parameter to be measured) the generated voltage is limited by the length of the conductor (the diameter of the pipe) and the flux density. In turn, the flux density is given by:

$$B = \mu . H$$

where:

μ = permeability; and
H = magnetising field strength (ampere-turns/m).

Because the permeability of the magnetic circuit is largely determined by the physical constraints of the pipe (the iron-liquid gap combination), the magnetic flux density B (and hence the induced voltage) can only be maximised by increasing H – a function of the coil (number of windings and its length) and the magnetising current.◀

6.3 Construction

Because the working principle of the electromagnetic flowmeter is based on the movement of the conductor (the flowing liquid) through the magnetic field, it is important that the pipe carrying the medium (the metering tube) should have no influence on the field. Consequently, in order to prevent short circuiting of the magnetic field, the metering tube must be manufactured from a non-ferromagnetic material such as stainless steel or Nickel-Chromium.

It is equally important that the signal voltage detected by the two sensing electrodes is not **electrically** short circuited through the tube wall. Consequently, the metering tube must be lined with an insulating material. Such materials have to be selected according to the application and their resistance to chemical corrosion, abrasion, pressure and temperature (Table 6.1).

Table 6.1. Commonly used magnetic flowmeter liner materials

Material	General	Corrosion resistance	Abrasion resistance	Temperature limit (°C)	Pressure limit (bar)
Teflon PTFE	Warm deformable resin with excellent ant-stick properties and suitable for food and beverage	Excellent	Fair	180	40
Teflon PFA	Melt-processable resin with better shape accuracy, abrasion resistance and vacuum strength than PTFE	Excellent	Good	180	40
Polyurethane	Extreme resistance to wear and erosion but not suitable for strong acids or bases	Wide range	Excellent	50	250
Neoprene	Combines some of the resistance to chemical attack of PTFE with a good degree of abrasion resistance	Wide range	Good to excellent	80	100
Hard rubber (Ebonite)	Inexpensive – finds its main application in the water and waste water industries	Fair to excellent	Fair	95	250
Soft rubber	Mainly used for slurries	Fair	Excellent	70	64
Modified phenolic	Developed for harsh environments containing H_2S/CO_2 concentrations and acids	Very high	Good	200	Yield strength of pipe
Fused aluminium oxide	Highly recommended for very abrasive and/or corrosive applications.	Excellent	Excellent	180	40

Teflon PTFE

A warm deformable resin, Teflon PTFE is the most widely used liner material. Characteristics include:

- very high temperature capability (180°C)
- excellent anti-stick characteristics reduce build-up
- inert to a wide range of acids and bases
- approved in food and beverage applications.

Teflon PFA

Teflon PFA is a melt-processable resin that offers:

- a better shape accuracy than PTFE;
- better abrasion resistance, since there are no bulges or deformations;
- better vacuum strength because of the ability to incorporate stainless steel reinforcement.

Polyurethane
Generally, Teflon PTFE/PFA does not have adequate erosion resistance for some applications and, often, the best choice when extreme resistance to wear and erosion is required is polyurethane. Other characteristics include:
- cannot be used with strong acids or bases
- cannot be used at high temperatures since its maximum process temperature is 40 °C.

Neoprene
- resistant to chemical attack
- good degree of abrasion resistance
- temperature of 80 °C.

Hard rubber
- inexpensive general purpose liner
- wide range of corrosion resistance
- main application in the water and waste water industries

Soft rubber
- relatively inexpensive
- high resistance to abrasion
- main application in slurries.

Modified phenolic
Developed by Turbo Messtechnik for harsh environments containing H_2S/CO_2 concentrations and acids, this is a powder based line with high-resistant fillers and organic pigments. It is suitable for high temperatures (200 °C) and high pressures.

Fused aluminium oxide
- highly recommended for very abrasive and/or corrosive applications
- high temperatures up to 180°C.
- used extensively in the chemical industry

6.4 Electrodes

The electrodes, like the liners, are in direct contact with the process medium and again the materials of construction must be selected according to the application and their resistance to chemical corrosion, abrasion, pressure and temperature. Commonly used materials include: 316 stainless steel, platinum/rhodium, Hastelloy C, Monel, and tantalum.

One of the main concerns is the need to ensure that there is no leakage of the process medium. In the construction design shown in Figure 6.4, the electrode seal is maintained through the use of five separate sealing surfaces and a coil spring. However, to ensure that the overall integrity of the system is maintained, even if a process leak should occur past the liner/ electrode interface, the electrode compartment can also be separately sealed. Usually rated for full line pressure, such containment ensures that in the event of a leak, no contamination of the field coils occurs.

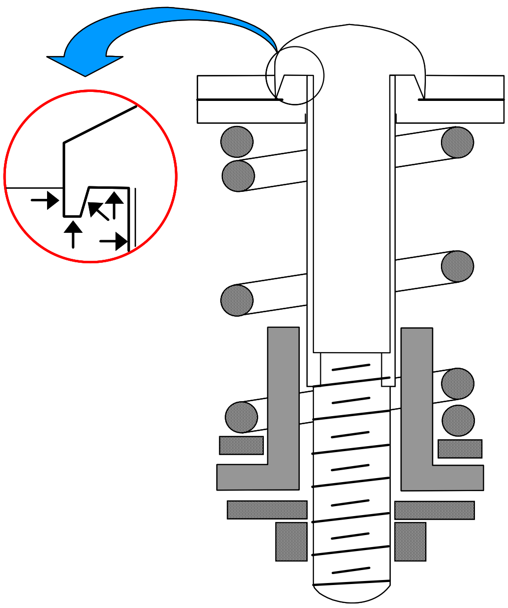


Figure 6.4. The electrode seal is maintained through the use of five separate sealing surfaces and a coil spring (courtesy Emerson).

Where heavy abrasion or contamination of the electrodes might occur, many manufacturers offer the option of field replaceable electrodes (Figure 6.5).

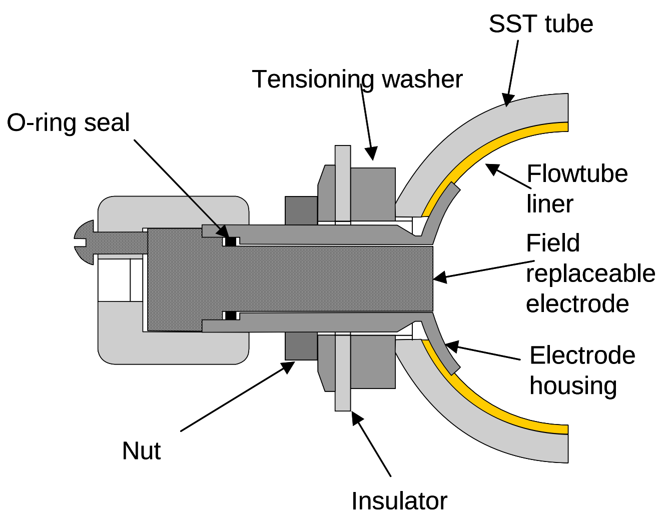


Figure 6.5. Field replaceable electrode (courtesy Emerson).

Fouling of the electrodes by insulating deposits can considerably increase the internal resistance of the signal circuit – changing the capacitive coupling between the field coils and signal circuitry.

6.5 Conductivity

▶ The two main characteristics of the process medium that need to be considered are its conductivity and its tendency to coat the electrode with an insulating layer. As shown in Figure 6.6; to develop most of the electrode potential (e) across the input impedance (Ri) of the meter amplifier, and to minimise the effect of impedance variations due to changes in temperature, then Ri needs to be at least 1000 times higher than the maximum electrode impedance Rs.

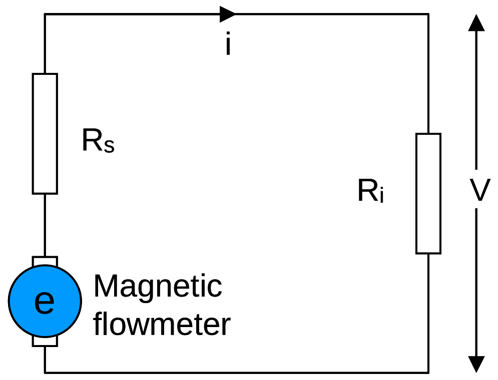


Figure 6.6. To develop most of the electrode potential (e) across the input impedance (Ri) of the meter amplifier the Ri needs to be at least 1000 times higher than the maximum electrode impedance Rs.

Modern high input impedance amplifiers are available in the range 10^{13} to 10^{14} Ω. Consequently, with an amplifier having, for example, an input impedance of 10^{13} Ω, the error due to impedance matching is less than 0.01% and a change in electrode impedance from 1 to 1000 MΩ will effect the voltage by only 0.001%.

The electrode impedance depends on fluid conductivity and varies with the size of the metering tube. In older a.c. driven instruments the minimum conductivity of the fluid usually lay between 5 - 20 µS/cm. For d.c. field instruments the minimum conductivity was about 1 µS/cm. However modern instruments employ a variety of technologies, including capacitively coupled meters that can be used on liquids with conductivity levels down to 0.05 µS/cm. ◀

In some applications, coating of the electrodes is cause for concern and, over the years, a number of solutions have been offered including a mechanical scraper assembly and ultrasonic cleaning.

A solution offered by Turbo Messtechnik employs electrolytic electrode cleaning. If one or more of the electrodes becomes isolated by gaseous slugs, sticky media or encrustation (Figure 6.7 (a)), the instrument detects the abnormally low conductivity and applies 60 V a.c. voltage across the electrodes. After approximately 1 minute the electrolytic action starts to form microporous paths through the isolating 'barrier' (Figure 6.7 (b)). As these paths become progressively larger, the isolating barrier starts to break away from the electrode (Figure 6.7 (c))to re-establish contact with the process media. Normally a 2½ minute cycle is sufficient for normal flow sensing.

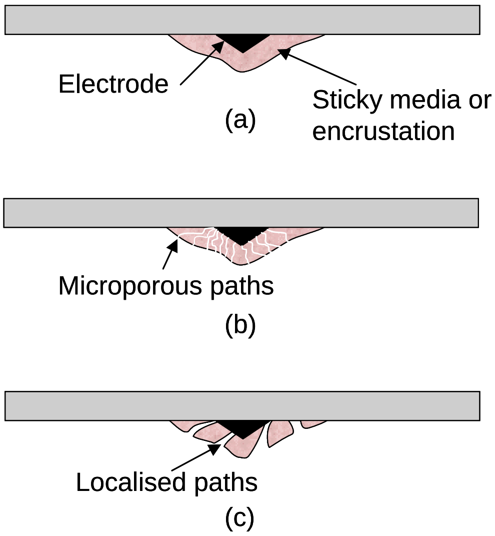


Figure 6.7. If the electrode is isolated by encrustation (a) a 60 V a.c. voltage is applied across the electrodes and electrolytic action starts to form microporous paths through the isolating 'barrier' (b). As these paths become progressively larger, the isolating barrier starts to break away from the electrode (c) (courtesy Turbo Messtechnik).

Most refinery products, and some organic products, have insufficient conductivity to allow them to be metered using electromagnetic flowmeters (Table 6.2).

Table 6.2. Conductivities of some typical fluids.

Liquid	Conductivity (μS/cm)
Carbon tetrachloride at 18°C	4×10^{-12}
Toluene	10^{-8}
Kerosene	0.017
Analine at 25°C	0.024
Soya bean oil	0.04
Distilled water	0.04
Acetone at 25°C	0.06
Phosphorous	0.4
Benzole alcohol at 25 °C	1.8
Acetic acid (1% solution)	5.8×10^{2}
Acetic acid (10% solution)	16×10^{2}
Latex at 25°C	5×10^{3}
Sodium silicate	24×10^{3}
Sulphuric acid (90% solution	10.75×10^{4}
Ammonium nitrate (10% solution)	11×10^{4}
Sodium hydroxide (10% solution)	31×10^{4}
Hydrochloric acid (10% solution)	63×10^{4}

It should be noted that the conductivity of liquids can vary with temperature and care should be taken to ensure the performance of the liquid in marginal conductivity applications is not affected by the operating temperatures. Most liquids have a positive temperature coefficient of conductivity. However negative coefficients are possible in a few liquids.

6.6 Capacitive coupled electrodes

The foregoing solutions do not solve the problem of 'electrode coating' in which an insulating deposit effectively isolates the electrodes. These insulating deposits are often found in the paper manufacturing industry and in sewage treatment applications where grease and protein conglomerates can develop into thick insulating layers.

In the capacitive coupled flowmeter developed by Bailey-Fisher & Porter (Figure 6.8) the electrodes, which are normally wetted by the process liquid, have been replaced by capacitive plates buried in the liner as one of the plates; the meter lining acts as the dielectric; and the second capacitive plate is formed by the metallic electrode that is embedded in the tube liner.

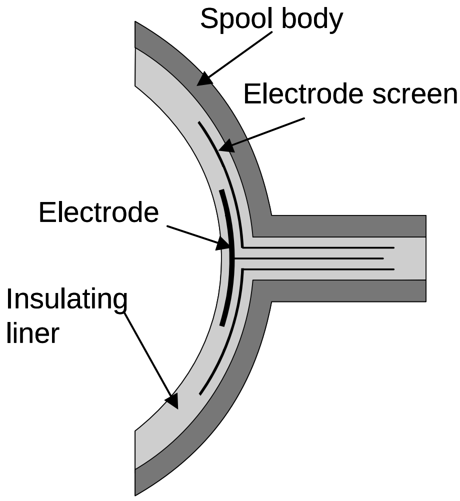


Figure 6.8. The electrodes have been a replaced by capacitive plates buried in the liner.

In an alternative solution offered by Krohne, the electrodes take the form of two large plates bonded to the outside of a ceramic flowtube (Figure 6.9) – with the preamplifer mounted directly on the flow tube. Capable of use with liquids with conductivity levels down to 0.05 μS/cm the capacitive coupled magnetic flow meter features: no gaps or crevices, no risk of electrode damage due to abrasion; no leakage; and no electrochemical effects.

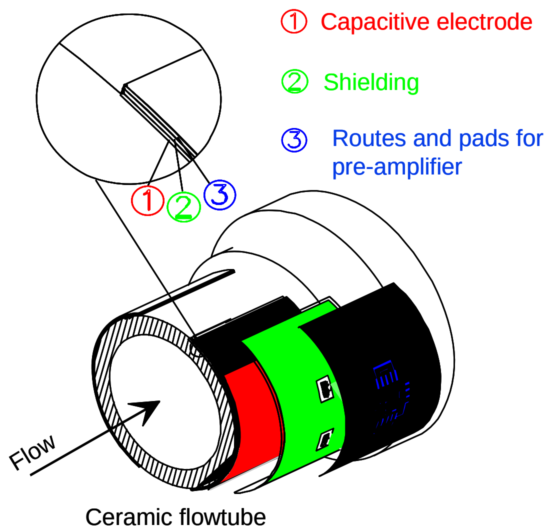


Figure 6.9. Capacitive electrodes formed by two large plates bonded to the outside of a ceramic flow tube (courtesy Krohne).

6.7 Field characterisation

▶ The purpose of a flowmeter is to measure the true average velocity across the section of pipe, so that this can be related directly to the total volumetric quantity in a unit of time. The voltage generated at the electrodes is the summation of the incremental voltages generated by each elemental volume of cross-section of the flowing fluid as it crosses the electrode plane with differing relative velocities.

Initially, designs assumed the magnetic field to be homogeneous over the measured cross-section and length of the pipe in order to achieve precise flow measurement. However, early investigators showed that, for a given velocity, the medium does not generate the same voltage signal in the electrodes at all points. Thus, for a given velocity (v) the medium flowing at position A_1 (Figure 6.10) does not generate the same voltage signal as that flowing in position A_2.

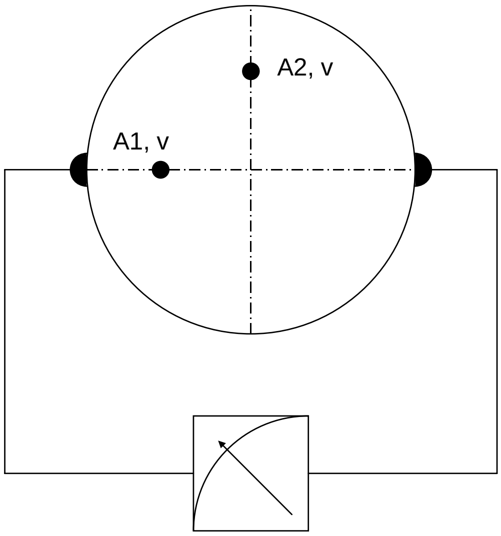
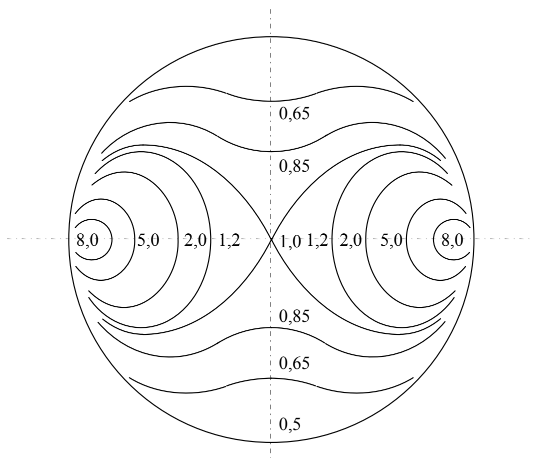


Figure 6.10. For a given velocity (v) the medium flowing at position A_1 does not generate the same voltage signal as that flowing position A_2 (Courtesy Endress + Hauser).

Rummel and Ketelsen plotted the medium flowing at various distances away from the measuring electrodes (Figure 6.11) and showed how these contribute in different ways towards the creation of the measuring signal. This shows that a flow profile that concentrates velocity in the area of one electrode will produce eight times the output of that at the pipe centre – leading to errors that cannot be overlooked.

Figure 6.11. Weighting factor distribution in electrode plane (Rummel and Ketelsen).



One solution to this problem is to use a non- homogeneous field that compensates for these non-linear concentrations.

Subsequent to his research, Ketelsen designed a magnetic flowmeter making use of a 'characterised field'. As distinct from the homogeneous field in which the magnetic flux density (B) is constant over the entire plane (Figure 6.12 (a)), the 'characterised field' is marked by an increase in B in the x-direction and a decrease in the y-direction (Figure 6.12 (b)).

Because commercial exploitation of this design is limited in terms of a patent in the name of B. Ketelsen, assigned to Fischer & Porter GmbH, a 'modified field' has been developed in which the lines of magnetic flux, at any place in the electrode-plane, are characterised by an increase in B in the x-direction, from the centre to the wall, but is constant in the y-direction (Figure 6.12 (c)). This 'modified field' is, therefore, a compromise between the 'characterised field' and the 'homogeneous field'.

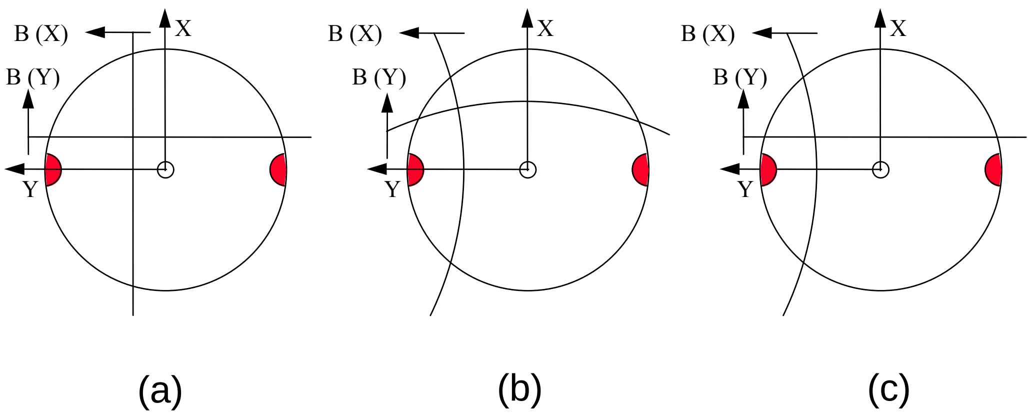


Figure 6.12. The three most common forms of magnetic fields: (a) the homogeneous field in which B is constant over the entire plane (b) a 'characterised field' in which B increases in the x-direction but decreases in the y-direction; and (c) the modified field in which B increases in the x-direction but is constant in the y-direction.

◀

6.8 Measurement in partially filled pipes

A fundamental requirement for accurate *volumetric* flow measurement is that the pipe should be full. Given a constant velocity then, as the fill level decreases, the induced potential at the electrodes is still proportional to the media *velocity*. However, since the cross sectional area of the media is unknown it is impossible to calculate the volumetric flow rate.

In the water utility industry where large bore flowmeters are used and the hydraulic force is based on gravity, the occurrence of a partially filled pipe, due to low flow, is quite frequent.

Although installing the flowmeter at the lowest point of the pipeline in an invert or U-section (Figure 6.13) will combat this problem, there are still many situations where even the best engineering cannot guarantee a full pipe – thus giving rise to incorrect volume readings.

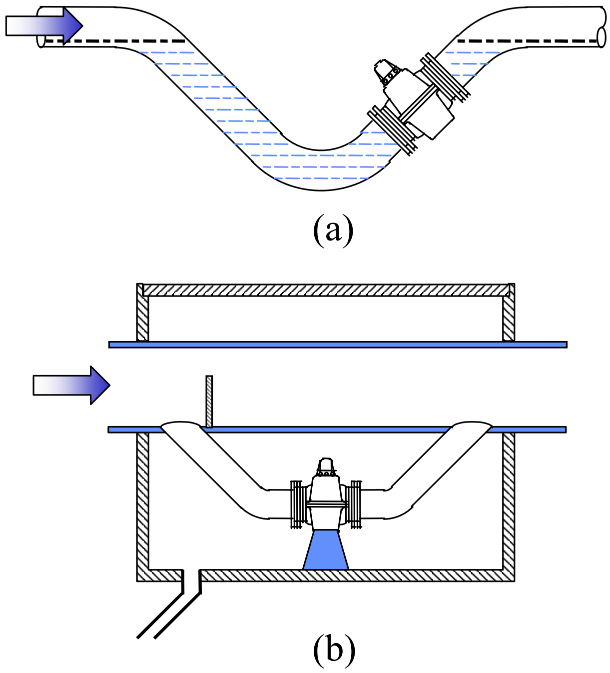


Figure 6.13. Flowmeter installed in (a) an invert or (b) a U-section can often ensure that the meter remains full when the media pipe is only partially full (Courtesy ABB).

One answer to this problem would be to actually determine the cross-sectional area and thus calculate the volumetric flow.

In the solution offered by ABB in their Parti-MAG, two additional electrode pairs are located in the lower half of the meter to cater for partial flowrate measurements down to 10%. In addition, the magnetic field is switched successively from a series to a reverse coil excitation.

The series excitation mode (Figure 6.14) corresponds to the excitation mode for a conventional meter. As a result of this field, a voltage is induced in the electrode pairs that is related to the media velocity.

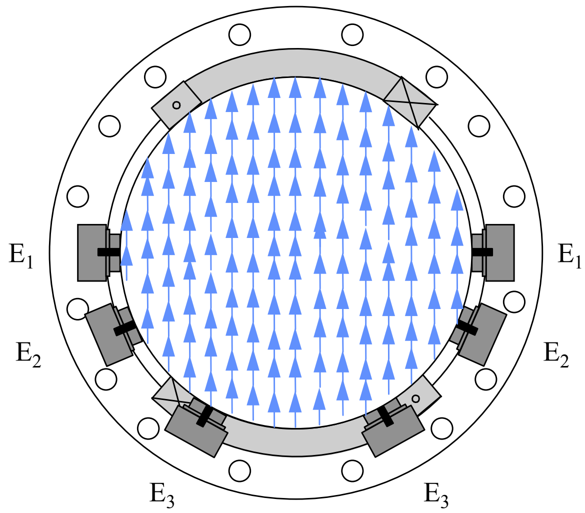


Figure 6. 14. The series excitation mode corresponds to the excitation mode for a conventional meter (Courtesy of ABB).

In the reverse excitation mode (Figure 6. 15) the induced voltages in the upper and lower halves of the meter are of equal magnitude but opposite sign. Thus, in a full pipe the potential would be zero at the electrode pair E_1 and some definite value at the electrode pairs E_2 and E_3. As the level falls, the signal contribution from the upper half decreases while that from the lower half remains the same – resulting in a change in the potential at the various electrode pairs that can be related directly to the change in media level. Microprocessor technology is then used to compute the cross-sectional area and thus the volumetric flow.

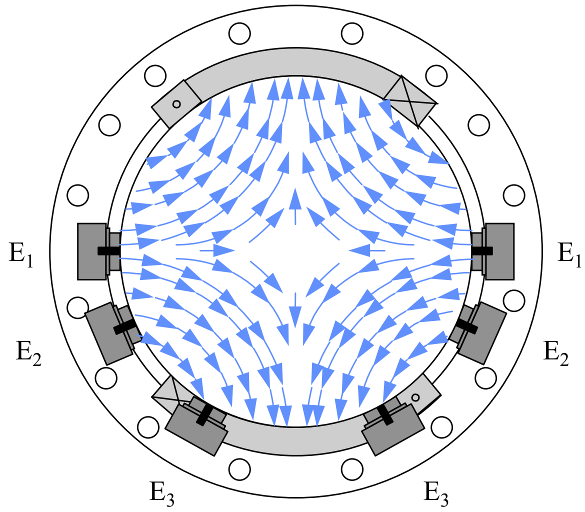


Figure 6.15. In the reverse excitation mode the induced voltages in the upper and lower halves of the meter are of equal magnitude but opposite sign (Courtesy of ABB).

A slightly different scheme is used in Krohne's TIDALFLUX meter. This instrument combines an electromagnetic flowmeter with an independent capacitive level measuring system.

The electromagnetic flow measuring section functions like a conventional electromagnetic flowmeter, using a single set of electrodes that are placed near the bottom of the pipe as shown in Figure 6.16. In this manner, even when the filling level falls to less than 10% of the pipe diameter, the electrodes are still covered and capable of providing a flow velocity-related output.

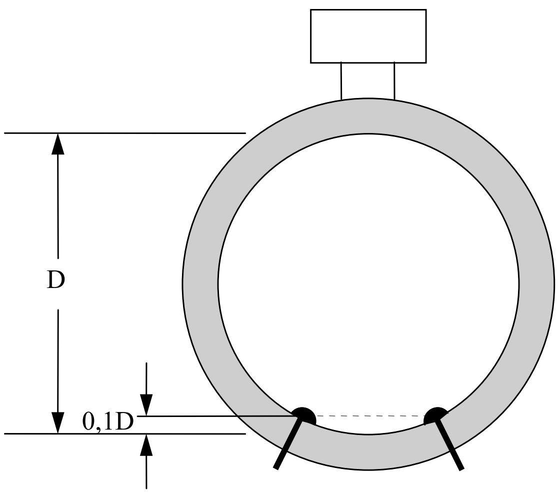


Figure 6.16. The two sensing electrodes are positioned so that the electrodes are still covered when the filling level falls to less than 10% of the pipe diameter (Courtesy Krohne).

The level measuring section makes use of a system of insulated transmission and detection plates embedded in the flowmeter liner (Figure 6.17) in which the change in capacitive coupling is proportional to the wetted cross-section.

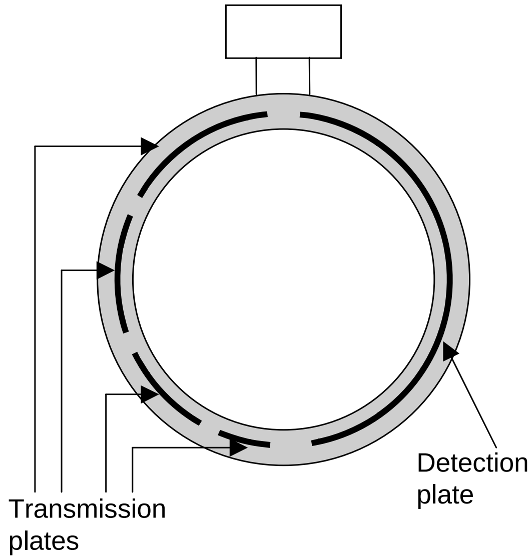


Figure 6.17. The level measuring section makes use of insulated transmission and detection plates embedded in the flowmeter (Courtesy Krohne).

Using these two measured values it is now possible to compute the actual volumetric flow (Figure 6.18) from:

$$Q = v.A \quad \text{......(6.2)}$$

where:

Q = volumetric flow
v = velocity-related signal
A = wetted cross-sectional area.

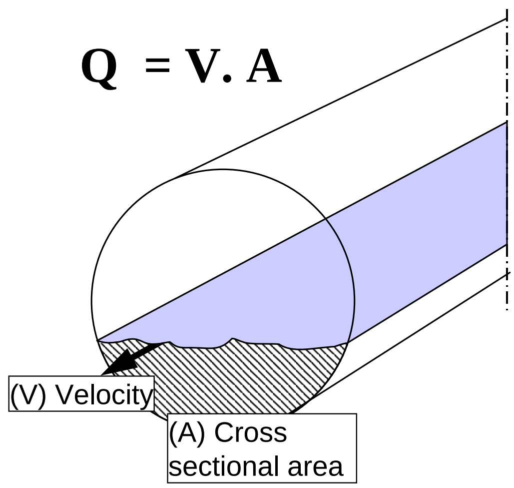


Figure 6.18. The volumetric flow is computed using the two measured values of velocity and cross-sectional area (Courtesy Krohne).

6.9 Empty pipe detection

In many cases, measurement of partially filled pipes in not required. Nonetheless, in order to draw attention to this situation, many meters incorporate an `Empty Pipe Detection' option.

In the most common system (Figure 6.19), a conductivity probe, mounted on top of the pipe, senses the presence of the conductive medium. If the medium clears the sensor, due to partial filling of the pipe, the conductivity falls and an alarm is generated.

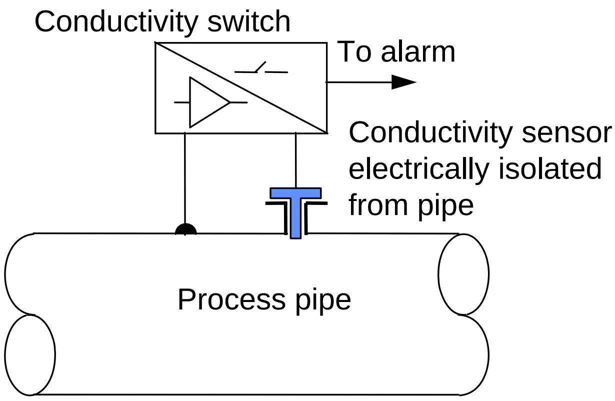


Figure 6.19. Conductivity probe for empty pipe detection.

An alternative scheme is to use a high frequency current generator across the flowmeter sensing probes. Because normal flow measurement uses relatively low frequencies, the high frequency signal used to measure the conductivity is ignored by the flow signal amplifier.

`Empty Pipe Detection' is not only used to indicate that the volume reading is incorrect. For example, in a two-line standby system, one line handles the process and the other line is used for standby. Since the standby line does not contain any of the process medium, the flowmeter sensing electrodes are `open circuit' and the amplifier output signal will be subject to random drifting. The resultant falsely generated inputs to any process controllers, recorders, etc, connected to the system will give rise to false status alarms. Here, the `Empty Pipe Detection' system is used to 'freeze' the signal to reference zero.

Another application for `Empty Pipe Detection' is to prevent damage to the field coils. Magnetic flowmeters based on a `pulsed d.c.' magnetic field, generate relatively low power to the field coils – typically between 14 and 20 VA. This is usually of little concern regarding heat generation in the field coils. However, flow sensors based on an `a.c generated' magnetic fields, consume power in excess of a few hundred VA. In order to absorb the heat generated in the field coils, a medium is required in the pipe to keep the temperature well within the capability of the field coil insulation. An empty pipe will cause overheating and permanent damage to the field coils and, consequently, this type of flowmeter requires an `Empty Pipe Detection' system to shut down the power to the field coils.

6.10 Field excitation

The metallic electrodes in contact with the flowing liquid form a galvanic element that creates an interfering electrochemical d.c. voltage. This voltage is dependent on the temperature, the flow rate, the pressure and the chemical composition of the liquid as well as on the surface condition of the electrodes. In practice, the voltage between the liquid and each electrode will be different – giving rise to an unbalanced voltage between the two electrodes. In order to separate the flow signal from this interfering d.c. voltage, an a.c. excitation field is used – allowing the interfering d.c. voltage to be easily separated from the a.c. signal voltage by capacitive or transformer coupling. Whilst a.c. electromagnetic flowmeters have been used successfully for many years, the use of an alternating field excitation makes them susceptible to both internal and external sources of errors.

Non-homogeneous conductivity
Although electromagnetic flowmeters are independent of liquid conductivity over a wide range, it is assumed that the conductivity is homogeneous and is thus constant along the cross section and along the length of the primary head. However, in many sewage and waste water applications it is often found that, at low flow rates, layers of different density and conductivity are formed. As a consequence the eddy current distribution that is created by the time derivative of the induction, is completely deformed and therefore interference voltages are produced, which cannot be fully suppressed in the converter.

Fouling of the electrodes
Fouling of the electrodes by insulating deposits can considerably increase the internal resistance of the signal circuit – changing the capacitive coupling between the field coils and signal circuitry.

Direct coupling
Because field excitation is derive directly from the mains voltage, it is impossible to separate the signal voltage from external interference voltages.Interference voltages can be transferred by either capacitive or inductive coupling from heavy current carrying cables laid in proximity to the signal cable. Although these interference voltages may be largely suppressed by multiple screening of the signal cable, they might not be completely eliminated.

Axial currents
Stray currents from other systems are occasionally carried by the pipeline and/or the flowing media that generate voltages at the electrodes cannot be distinguished from the signal voltage.

Poor earthing
Earthing of the primary head as well as the pipeline by earthing rings or properly earthed flanges, ensures that the liquid is at zero potential. If the earthing is not symmetrical, earth loop currents give rise to interference voltages – producing zero-point shifts.

The result of these various interference voltages requires the use of a manually operated zero control adjustment and the attendant problem of having to stop the flow to check the setting.

The a.c. electromagnetic flowmeter is a relatively low cost system having an accuracy in the order of around 2%.

6.11 The pulsed d.c. field

▶ The pulsed d.c. field is designed to overcome the problems associated with both a.c. and d.c. interference. In the pulsed d.c. meter, the d.c. field is periodically switched on and off at specific intervals. The electrochemical d.c. interference voltage is stored when the magnetic field is switched off and then subtracted from the signal representing the sum of the signal voltage and interference voltage when the magnetic field is switched on.

Figure 6.20 illustrates the voltage at the sensors in which the measured voltage V_m is superimposed on the spurious unbalanced offset voltage V_u. By taking (and storing) samples during the periods A and B, the mean value V_m may be obtained by algebraic subtraction of the two values:

$$V_m = (V_u + V_m) - V_u \quad \text{...(6.3)}$$

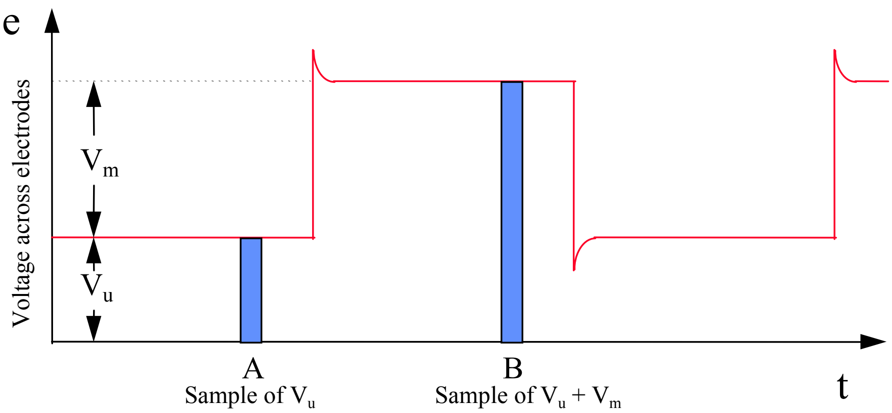


Figure 6.20. The voltage at the sensors in which the measured voltage V_m is superimposed on the spurious unbalanced offset voltage V_u.

This method assumes that the value of the electrochemical interference voltage remains constant during this measuring period between the samples A and B. However if the interference voltage changes during this period serious errors are likely to occur. Figure 6.21 shows the unbalanced offset voltage as a steadily increasing ramp. Here, the error is as high as the amount by which the unbalanced voltage has changed during the measuring periods A and B and could result in an induction error of as much as 100 %.

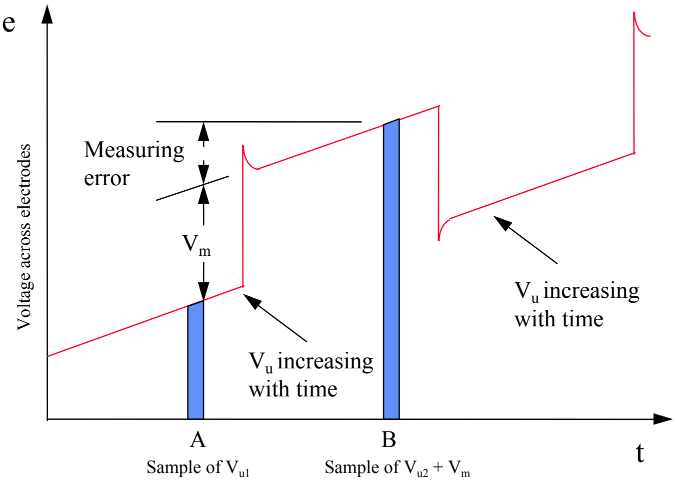


Figure 6.21. With the unbalanced offset voltage a steadily increasing ramp, the error is as high as the amount by which the unbalanced voltage has changed during the measuring periods A and B.

One method of overcoming this problem is by a method of linear interpolation as illustrated in Figure 6.22. Prior to the magnetic induction the unbalanced voltage A is measured. During the magnetic induction phase the value B (which is the sum of unbalanced voltage and flow signal) is measured and then, after magnetic induction, the changed unbalanced voltage C is measured.

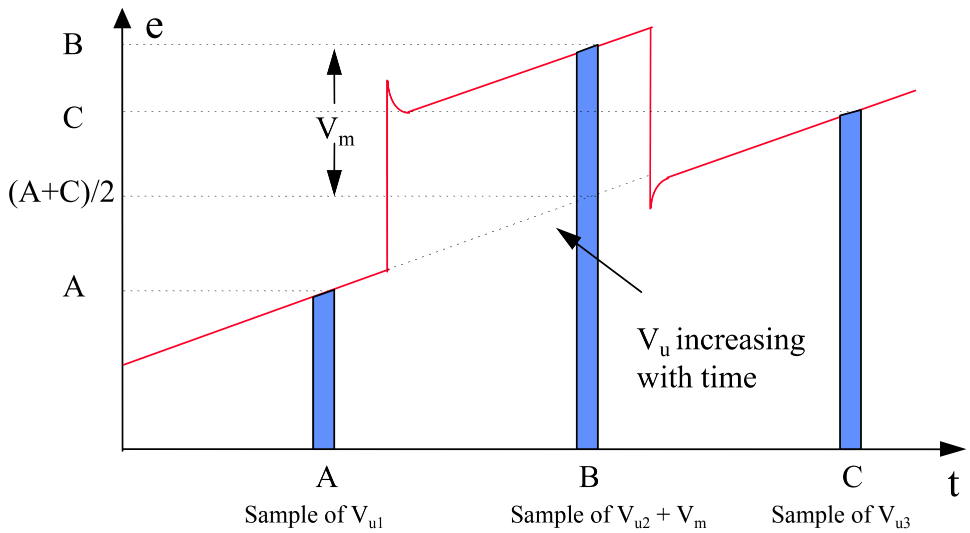


Figure 6.22. The unbalanced voltage A is measured prior to the magnetic induction; the value B (the sum of unbalanced voltage and flow signal) is measured during the induction phase; and the changed unbalanced voltage C is measured after magnetic induction.

The mean value (A + C)/2 of the balanced voltage prior to and after magnetic induction is electronically produced and subtracted from the sum signal measured during magnetic induction. So, the exact flow signal:

$$Vm = B - (A + C)/2 \quad \text{...(6.4)}$$

is obtained which is free from the unbalanced voltage. This method corrects not only the amplitude of the d.c. interference voltage, but also its change ,with respect to time.

6.12 Bipolar pulse operation

An alternative method of compensation is shown in Figure 6.23 using an alternating (or bipolar) d.c. pulse. Under ideal or reference conditions, the values of V_1 and V_2 would be equal and would both have the value Vm, the measured value. Thus:

$$V_1 - V_2 = (V_m) - (-V_m) = 2V_m \quad \text{...(6.5)}$$

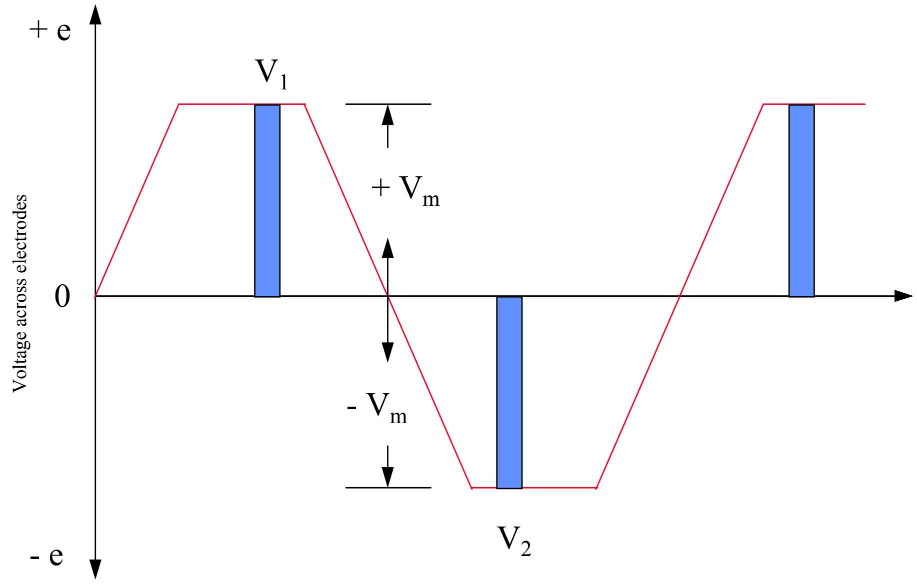


Figure 6.23. Bipolar pulse compensation under ideal or reference conditions.

If, now, the zero or no-flow signal is off-set by an unbalanced voltage in, for example, a positive direction (Figure 6.24) , then:

$$V_1 = V_u + V_m \quad \text{...}(6.5)$$

and $$V_2 = V_u - V_m \quad \text{...}(6.6)$$

and $$V_1 - V_2 = (V_u + V_m) - (V_u - V_m) = 2V_m \quad \text{...................................}(6.7)$$

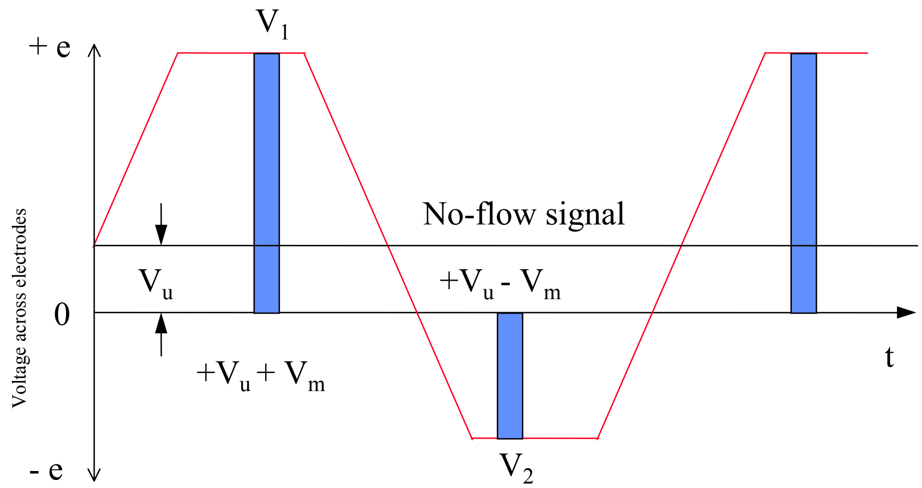


Figure 6.24. Bipolar pulse compensation eliminates error due to unbalanced offset voltage.

Again, linear interpolation methods may be applied as illustrated in Figure 6.25 where five separate samples are taken during each measurement cycle. A zero potential measurement is taken at the commencement of the cycle; a second measurement at the positive peak; a third at zero potential again; a fourth at negative peak and finally another zero measurement at the completion of the cycle. The result, in this case, will be:

$$2\ V_m = (V_1 - (Z_1 + Z_2)/2 - (V_2 - (Z_2 + Z_3)/2) \quad \ldots\ldots(6.8)$$

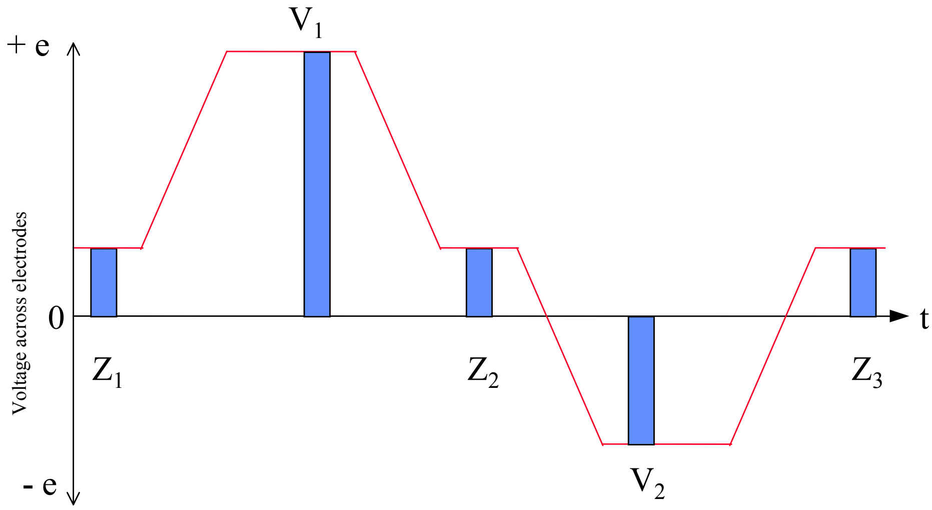


Figure 6.25. Bipolar pulse compensation with linear interpolation.

◀

6.13 Meter sizing

Generally the size of the primary head is matched to the nominal diameter of the pipeline. However, it is also necessary to ensure that the flow rate of the medium lies between the minimum and maximum full scale ranges of the specific meter. Typical values of the minimum and maximum full scale ranges are 0,3 and 12 m/s respectively.

Experience has also shown that the optimum flow velocity of the medium through an electromagnetic flowmeter is generally 2 to 3 m/s – dependent on the medium. For example, for liquids having solids content, the flow velocity should be between 3 to 5 m/s to prevent deposits and to minimise abrasion.

Knowing the volumetric flowrate of the medium in, for example, cubic metres per hour, and knowing the pipe diameter, it is easy to calculate and thus check to see if the flow velocity falls within the recommended range. Most manufacturers supply nonograms or tables that allow users to ascertain this data at a glance.

Occasionally, in such cases where the calculated meter size needs to be smaller than that of the media pipe size, a transition using conical sections can be installed .The cone angle should be 8 ° or less and the pressure drop resulting from this reduction can, again, be determined from manufacturers' tables (Figure 6.26).

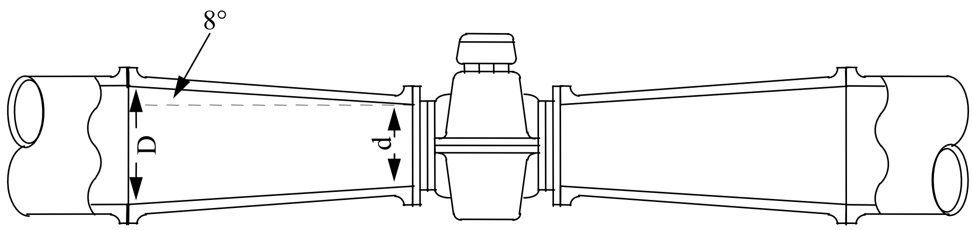


Figure 6.26. Conical section used to cater for reduced meter size.

6.14 Conclusion

The electromagnetic (EM) flowmeter is regarded by many users as the universal answer to more than 90% of all flowmetering applications. Some of the many benefits offered by the EM flowmeter include:

- no pressure drop;
- short inlet/outlet sections (5D/2D);
- relationship is linear (not square root);
- insensitive to flow profile changes (laminar to turbulent) including many non-Newtonian liquids;
- rangeability of 30:1 or better;
- inaccuracy of better than ±0.2% of actual flow over full range;
- no recalibration requirements;
- bi-directional measurement
- no taps or cavities;
- no obstruction to flow;
- not limited to clean fluids;
- high temperature capabilities;
- high pressure capabilities;
- volumetric flow;
- can be installed between flanges; and
- can be made from corrosion resistance materials at low cost.

Chapter 7. Ultrasonic Flowmeters

Chapter 7
Ultrasonic Flowmeters

7.1 Introduction

Ultrasonic flowmeters, suitable for both liquids and gases, have been available for more than twenty years and are currently the only truly viable non-intrusive measuring alternative to the electromagnetic flowmeter.

Unfortunately, although originally hailed as a general panacea for the flow measurement industry, lack of knowledge and poor understanding of the limitations of early instruments (especially the Doppler method) often lead to its use in unsuitable applications.

Nonetheless, the ultrasonic meter is probably the only meter capable of being used on large diameter pipes (above 3 m bore) at a reasonable cost and performance (around 1%).

In essence there are three basic principles used in ultrasonic metering: the Doppler method; the time-of-flight method; and the frequency difference method.

7.2 Doppler method

Doppler flowmeters are based on the Doppler effect — the change in frequency that occurs when a sound source and receiver move either towards or away from each other. The classic example is that of an express train passing through a station. To an observer, standing on the platform, the sound of the train appears to be higher as the train approaches and then falls as the train passes through the station and moves away. This change in frequency is called the Doppler shift.

In the Doppler ultrasonic flowmeter, an ultrasonic beam (usually of the order of 1 to 5 MHz) is transmitted, at an angle, into the liquid (Figure 7.1). Assuming the presence of reflective particles (dirt, gas bubbles or even strong eddies) in the flowstream, some of the transmitted energy will be reflected back to the receiver. Because the reflective particles are moving towards the sensor, the frequency of the received energy will differ from that of the transmitted frequency (the Doppler effect).

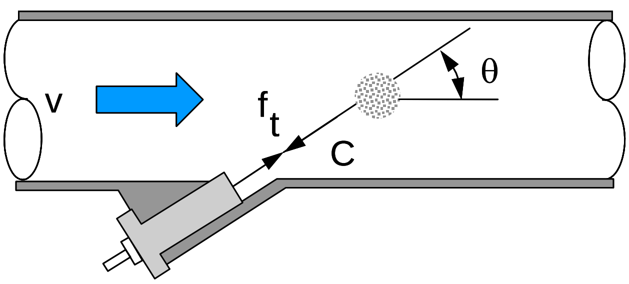


Figure 7.1. In the Doppler ultrasonic flowmeter, an ultrasonic beam is transmitted, at an angle, into the liquid.

This frequency difference, the Doppler shift, is directly proportional to the velocity of the particles.

▶ Assuming that the media velocity (v) is considerably less than the velocity of sound in the media (C), the Doppler frequency shift (Δf) is given by:

$$\Delta f = \frac{2f_t \, v \cos\theta}{C} \qquad \text{.......................................(7.1)}$$

where f_t is the transmitted frequency.

From this it can be seen that the Doppler frequency, Δf, is directly proportional to flow rate.

The velocity of sound in water is about 1500 m/s. If the transmitted frequency is 1 MHz, with transducers at 60°, then for a media velocity of 1 m/s the Doppler shift is around 670 Hz. ◀

Since this technique requires the presence of reflecting particles in the media, its use in ultra-clean applications or, indeed, with any uncontaminated media, is generally, precluded. Although some manufacturers claim to be able to measure 'non-aerated' liquids, in reality such meter rely on the presence of bubbles due to micro-cavitation originating at valves, elbows or other discontinuities.

In order for a particle to be 'seen', it needs to be approximately 1/10 larger than the wavelength of the acoustic frequency in the liquid. In water, a 1 MHz ultrasonic beam would have a wavelength of about 1,5 mm and so particles would need to be larger than 150 μm in order to reflect adequately.

Whilst air, oil particle and sand are excellent sonic reflectors, the presence of too may particles can attenuate the signal so that very little of the signal reaches the receive transducer.

Probably the single biggest drawback of this technology is that in multiphase flows, the particle velocity may bear little relationship to the media velocity. Even in single phase flows, because the velocity of the particles is determined by their location within the pipe, there may be several different frequency shifts — each originating at different positions in the pipe. As a result, the Doppler method often involves a measurement error of 10 % or even more.

In the insertion type probe shown in Figure 7.2, the reflective area is, to a large extent, localised and the potential source of errors is thereby reduced.

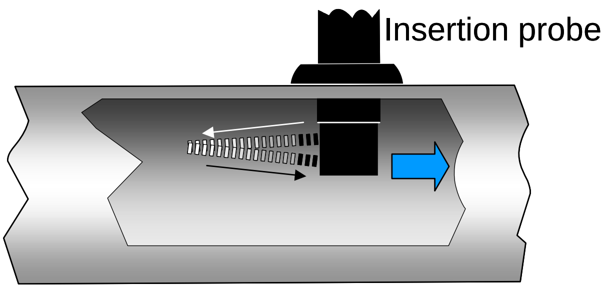


Figure 7.2. Insertion type probe Doppler probe (courtesy Dynasonics).

Generally, Doppler meters should not be considered as high performance devices and are cost effective when used as a flow monitor. They work well on dirty fluids and typical applications include sewage, dirty water, and sludge. Doppler meters are sensitive to velocity profile effects and they are temperature sensitive.

7.3 Transit time meter

The ultrasonic transit time measuring method is based on the fact that, relative to the pipe and the transducers, the propagation speed of an ultrasonic pulse travelling against the media flow will be reduced by a component of the flow velocity. Similarly, the speed of propagation of the pulse travelling downstream is increased by the fluid velocity. The difference between these two transit times can be directly related to the flow velocity.

In practice, the meter comprises two transducers (A and B) mounted at an angle to the flow and having a path length L (Figure 7.3) — with each acting alternately as the receiver and transmitter. The transit time of an ultrasonic pulse, from the upstream to the downstream transducer, is first measured and then compared with the transit time in the reverse direction.

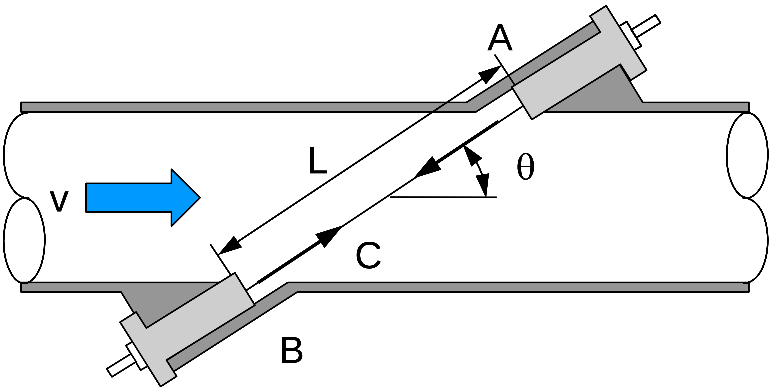


Figure 7.3. In the transit time meter two transducers (A and B) each act alternately as the receiver and transmitter.

▶ Mathematically:

$$T_{AB} = \frac{L}{(C \quad v\cos\theta)} \quad \text{...(7.2)}$$

and:

$$T_{BA} = \frac{L}{(C + v\cos\theta)} \quad \text{...(7.3)}$$

where:

T_{AB}	=	upstream travel time
T_{BA}	=	downstream travel time
L	=	path length through the fluid
C	=	velocity of sound in medium
v	=	velocity of medium.

The difference in transit time ΔT is:

$$\Delta T = T_{AB} - T_{BA} \quad \text{..(7.4)}$$

$$\Delta T = \frac{L}{(C \quad v\cos\theta)} \; \frac{L}{(C+v\cos\theta)} \quad \text{..(7.5)}$$

$$\Delta T = \frac{2Lv\cos\theta}{(C^2 \quad v^2\cos^2\theta)} \quad \text{..(7.6)}$$

Since the velocity of the medium is likely to be much less than the velocity of sound in the medium itself (15 m/s compared to 1500 m/s), the term $v^2 \cos^2 \theta$ will be very small compared with C^2 and may thus be ignored for all practical flow velocities. Thus:

$$\Delta T = \frac{2Lv\cos\theta}{(C^2)} \quad \text{..(7.7)}$$

$$v = \frac{\Delta T C^2}{2L\cos\theta} \quad \text{..(7.8)}$$

This shows that the flow velocity v is directly proportional to the transit time difference ΔT. This also illustrates that v is directly proportional to C^2 (the square of the speed of sound) which will vary with temperature, viscosity, and material composition.

Fortunately, it is possible to eliminate the variable C^2 from the equation:

$$C = \frac{L}{T_M} \quad \text{..(7.9)}$$

where: T_M is the mean transit time given by:

$$T_M = \frac{(T_{AB} - T_{BA})}{2} \quad \text{..(7.10)}$$

Therefore:

$$C = \frac{2L}{(T_{AB} - T_{BA})} \quad \text{..(7.11)}$$

and:

$$C^2 = \frac{4L^2}{(T_{AB} - T_{BA})^2} \quad \text{..(7.12)}$$

now:

$$v = \Delta T.4L^2 / 2L \cos\theta \, (T_{AB} + T_{BA})^2 \quad \text{..............................(7.13)}$$

or:

$$v = k \, \Delta T/(T_{AB} + T_{BA})^2 \quad \text{..(7.14)} \blacktriangleleft$$

Since both the length L and the angle θ are likely to remain constant it is only necessary to calculate the sum and difference of the transit times in order to derive the flow rate independent of the velocity of sound in the medium.

As distinct from Doppler meters, transit time meters work better on clean fluids and typical applications include: water, clean process liquids, liquefied gases and natural gas pipes.

The accuracy of measurement is determined by the ability of the instrument to measure accurately the transit time. In a 300 mm diameter pipe, for example, with the transducers set at 45 °, and the media flowing at 1 m/s, the transit time is about 284 µs and the time difference ΔT is less than 200 ns. This means that in order to measure the velocity with a full scale accuracy of 1 %, must be at the very least down to 2 ns. With smaller diameter pipes, the measurement accuracy would need thus to be in the picosecond range.

Obviously, with longer path lengths, this stringent time measurement requirement becomes easier to meet. Performance thus tends to be better with large bore pipes, and providing multiple traverses as illustrated in Figure 7.4 can increase the path length.

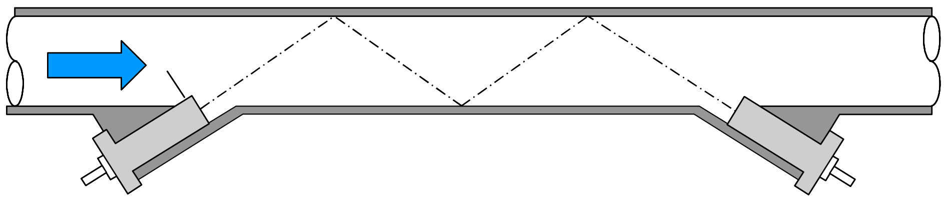


Figure 7.4 Increasing the path length using a double traverse, single 'V' path on the centre line.

These arrangements are frequently used for gas measurement in lines and gas flow measurement. The double traverse, single path flow meter is frequently used for low-cost liquid measurement and accurate real-time measurement of hazardous and non-hazardous gas flows in lines from 100 to 900 mm DN.

The 'U'-form meter as shown in Figure 7.5 can be used for very low flows.

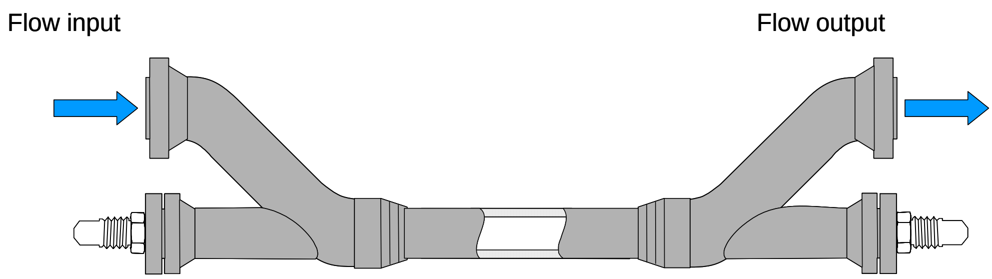


Figure 7.5. The 'U'-form meter can be used for very low flows.

7.4 Flow profile

▶ The average velocity along an ultrasonic path (Figure 7.6) is given by:

$$V_{average} = \int_0^D V \,.\, dx$$

where:

D = pipe internal diameter
X = distance across the pipe

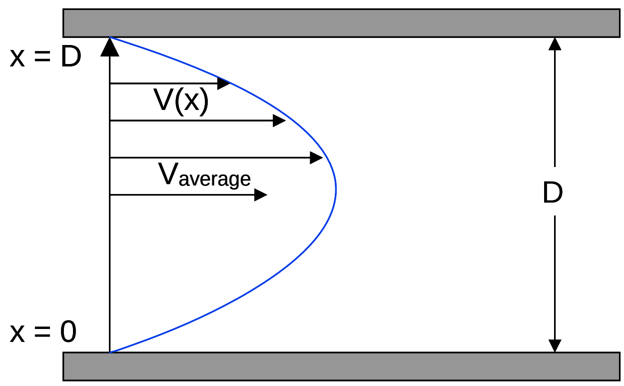


Figure 7.6. Average velocity along an ultrasonic path.

Thus, with a single path across the flow, the average flow is made up of the sum of the instantaneous velocities at each point across the diameter of the pipe.◀

The transit time meter thus provides a picture of the total flow profile along the path of the beam. However, the validity of the measurement can only be relied on if the flow profile is not subject to an asymmetric velocity profile or symmetric swirl. In addition it is important to know the flow profile. If, for example, the flow profile is not fully developed, then, as shown in Figure 7.7, the laminar-to-turbulent error can be up to 33%.

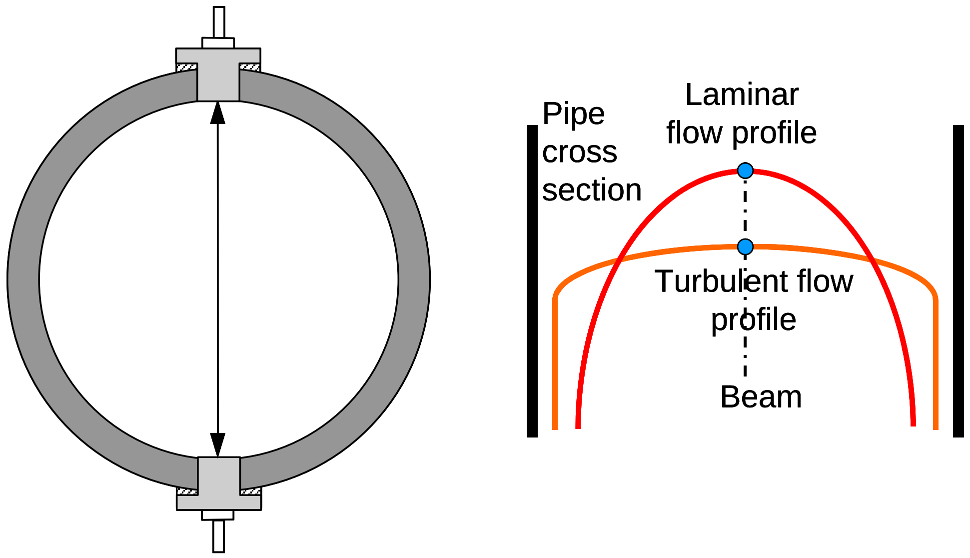


Figure 7.7. A single path produces a laminar-to-turbulent error up to 33% (courtesy Krohne).

Using a dual path as shown in Figure 7.8, the laminar-to-turbulent error can be reduced to 0.5 %.

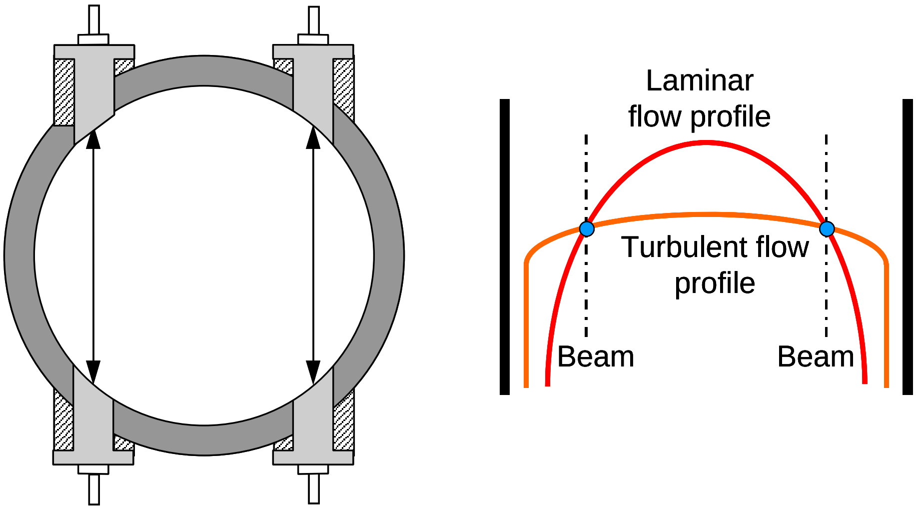


Figure 7.8. A dual path reduces the laminar-to-turbulent error to 0.5% (courtesy Krohne).

An alternative method is shown in Figure 7.9. Here, internal reflectors, used to impart a helical path to a single beam device, result in high accuracy measurement for a wide flow range, from laminar to turbulent and even in the transitional region.

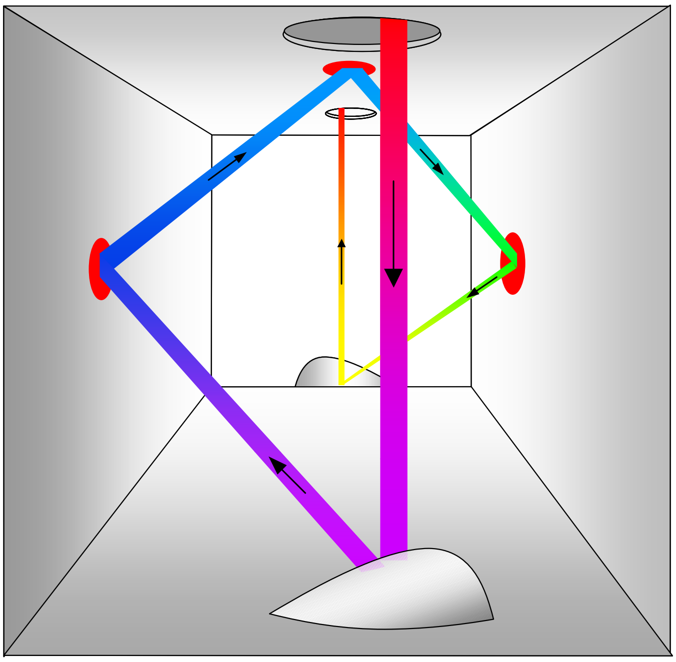


Figure 7.9. Single beam with helical path produces high accuracy measurement for a wide flow range from laminar to turbulent (courtesy Siemens).

In the Krohne multi-channel custody-transfer ultrasonic flowmeter, ten sensors form five measurement paths located in the cross-section of the flow tube (Figure 7. 10).

This approach provides a wealth of information on the flow profile (Figure 7.11) in laminar and in turbulent flow conditions and provide highly accurate flow even in the presence of non-symmetric flow profiles and swirl. — thus providing a measurement that is essentially independent of the flow profile — with accuracies to 0.15% and repeatability down to 0.02%.

Another advantage of using multiple measurement channels is redundancy.

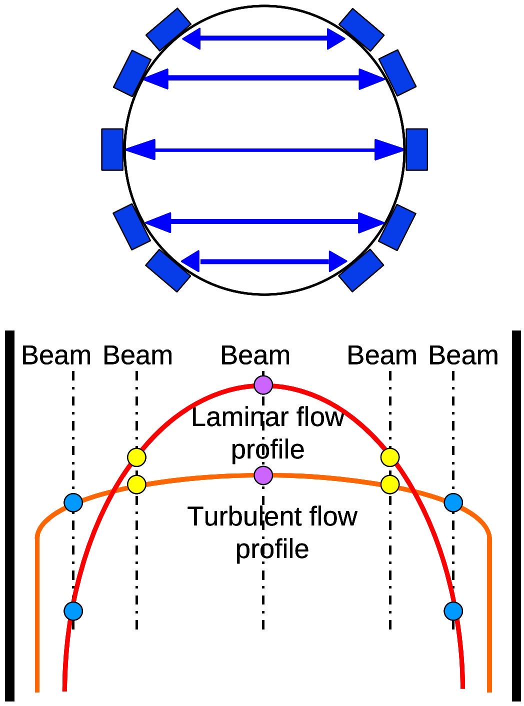


Figure 7.10. Five measurement paths provide a measurement that is essentially independent of the flow profile (courtesy Krohne).

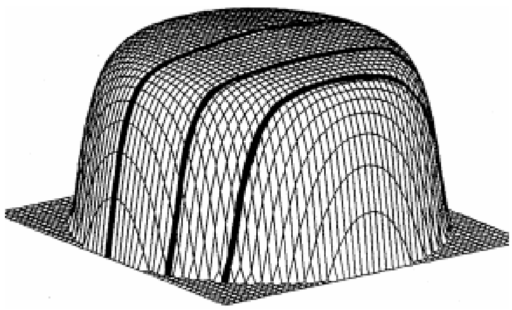


Figure 7.11. Determination of the flow profile (courtesy Krohne).

7.5 Frequency difference

The frequency difference or 'sing-around' flowmeter makes use of two independent measuring paths — with each having a transmitter (A and A') and a receiver (B or B') (Figure 7.6). Each measuring path operates on the principle that the arrival of a transmitted pulse at a receiver triggers the transmission of a further pulse. As a result, a pair of transmission frequencies is set up — one for the upstream direction and another for the downstream direction. The frequency difference is directly proportional to the flow velocity.

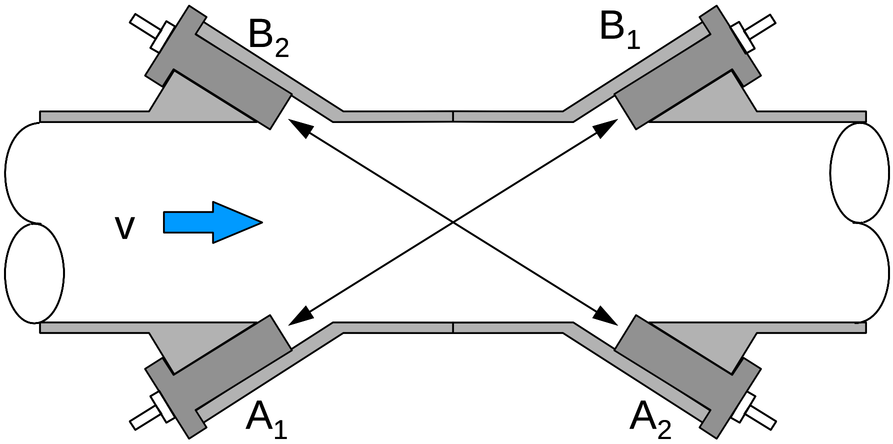


Figure 7.6. 'Sing-around' flowmeter makes use of two independent measuring paths each having a transmitter (A and A') and a receiver (B or B').

▶ Thus:

$$F_1 = \frac{(C \quad v\cos\theta)}{L} \qquad \text{.......................................(7.15)}$$

and:

$$F_2 = \frac{(C + v\cos\theta)}{L} \qquad \text{.......................................(7.16)}$$

The frequency difference ΔF is given by:

$$\Delta F = F_1 \quad F_2 = \frac{2v\cos\theta}{L} \qquad \text{.......................................(7.17)}$$

and:

$$v = \frac{\Delta F L}{2\cos\theta} \qquad \text{.......................................(7.18)}$$

◀

The main advantage of this system is that because the frequency difference is directly proportional to flow, no maths function is required. Further, the measurement is independent of the velocity of sound in the medium.

7.6 Clamp on instruments

Transducers that are clamped externally to the walls of the pipe provide portable non-intrusive flow measurement systems that can be installed within a few minutes to virtually any pipe (Figure 7.13). Pipe materials include: metal, plastic, ceramic, asbestos cement and internally and externally coated pipes.

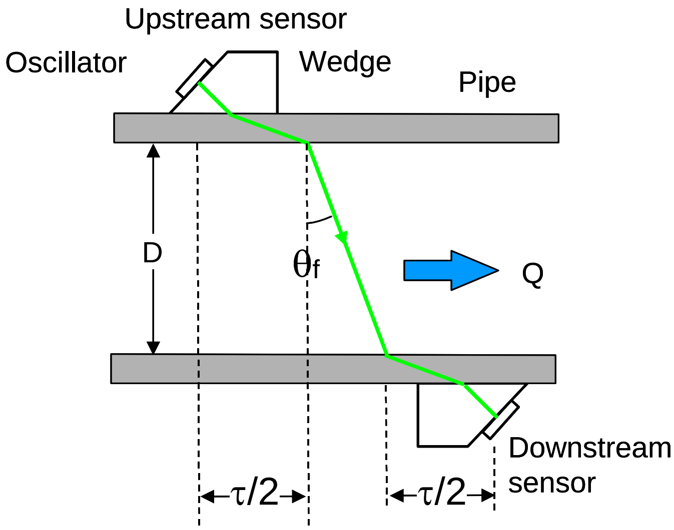


Figure 7.13. Clamp-on transducers must take into account the thickness and material of construction of the pipe wall (courtesy Fuji Electric).

Clamp-on transducers are also often used in permanent installations that cannot justify a permanent in-line meter but nonetheless require periodic metering.

Because the ultrasonic pulses must traverse the pipe wall and any coatings, the thicknesses must be known. In addition, the presence of deposits on the inside pipe surface will affect the transmitted signal strength and, therefore, performance.

Despite these obstacle, modern clamp-on ultrasonic meters, incorporating microprocessor technology that allows the transducer mounting positions and calibration factors to be calculated for each application, provide measuring accuracies of 1 to 3% — depending on the application.

In conventional designs, a change in the characteristics of the liquid, which affects the speed of sound, will have a direct effect on the refraction angle. With sufficient change in the refraction angle, the signal from one transducer will not be received by the other. This limitation is overcome with the wide beam approach (Figure 7.14) in which the pipe wall is incorporated into the signal transmission system. During set-up, the meter selects a transmission frequency that excites a natural acoustic waveguide mode of the pipe to induce a sonic wave that travels axially down the pipe wall. In this manner the pipe itself becomes the launching point of the acoustical signal and allows a much wider signal beam to be transmitted from one transducer to the other. The result is that any change in the refraction angle will have negligible effect on the strength of the received signal.

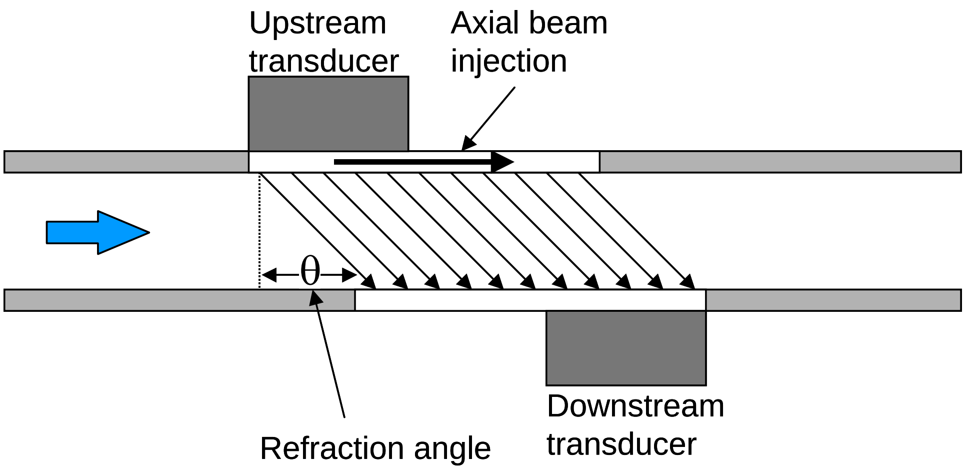


Figure 7.14. By selecting a transmission frequency that excites a natural acoustic waveguide mode of the pipe, the pipe itself becomes the launching point of the acoustical signal and allows a much wider signal beam to be transmitted from one transducer to the other (courtesy Controlotron Corporation).

7.7 Velocity of Sound Measurement

Because ultrasonic meters measure volumetric flow which is, in most cases, not relevant for plant operation purposes, their output is correlated to mass flow — assuming a fixed actual density (reference density) under operating conditions. Consequently, deviations in actual density will cause a misreading in mass flow which is inversely proportional to the deviation compared with the reference density.

Since the velocity of sound is a characteristic property of a fluid, its measurement, in conjunction with the temperature and pressure of the fluid, can be used as a measure/indication of:

- actual flowing density
- concentration (e.g. for fluids consisting of two distinctive components);
- molecular weight (W pressure, temperature, Cp/Cv ratio and compressibility are known).

Furthermore, since deviations of the velocity of sound signal/range will indicate a change in fluid composition, its output may thus be used as an 'interface detector' — alerting operators to different plant operating conditions and/or feed stock changes or changes in composition e.g. contamination in heavy crude.

Since the signal strength will also be measured, deviations in signal strength could indicate viscosity changes, an increased level of solids (crystal formation, catalyst carry over) and/or bubbles (flashing off of dissolved gases under changed pressure/temperature conditions) in the fluid.

In applications where it is required to determine changes in the constituency of the medium, the instrument should be capable of determining and displaying the speed of sound through the medium as a separate parameter.

7.7.1 Factors influencing the Velocity of Sound

Except in carbon dioxide gas service, the velocity of sound is independent of the ultrasonic frequency. Generally the velocity of sound:

- increases with increasing density;
- decreases with increasing temperature for liquids; and
- increases with increasing temperature for gases.

An important exception is water which has a discontinuity in its relationship between velocity of sound and temperature: For water below a temperature of 74 °C, the velocity of sound will increase with increasing temperature. Above 74 °C the velocity of sound will decrease if the temperature increases.

7.8 Beam scattering

As indicated earlier, beam scattering/dispersion may occur if the fluid contains too many particles (crystals, catalyst particles). Further, as soon as the fluid ceases to be single phase, beam scattering may occur under bubble flow or mist flow conditions.

At the frequency and intensity of the ultrasonic energy typically used in industrial applications, propagation through liquids may be up to distances of 10 m. However, the same energy will only propagate a few millimetres in air. Therefore, evenly distributed air bubbles will disperse the energy by reflection from the liquid/air boundaries and cause significant attenuation (Figure 7.15). The generally accepted upper limit for entrained gases is about 1% by volume and for solids is 1 to 5%.

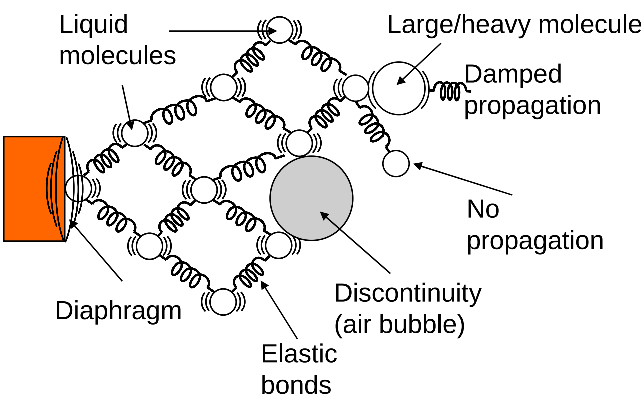


Figure 7.15. Sound propagation in a mixed medium.

Bubble flow could appear with liquids operating close to their boiling point where only a marginal pressure decrease could cause the liquid to evaporate and form bubbles.

Another flashing off phenomena (not so well recognised as boiling off) occurs if gas is dissolved in liquid. Generally, as the pressure decreases or the temperature rises, the dissolved gas can no longer be contained in the liquid and will flash off until a new equilibrium is reached. Typical examples of gases soluble in liquid are:

- H_2S in water
- H_2S in DIPA (diisopropylamine)
- $CO/C0_2$ in water
- $C0_2$ in methanol

In order to minimise or prevent bubble flow, the meter should be moved to a location in the line with a higher pressure, e.g. downstream of a pump

In immiscible mixtures (e.g. water/oil), beam scattering should be avoided by thorough upstream agitation to ensure that no oil droplets in water or water droplets in oil are present at the meter.

Product layering may also introduce beam scattering and should be avoided by proper mixing. Product layering occurs not just as a result of poorly mixed products, but at locations where cold and hot streams are mixed.Layering will most likely occur directly downstream of a tie-in of a cold stream with a hot stream, of the same product, as a result of density differences. To avoid product layering, the fluid should be thoroughly mixed upstream of the meter using reducers ($d/D \leq 0.7$) or static mixers.

7.9 Summary

Apart from not obstructing the flow, ultrasonic flowmeters are not affected by corrosion, erosion or viscosity. Most ultrasonic flowmeters are bi-directional, and sense flow in either direction.

7.9.1 Advantages

- Suitable for large diameter pipes.
- No obstructions, no pressure loss.
- No moving parts, long operating life.
- Fast response.
- Weld-on transducers may be installed on existing pipe-lines.
- Multi-beam systems can be used to eliminate the effects of profile
- Not affected by fluid properties.

7.9.2 Disadvantages

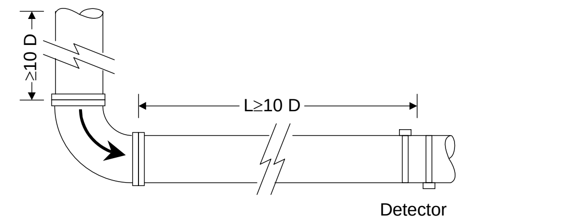
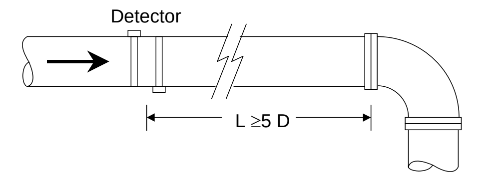
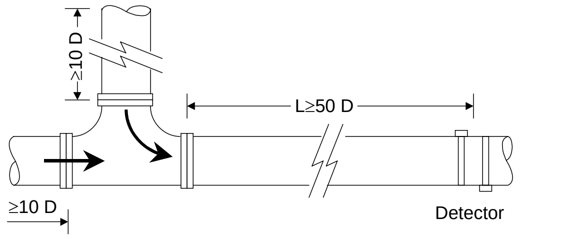
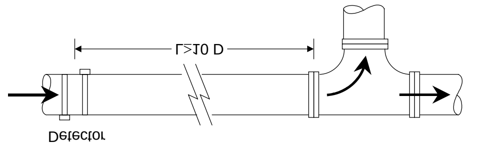
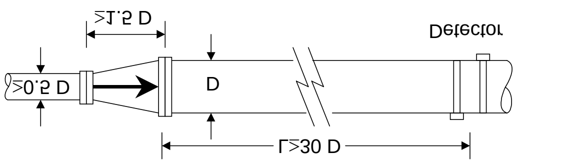
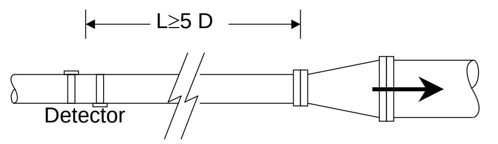
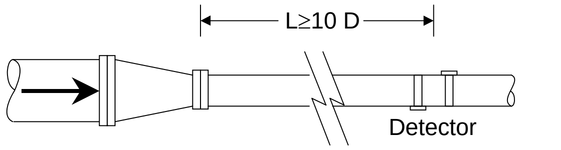
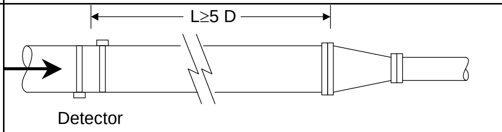
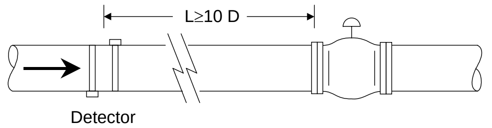
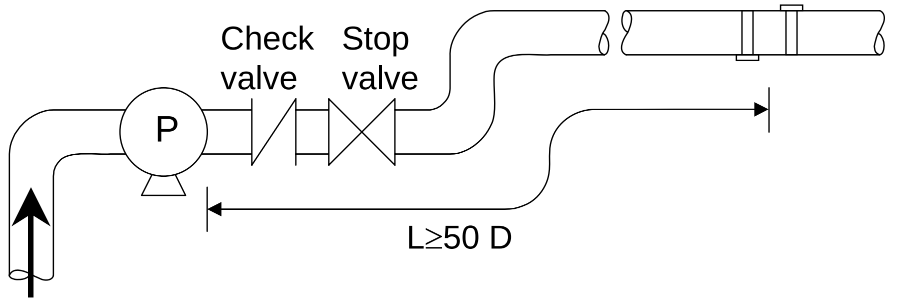
- In single-beam meters the accuracy is dependent on flow profile.
- Fluid must be acoustically transparent.
- Expensive.
- Pipeline must be full

7.9.3 Application limitations

For the transit time meter, the ultrasonic signal is required to traverse across the flow, therefore the liquid must be relatively free of solids and air bubbles. Anything of a different density (higher or lower) than the process fluid will affect the ultrasonic signal.

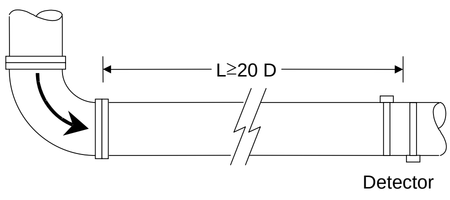
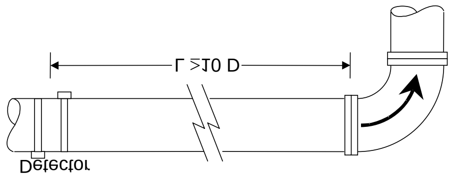
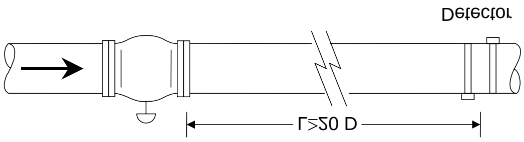
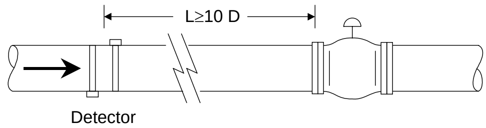
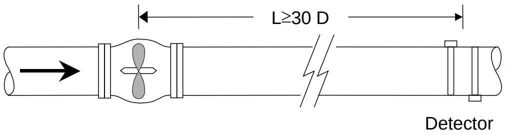
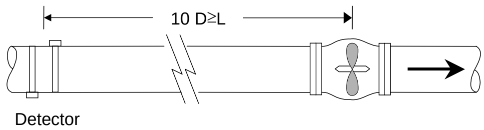
Turbulence or even the swirling of the process fluid can affect the ultrasonic signals. In typical applications the flow needs to be stable to achieve good flow measurement, and typically allowing sufficient straight pipe up and downstream of the transducers does this. The straight section of pipe required upstream and downstream is dependent on the type of discontinuity and varies for gas and liquid as shown in Tables 8.1 and 8.2.

Table 8.1. Minimum straight line pipe lengths for general purpose liquid measurement (Courtesy Fuji Electric)

Classification	Upstream	Downstream
90° bend		
Tee		
Diffuser		
Reducer		
Valve		
Pump		

D = internal diameter of pipe

Table 8.2. Minimum straight line pipe lengths for general purpose gas measurement (Courtesy Fuji Electric)

Classification	Upstream	Downstream
90° bend		
Valve		
Fan		
Pump		

D = internal diameter of pipe

Chapter 8. Mass Flow Measurement

Industrial Flow Measurement

Chapter 8

Mass Flow Measurement

8.1 Introduction

Most chemical reactions are based largely on their mass relationship. Consequently, by measuring the mass flow of the product it is possible to control the process more accurately. Further, the components can be recorded and accounted for in terms of mass.

Mass flow is a primary unit of flow measurement and is unaffected by viscosity, density, conductivity, pressure and temperature. As a result it is inherently more accurate and meaningful for measuring material transfer.

Traditionally, mass flow has been measured inferentially. Electromagnetic, orifice plate, turbine, ultrasonic, venturi, vortex shedding, etc, all measure the flow of the medium in terms of its velocity through the pipe (e.g. metres per second). However, because the dimensions of the pipe are fixed, we can also determine the volumetric flow rate (e.g. litres per second). Further, by measuring density and multiplying it by the volumetric flow rate, we can even infer the mass flow rate. However, such indirect methods commonly result in serious errors in measuring mass flow.

8.2 The Coriolis force

Possibly the most significant advance in flow measurement over the past few years has been the introduction of the Coriolis mass flowmeter. Not only does this technology allow mass flow to be measured directly but Coriolis meters are readily able to cope with the extremely high densities of, for example, dough, molasses, asphalt, liquid sulphur, etc, found in many industries.

The Coriolis meter is based on the Coriolis force – sometimes, incorrectly, known as gyroscopic action. Consider two children, Anne and Belinda, sat on a rotating platform. Anne is situated mid-way between the axis and the outer edge of the platform while Belinda is sat at the outer edge itself (Figure 8.1). If Anne now throws a ball directly to Belinda, Belinda will fail to receive the ball!

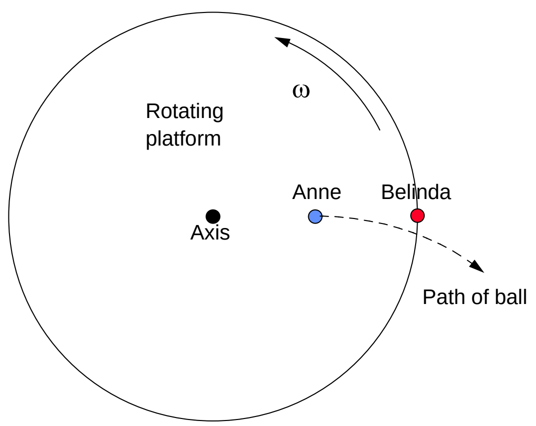


Figure 8.1. If Anne throws a ball directly to Belinda, Belinda will fail to receive the ball due to the Coriolis effect.

The reason will have nothing to do with Anne's ability to throw a straight ball (we'll assume she's a perfect pitcher) or Belinda's ability to catch a ball (we'll assume she's a perfect catcher). The reason is due to what is termed the Coriolis effect.

What Anne ignored is that although the platform is rotating at a constant angular speed (ω) she and Belinda are moving at different circular or peripheral speeds. Indeed, the further you move away from the axis, the faster your speed.

▶ In fact, the peripheral speeds of each are directly proportional to the radius i.e.:

$$v = r.\omega \quad \text{...(8.1)}$$

where:

v = peripheral velocity
r = radius
ω = angular speed.

In this case, Belinda at the edge of the platform will have a peripheral speed of twice that of Anne (Figure 8.2). Thus, when Anne throws the ball radially outwards towards Belinda, the ball initially has not only the velocity (v) radially outwards, but also a tangential velocity v_A due to the rotation of the platform. If Belinda had this same velocity v_A the ball would reach her perfectly. But Belinda's speed (v_B) is twice that of v_A. Thus when the ball reaches the outer edge of the platform it passes a point that Belinda has already passed and so the ball passes behind her.

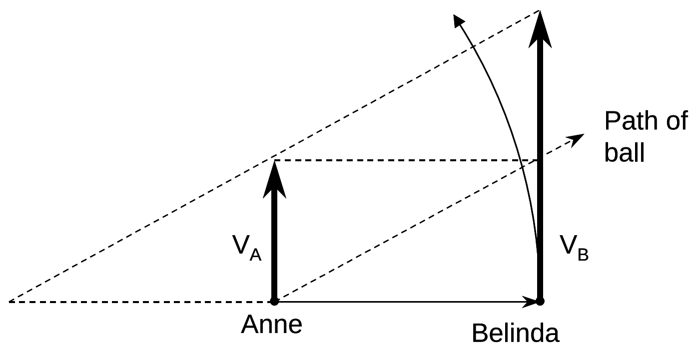


Figure 8.2. Belinda at the edge of the platform will have a peripheral speed of twice that of Anne and thus the ball's peripheral speed needs to be accelerated from v_A to v_B.

Consequently, to move the ball from Anne to Belinda its peripheral speed needs to be accelerated from v_A to v_B. This acceleration is a result of what is termed the Coriolis force, named after the French scientist who first described it, and is directly proportional to the product of the mass in motion, its speed and the angular velocity of rotation:

$$F_{cor} = 2m\omega v \quad \text{...(8.2)}$$

where:

F_{cor} = Coriolis force
v = peripheral velocity
ω = angular speed
m = the mass of the ball

Looking at this from another point, if we could measure the Coriolis force and knowing the peripheral velocity and the angular speed, we could determine the mass of the ball.

How does this relate to mass measurement of fluids? ◀

Consider a simple, straight liquid-filled pipe rotating around axis A, at an angular velocity ω (Figure 8.3). With no actual liquid flow, the liquid particles move on orbits equivalent to their distance r from the axis of rotation. Thus, at distance r_1, the tangential velocity of a particle would be r1.ω whilst at double the distance r_2, the tangential velocity would also double to $r_2.\omega$.

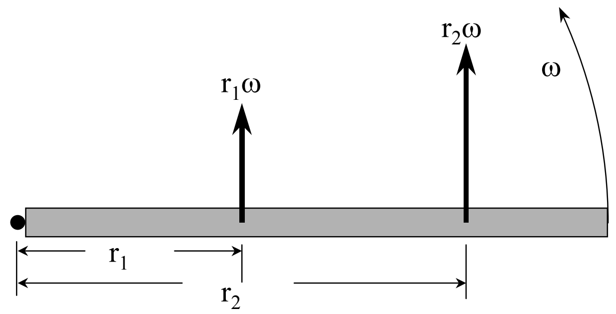


Figure 8.3. As the liquid flows away from the axis A, each mass particle will be accelerated by an amount equivalent to its movement along the axis from a low to a higher orbital velocity.

If now, the liquid flows in a direction away from the axis A, at a flow velocity v, then as each mass particle moves, for example, from r_1 to r_2 it will be accelerated by an amount equivalent to its movement along the axis from a low to a higher orbital velocity. This increase in velocity is in opposition to the mass inertial resistance and is felt as a force opposing the pipe's direction of rotation – i.e. it will try to slow down the rotation of the pipe. Conversely, if we reverse the flow direction, particles in the liquid flow moving towards the axis are forced to slow down from a high velocity to a lower velocity and the resultant Coriolis force will try to speed up the rotation of the pipe.

Thus, if we drive the pipe at a constant torque, the Coriolis force will produce either a braking torque or an accelerating torque (dependent on the flow direction) that is directly proportional to the mass flow rate.

Although the possibility of applying the Coriolis effect to measure mass flow rate was recognised many years ago, it is little more than twenty years since the first practical design was devised.

During this development period, many pipe arrangements and movements have been devised – with the major drawback of early systems lying in their need for rotational seals. This problem was overcome by using oscillatory movement rather than rotational.

8.3 A practical system

One of the simplest arrangements that incorporates all the positive features of a Coriolis-based mass flow meter is illustrated in Figure 8.4. Here, a tubular pipe, carrying the liquid, is formed in a loop and vibrated around the z axis. The straight parts of the pipe, A-B and C-D, oscillate on the arcs of a circle and without any flow will remain parallel to each other throughout each cycle.

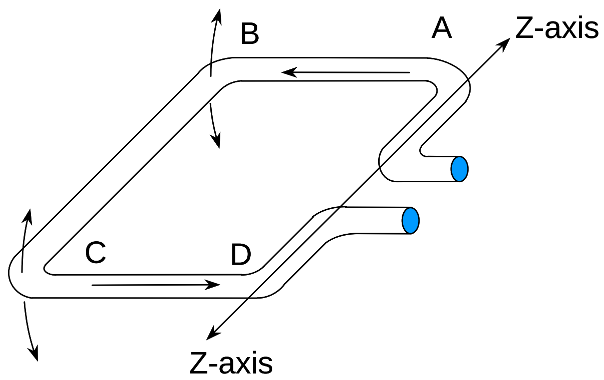


Figure 8.4. A pipe, formed in a loop, is vibrated around the z axis so that the straight parts of the pipe, A-B and C-D, oscillate on the arcs of a circle.

If a liquid now flows through the tube in the direction shown, then the fluid particles in section A-B will move from a point having a low rotary velocity (A) to a point having a high rotary velocity (B). This means that each mass particle must be accelerated in opposition to the mass inertial resistance. This opposes the pipe's direction of rotation and produces a Coriolis force in the opposite direction. Conversely, in section C-D, the particles move in the opposite direction – from a point having a high rotary velocity (C) to a point having a low rotary velocity (D).

The resultant effect of these Coriolis forces is to delay the oscillation in section A-B and accelerate it in section C-D. As a result section A-B tends to lag behind the undisturbed motion whilst section C-D leads this position. Consequently, the complete loop is twisted by an amount that is directly and linearly proportional to the mass flow rate of the fluid – with the twisting moment lent to the pipe arrangement being measured by sensors. Figure 8. 5 shows a practical arrangement in which two tubes are vibrated in opposition to each other.

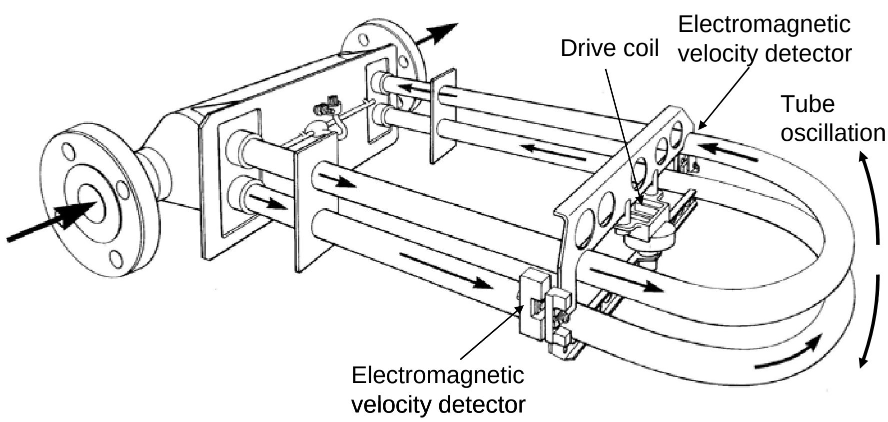


Figure 8.5. Typical arrangement of a Coriolis type instrument (Courtesy Micro Motion)

Figure 8.6 shows the oscillatory motion applied to a single tube whilst Figure 8.7 shows the forces acting on the tube in which there is fluid flow. As a result, the complete loop is twisted by an amount that is directly and linearly proportional to the mass flow rate of the fluid (Figure 8.8) – with the twisting moment lent to the pipe arrangement being measured by sensors.

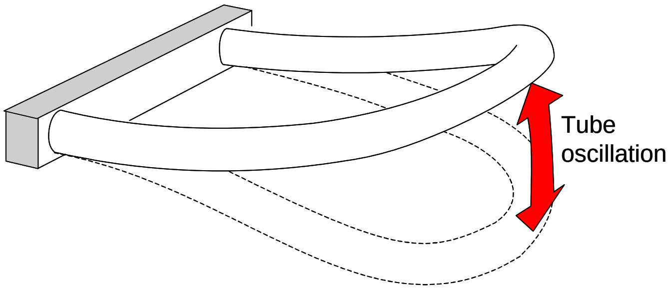


Figure 8.6. Oscillatory motion applied to a single tube (courtesy Micro Motion).

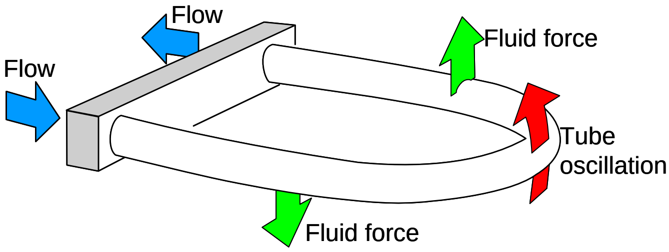


Figure 8.7. Forces acting on the tube as a result of fluid flow (courtesy Micro Motion).

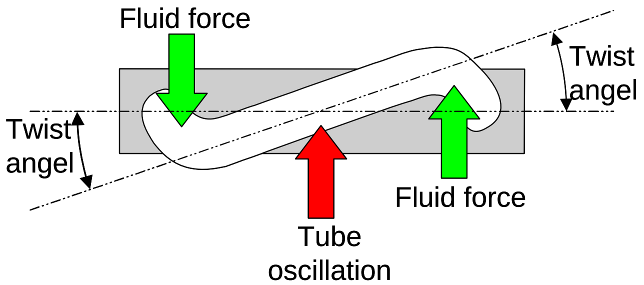


Figure 8.8. The complete loop is twisted by an amount that is directly and linearly proportional to the mass flow rate of the fluid (courtesy Micro Motion).

Because of this twisting motion, one of the major design factors of the oscillating tube is to prevent the pipe fracturing because of stress ageing. Here, computer simulation has given rise to a geometric design for thick-walled tubes that does not expose them to bending stress but to torsional strain applied evenly to the cross-section of the tube.

A further factor in reducing stress fractures is to limit the oscillation amplitude to approximately 1 mm that, in an optimally designed system, would be about 20 % of the maximum permitted value. Thus, because the distortion caused by the Coriolis forces is about 100 times smaller (a magnitude of about 10 µm) a measurement resolution of ± 0.1 % amounts to only a few nanometres. Although the possibility of stress fractures occurring is small, consideration must be given to the fact that a stress fracture **could** occur – resulting in the release of the process medium. As a result, considerable attention has been paid to secondary containment of the process medium.

It should be noted that secondary containment does not necessarily match the maximum process pressure specifications. Thus, for example, whilst the measuring tube and flanges may be suitable for up to 400 bar, or more, the secondary containment may only be rated up to a pressure of 100 bar.

8.4 Multiple phase flow

Whilst fundamentally suitable for both gaseous and liquid media, in practice the Coriolis technique is really only suitable for those gases with mass flow rates typical of liquid medium. These are generally only obtained with high density gases.

Mixtures having low admixtures of finely injected gas in liquids or fine grain solid admixtures, react almost like a single phase liquid in that the admixtures merely alter the density. A Coriolis mass measurement is thus still effective.

At higher levels of non-homogeneity, two problem areas occur. First, a non-homogenous mixture results in an irregular fluctuating density and, thus, a constantly fluctuating resonant frequency that can put the system out of phase. A second problem is that the Coriolis method assumes that all particles of the medium are accelerated on orbits in accordance with the movement of the pipes. With high proportions of gas, particles in the middle of the pipe will no longer complete the movement of the pipe. Conversely, the Coriolis forces of the mass particles in the centre of the pipe will no longer affect the pipe walls. The result is that the measuring value will be systematically reduced.

Most Coriolis-based systems can still tolerate an air-water gas volume of between 4 and 6%. However, because the behaviour of liquid-gas mixtures depends on the distribution of bubbles, and the velocity of sound depends very largely on the materials involved, these figures cannot simply be transferred to other mixtures. With liquids having a lower surface tension than water, for example, considerably higher proportions of gas can be tolerated.

The conditions for solids in water are a great deal more favourable and many good systems can tolerate suspensions of fine grain solids of up to 20% in water without any difficulty.

8.5 Density Measurement

The measurement of mass flow by the Coriolis meter is, fundamentally, independent of the density of the medium. However, the resonant frequency of the oscillating pipe will vary with density – falling as the density increases. In many instruments this effect is used to provide a direct measurement of density by tracking the resonant oscillation frequency.

The temperature of the pipe system changes with the temperature of the measured medium and alters its modulus of elasticity. This not only alters the oscillation frequency but also the flexibility of the loop system. Thus, the temperature must be measured as an independent quantity and used as a compensating variable. The temperature of the medium is, therefore, also available as a measured output.

8.6 Loop arrangements

There are many different designs of Coriolis Mass Flowmeter, in the majority of which the primary sensor involves an arrangement of convoluted tubes through which the measured fluid flows.

In any arrangement requiring the tube to be bent to form the desired convolutions, the outside wall is stretched and becomes thinner whilst the inner wall becomes thicker. This distortion will vary from one tube to another and, when the flowmeter requires two such convoluted tubes, it becomes difficult to balance them both dimensionally and dynamically. Furthermore, if the fluid to be measured is abrasive, this already weakened part of the flowmeter is likely to be most severely stressed. Abrasive material can also cause erosion that will change the stiffness of the resonant elements and so cause measurement errors.

In the parallel loop arrangement (Figure 8.9) the flow is split at the inlet to follow parallel paths through the two sections. The advantage of this is that the total cross-sectional area of the flow path is the sum of the cross-sections of both pipes. At the same time, since each pipe has a relatively small cross section it may be designed with to have a high flexibility – thus increasing the sensitivity to the Coriolis effect.

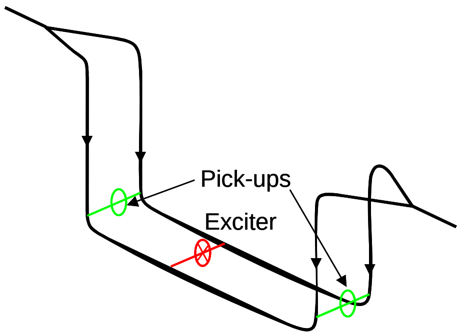


Figure 8.9. Parallel loop arrangement with flow splitter.

A disadvantage of this arrangement is that the action of splitting and then re-combining the flow introduces a significant pressure drop. Furthermore, the flow may not be divided equally, in which case an unbalance is generated – especially if solids or gases are entrained in the liquid flow. The same reasoning applies if the balance of the split is disturbed by partial or complete blockage of one section – again leading to measurement errors. The balance may also be disturbed by separation of the components in a two-phase flow, such as air or solids entrained in liquid flow. A similar problem exists with shear sensitive fluids.

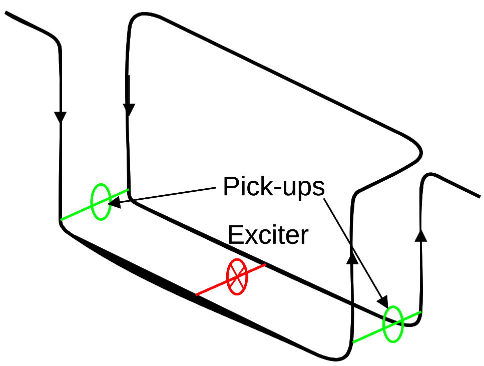


Figure 8.10. Serial loop arrangement.

In the serial arrangement (Figure 8.10) the total length of the pipe is considerably greater due to the second loop and must therefore have a larger cross-sectional area to reduce the pressure loss. This however leads to increased rigidity that makes it less sensitive to the Coriolis effect at low flow rates. At high flow rates however, there is less pressure drop, and the pipe is easier to clean.

8.7 Straight through tube

The development of a straight through tube mass flowmeter, without any loops or bends, is based on the fact that a vibrating tube, fixed at its ends, also has a rotational movement about the fixed points and thereby generates a Coriolis force.

In the first of such designs (shown in Figure 8.11) two tubes are vibrated at their resonant frequency. Infrared sensors are placed at two exactly defined locations at the inlet and outlet of the pipe to detect the phase of the pipe oscillation. At zero flow the oscillation of the system is in phase (Figure 8.12) . When liquid flows into the system the flowing medium is accelerated on the inlet (Figure 8.13) and decelerated on the outlet (Figure 8.14) and the oscillation of the system is out of phase. The measured phase difference is proportional to mass flow.

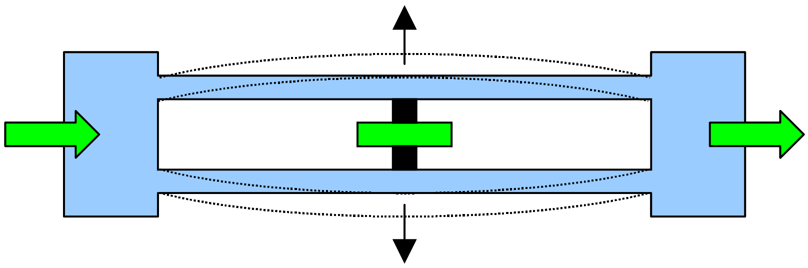


Figure 8.11. Two tubes are vibrated at their resonant frequency with sensors place at two exactly defined locations at the inlet and outlet of the pipe to detect the phase of the pipe oscillation.

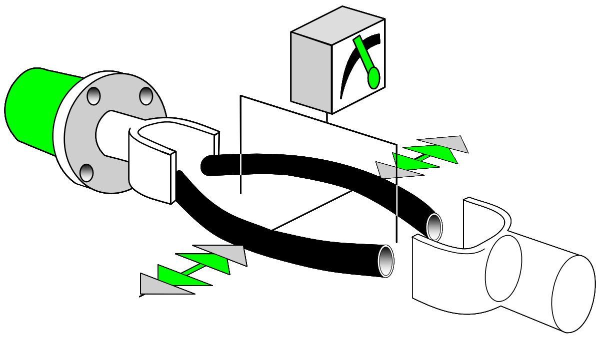


Figure 8.12. At zero flow the oscillation of the system is in phase (courtesy Endress + Hauser).

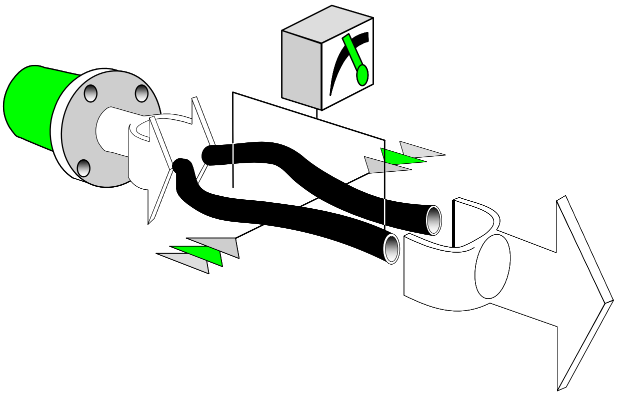


Figure 8.13 . When liquid flows into the system the flowing medium is accelerated on the inlet (courtesy Endress + Hauser).

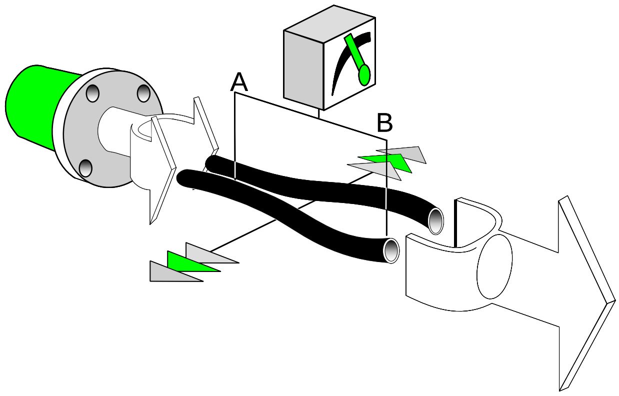


Figure 8.14. The flowing medium is decelerated on the outlet and the oscillation of the system is out of phase (courtesy Endress + Hauser).

In comparison with the 'looped' type Coriolis mass flowmeter, the straight through pipe obviously offers a much lower pressure loss and since it has no bends or loops, it is easier to clean.

Although this design avoids many of the problems associated with the convoluted tube meter, the flow splitter still causes a pressure drop and an unbalance can occur due to partial or complete blockage of one section. Straight dual-tube Coriolis meters are available in pipe sizes up to 250 mm diameter.

In more recent years several manufacturers have introduced single straight-tube designs with no bends or splitters. In the single tube system shown in Figure 8.15 a driver sets the measuring tube (AB) into a uniform fundamental oscillation mode.

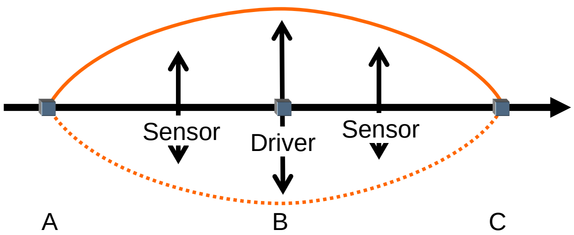


Figure 8.15. In the single tube system a driver sets the measuring tube (AC) into a uniform fundamental oscillation mode (Courtesy Krohne).

When the flow velocity is zero the Coriolis force Fc is also zero. Under flowing conditions, with the fluid particles in the product are accelerated between points AC and decelerated between points CB. As a result, a Coriolis force Fc is generated by the inertia of the fluid particles accelerated between points AC and of those decelerated between points CB, which causes an extremely slight distortion of the measuring tube (Figure 8.16).

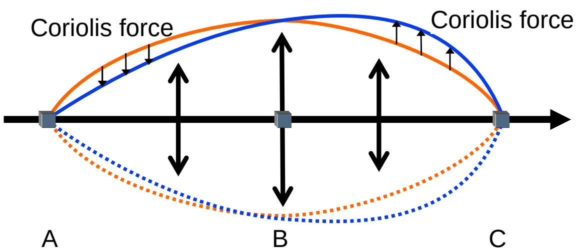


Figure 8.16 The Coriolis force Fc generated by the inertia of the fluid particles accelerated between points AC and of those decelerated between points CB, causes an extremely slight distortion of the measuring tube (Courtesy Krohne).

This distortion is superimposed on the fundamental component and is directly proportional to the mass flowrate.

Currently, single tube straight Coriolis meters are limited to a maximum pipe diameter of 100 mm.

8.8 Summary of Coriolis mass measurement

Coriolis meters may well supplant the electromagnetic flowmeter as the answer to the majority of flowmetering applications. For critical control, mass flow rate is the preferred method of measurement and, because of their accuracy, Coriolis meters are becoming common for applications requiring very tight control. Apart from custody transfer applications, they are used for chemical processes and expensive fluid handling.

8.8.1 Advantages

Some of the many benefits include:

- direct, in-line and accurate mass flow measurement of both liquids and gases;
- accuracies as high as 0.1% for liquids and 0.5% for gases;
- mass flow measurement ranges cover from less than 5 g/m to more than 350 tons/hr;
- measurement independent of temperature, pressure, viscosity, conductivity and density of the medium;
- direct, in-line and accurate density measurement of both liquids and gases;
- mass flow, density and temperature can be accessed from the one sensor; and
- can be used for almost any application irrespective of the density of the process;

8.8.2 Drawbacks

On the downside, despite tremendous strides in the technology, some of the drawbacks include:

- expensive
- many models are affected by vibration
- current technology limits the upper pipeline diameter to 150 mm; and
- secondary containment can be an area of concern.

8.9 Thermal mass flowmeters

Thermal mass flow measurement, which dates back to the 1930's, is a quasi-direct method, suited, above all, for measuring gas flow. Thermal mass flow meters infer their measurement from the thermal properties of the flowing medium (such as specific heat and thermal conductivity) and hence are capable of providing measurements which are proportional to the mass of the medium.

In the ranges normally encountered in the process industry, the specific heat c_p of the gas is essentially independent of pressure and temperature and is proportional to density and therefore to mass.

The two most commonly used methods of measuring flow using thermal techniques are either to measure the rate of heat loss from a heated body in the flow stream; or to measure the rise in temperature of the flowing medium when it is heated.

8.9.1 Heat loss or `hot wire' method

In its simplest form a hot body (a heated wire, thermistor, or RTD) is placed in the main stream of the flow (Figure 8.17). According to the first law of thermodynamics, heat may be converted into work and vice versa. Thus, the electrical power (I^2R) supplied to the sensor is equal to the heat convected away from it.

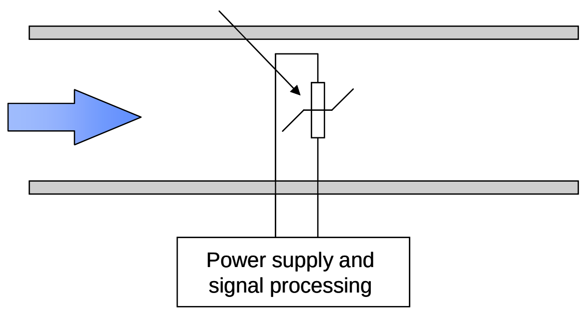


Figure 8.17. Basic schematic of `hot wire' method.

Since it is the molecules (and hence mass) of the flowing gas that interact with the heated boundary layer surrounding the velocity sensor and convect away the heat, the electrical power supplied to the sensor is a direct measure of the mass flow rate.

▶ The rate of heat loss of a small wire is given by:

$$P = h A (T_w - T_f) \quad \text{..(8.3)}$$

where:

P	=	heat loss in watts
h	=	heat transfer coefficient
A	=	surface area of the wire
T_w	=	wire temperature
T_f	=	fluid temperature

The heat transfer coefficiency depends on: the wire geometry, the specific heat; the thermal conductivity and density of the fluid; as well as the fluid velocity in the following way:

$$H = C_1 + C_2 \sqrt{\rho v} \quad \text{...(8.4)}$$

where C_1 and C_2 are constants that depend on the wire geometry and gas properties. The term $\sqrt{\rho v}$ indicates that the output of the hot wire flow meter is related to the product of density and velocity, which can be shown to be proportional to mass flow rate.◀

In practice, this device can be used only if the medium temperature is constant, since the measured electrical resistance of the hot wire cannot determine whether the change in resistance is the result of a change in flow speed or of a change in medium temperature. To solve this problem the temperature of the medium must be used as a reference value and a second temperature sensor immersed in the flow to monitor the medium temperature and correct for temperature changes (Figure 8.18).

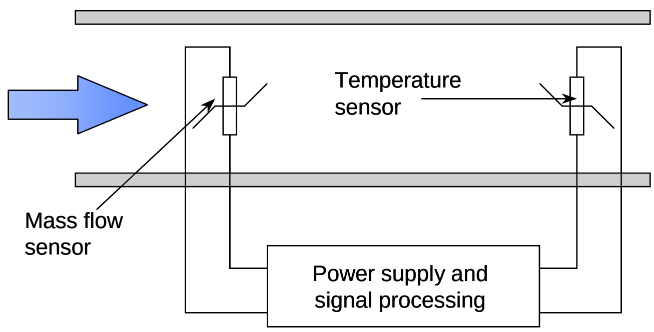


Figure 8.18. A second 'temperature sensor' monitors the gas temperature and automatically correct for temperature changes.

The mass measuring RTD has a much lower resistance than the temperature RTD and is self heated by the electronics. In a constant temperature system, the instrument measures I^2R and maintains the temperature differential between the two sensors at a constant level.

Complete hot wire mass flowmeters (Figure 8.19) are available for pipes up to 200 mm diameter (size DN 200). Above this size, insertion probes, which incorporate a complete system at the end of a rod, are used.

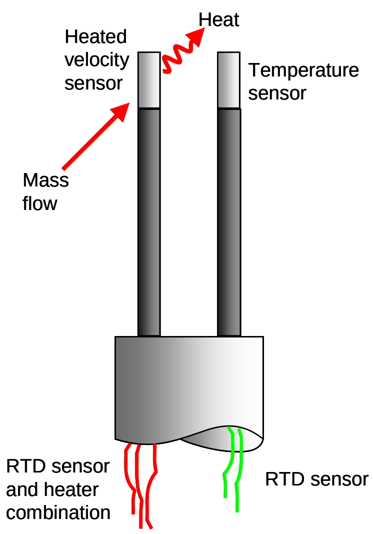


Figure 8.19. Typical in-line hot wire mass flowmeter (Courtesy Sierra Instruments Ltd).

The main limitation of this method is that by its very 'point' measurement it is affected by the flow profile within the pipe as well as by the media viscosity and pressure. Further, since the measurement is determined by the thermal characteristics of the media, the system must be calibrated for each particular gas – with each mass flow/temperature sensor pair individually calibrated over its entire flow range.

The measured value, itself, is primarily non-linear and thus requires relatively complex conversion. On the positive side, however, this inherent non-linearity is responsible for the instrument's wide rangeability (1000:1) and low speed sensitivity (60 mm/s).

Such instruments also have a fast response to velocity changes (typically 2 s) and provide a high level signal, ranging from 0.5 to 8 W over the range of 0 to 60 m/s.

One of the limitations of many conventional hot wire systems is that they soon to reach their performance limits when higher mass flow speeds need to be detected. The thermal current into the medium depends on the flow speed and thus a constant heat input would mean that when the flow speed is low there would be a build-up of heat and a corresponding temperature increase. And at high flow speeds the temperature differential would be around zero. To overcome this problem, the heat input may be adapted to the flow speed. This is achieved in the sensor shown in Figure 8.20 which consists of a high thermal-conductive ceramic substrate upon which are deposited a thick film heating resistor (Rh) and two temperature-dependent thick film resistors ($T_1$and T_2) (Figure 8.21).

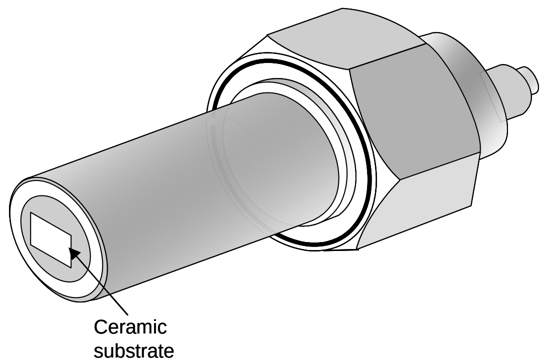


Figure 8.20. Sensor consists of a high thermal-conductive ceramic substrate upon which are deposited a thick film heating resistor and two temperature-dependent thick film resistors (courtesy Weber Sensors Group).

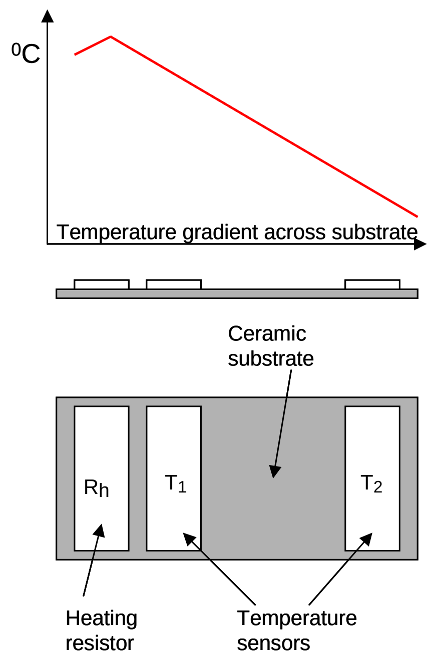


Figure 8.21. As the process medium flows along the front of the ceramic substrate the thermal current produced by the heating resistor forms a temperature gradient.

As the process medium flows along the front of the ceramic substrate, the thermal current produced by the heating resistor forms a temperature gradient as illustrated in Figure 8.21. The temperature differential between the two resistors is then used to regulate the current controlling the heating resistor.

8.9.2 Temperature rise method

In this method, the gas flows through a thin tube in which the entire gas stream is heated by a constantly powered source – with the change in temperature being measured by RTDs located upstream and downstream of the heating element (Figure 8.22). Because of the heat requirements this method is used for very low gas flows.

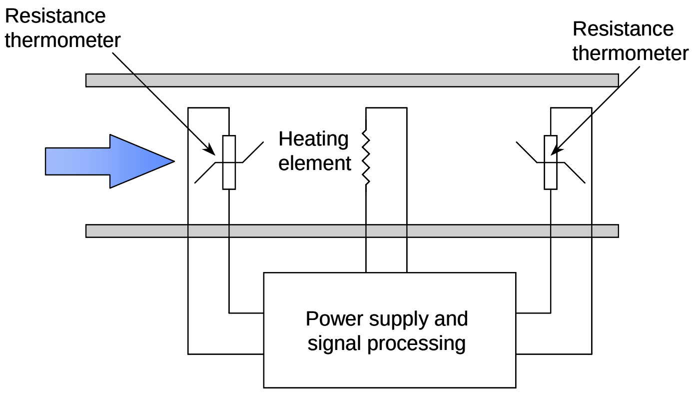


Figure 8.22. Basic schematic of 'temperature rise' method.

▶ Here, the mass flow rate q_m is:

$$q_m = k.\ q_Q/c_p.\Delta T \qquad (8.5)$$

where:

- k = constant
- q_Q = the heat input (W)
- c_p = specific heat capacity of the gas (J/kg.K)
- ΔT = temperature difference (°C)

◀

The main disadvantages of this method is that it is only suitable for low gas flows; the sensors are subject to erosion and corrosion; and the multiple tapping points increase chances of leakage.

8.9.3 External temperature rise method

An alternative arrangement places the heating element and temperature sensors external to the pipe. In the arrangement shown in Figures 8.23 and 8.24, the heating elements and temperature sensors are combined so that the RTD coils are used to direct a constant amount of heat through the thin walls of the sensor tube into the gas. At the same time, the RTD coils sense changes in temperature through changes in their resistance.

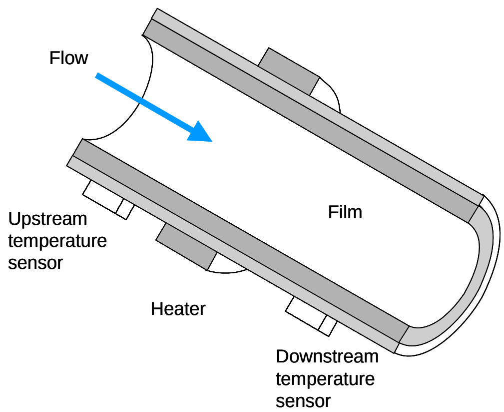


Figure 8.23. Thermal flowmeter with external elements and heater.

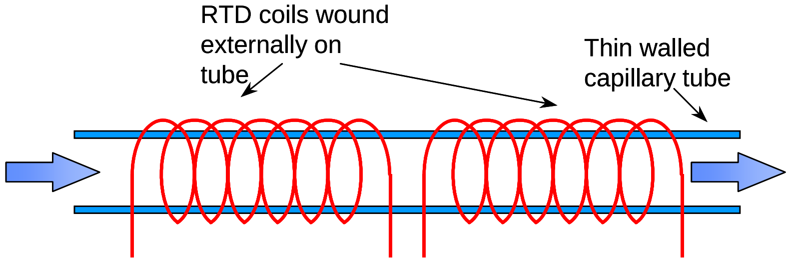


Figure 8.24. In the capillary tube meter the RTD coils are used to direct a constant amount of heat through the thin walls of the sensor tube into the gas (courtesy Sierra Instruments).

The main advantage of this method is that it provides non-contact, non-intrusive sensing with no obstruction to flow.

8.9.4 Capillary-tube meter

In a typical capillary-tube thermal mass flowmeter the medium divides into two paths, one (m_2) through the bypass and the other (m_1) through the sensor tube (Figure 8.25).

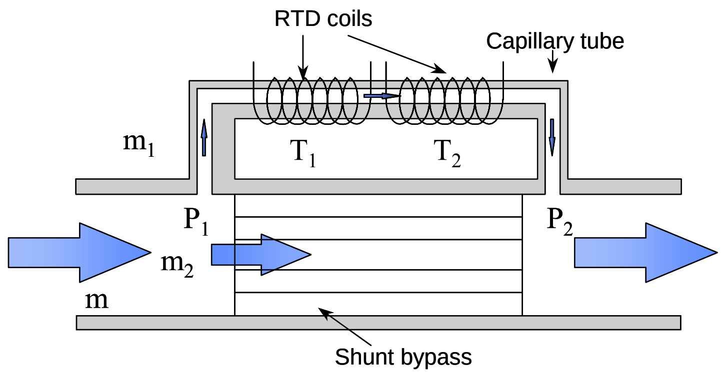


Figure 8.25. A typical capillary-tube thermal mass flowmeter (courtesy Sierra Instruments).

As the name implies, the role of the bypass is to bypass a defined portion of the flow so that a constant ratio of bypass flow to sensor flow (m_2/m_1) is maintained. This condition will only apply if the flow in the bypass is laminar so that the pressure drop across the bypass is linearly proportional to the bypass flow. An orifice bypass, for example, has non-laminar flow so that the ratio of total flow to sensor flow is non-linear.

One solution lies in the use of multiple disks or sintered filter elements. Another solution is the bypass element used by *Sierra* (Figure 8.26) which comprises a single machined element having small rectangular passages with a high length-to-width ratio. This element provides pure laminar flow and is easily removed and cleaned.

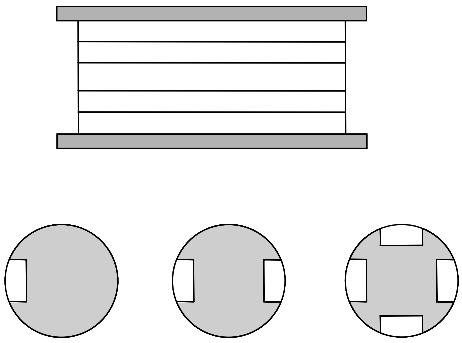


Figure 8.26. Single machined elements having small rectangular passages with a high length-to-width ratio provides pure laminar flow and are easily removed and cleaned (courtesy Sierra Instruments).

With a linear pressure drop (P_1-P_2) maintained across the sensor tube, a small fraction of the mass flow passes through the sensor tube. The sensor tube has a relatively small diameter and a large length-to-diameter ratio in the range 50:1 to 100:1 – both features being characteristic of capillary tubes.

These dimensions reduce the Reynolds number to a level less than 2 000 to produce a pure laminar flow in which the pressure drop (P_1 - P_2) is linearly proportional to the sensor's mass flow rate (m_1).
In operation, the long length-to-diameter ratio of the tube ensures that the entire cross-section of the stream is heated by the coils – with the mass flow carrying heat from the upstream coil to the downstream coil. This means the first law of thermodynamics can be applied in its simplest form.

This method is largely independent of the flow profile and the medium viscosity and pressure. It means that the flow calibration for any gas can be obtained by multiplying the flow calibration for a convenient reference gas by a constant K-factor. K-factors are now available for over 300 gases, giving capillary-tube meters almost universal applicability.

Although the output is not intrinsically linear with mass flow, it is nearly linear over the normal operating range. Accurate linearity is achieved with multiple-breakpoint linearization (for example at 25, 50, 75 and 100% of full scale).

In addition to its applicability to very low gas flows, the capillary tube method can also be used for larger flows by changing the bypass to effect a higher or lower value of the bypass ratio (m_2/m_1).

8.9.5 Liquid mass flow

Although the main application of the thermal mass flow meter lies with gases, the same technology can also be applied to the measurement of very low liquid flows, for example, down to 30 grams/hour. A typical meter is shown in Figure 8.27.

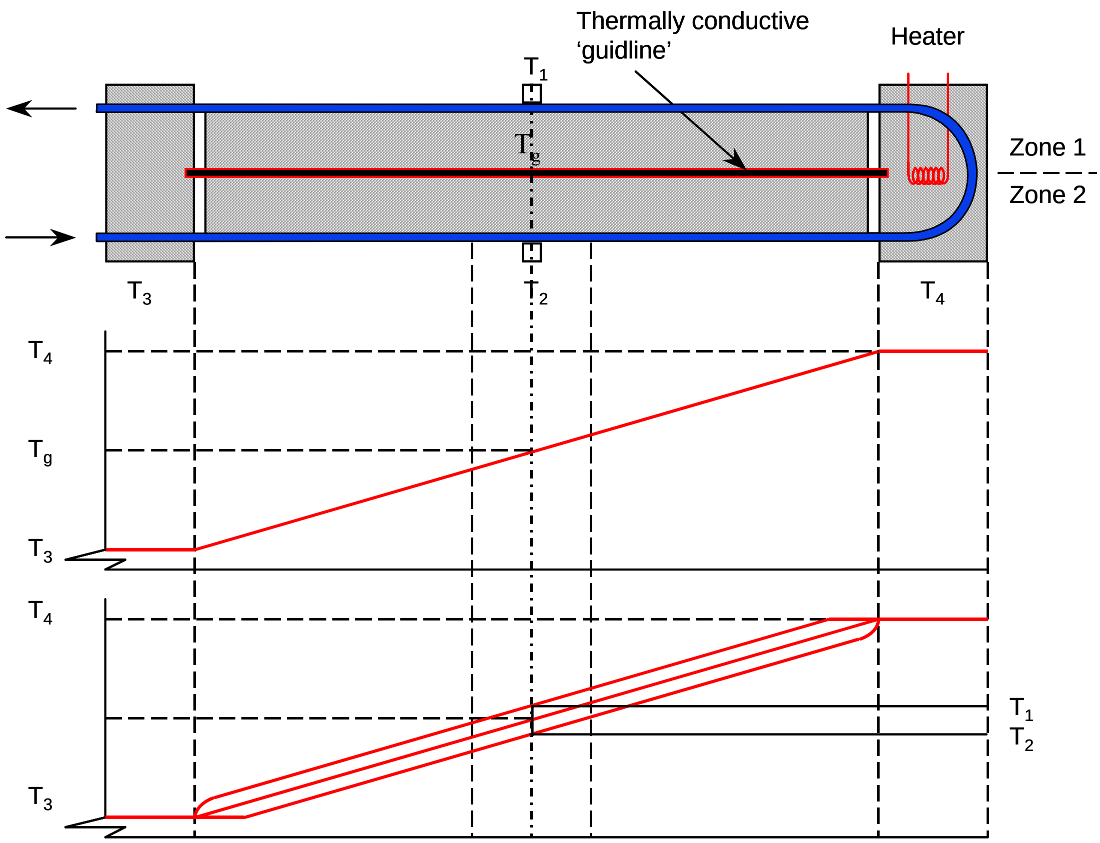


Figure 8.27. A typical liquid thermal mass flow meter (courtesy Brookes - Rosemount).

Here, the inlet and outlet of the sensor tube are maintained at a constant temperature by a heat sink – with the mid-point of the sensor tube heated to a controlled level e.g. 20°C above the temperature of the inlet-outlet heat sink. These two locations, together with the flow tube, are mechanically connected by a thermally conductive path.

In this manner, the flowing fluid is slightly heated and cooled along the sensor zones, 1 and 2 respectively, to create an energy flow perpendicular to the flow tube. Two RTDs (T_1 and T_2), located at the mid-point of the sensor tube determine the temperature difference. This temperature difference is directly proportional to the energy flow and is, therefore, directly proportional to the mass flow times the specific heat of the fluid.

Chapter 9. Open Channel Flow

Industrial Flow Measurement

Chapter 9

Open Channel Flow Measurement

9.1 Introduction

In many applications, liquid media is distributed in open channels. Open channels are found extensively in water irrigation schemes, sewage processing and effluent control, water treatment and mining beneficiation.

The most commonly used method of measuring flow in an open channel is through the use of a hydraulic structure (known as a primary measuring device) that changes the level of the liquid. By selecting the shape and dimensions of the primary device (a form of restriction) the rate of flow through or over the restriction will be related to the liquid level in a known manner. In this manner, a secondary measuring element may be used to measure the upstream depth and infer the flow rate in the open channel.

In order that the flow rate can be expressed as a function of the head over the restriction, all such structures are designed so that the liquid level on the upstream side is raised to make the discharge independent of the downstream level. The two primary devices in general use are the weir and the flume.

9.2 The weir

A weir (Figure 9.1) is essentially a dam mounted at right angles to the direction of flow, over which the liquid flows.

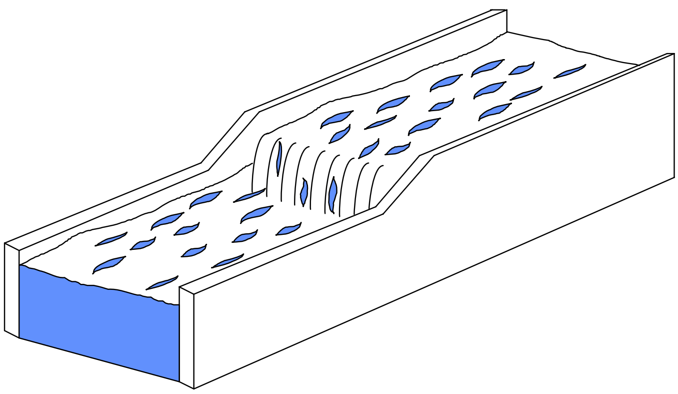


Figure 9.1. A basic weir – a dam mounted at right angles to the direction of flow.

The dam usually comprises a notched metal plate – with the three most commonly used being: the rectangular weir; the triangular (or V-notch) weir; and the trapezoidal (or Cipolletti) weir –each having an associated equation for determining the flow rate over the weir that is based on the depth of the upstream pool. The crest of the weir, the edge or surface over which the liquid passes, is usually bevelled – with a sharp upstream corner.

For the associated equation to hold true and accurate flow measurement determined, the stream of water leaving the crest (the nappe), should have sufficient fall (Figure 9.2). This is called free or critical flow, with air flowing freely beneath the nappe so that it is aerated. Should the level of the downstream water rise to a point where the nappe is not ventilated, the discharge rate may be inaccurate and dependable measurements cannot be expected.

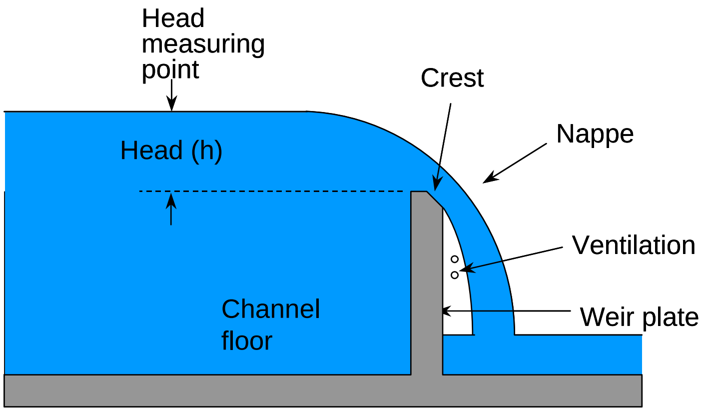


Figure 9.2. For accurate flow measurement, the nappe should have sufficient fall.

9.2.1 Rectangular weir

The rectangular weir was probably the earliest type in use and, due to its simplicity and ease of construction is still the most popular type.

In its simplest form (Figure 9.3 (a)), the weir extends across the entire width of the channel with no lateral contraction.

▶ The discharge equation (head vs. flow rate), without end contractions, is:

$$q = k\,L\,h^{1.5} \quad \ldots\ldots(9.1)$$

where:

q	=	flow rate;
k	=	constant;
L	=	length of crest; and
h	=	the head.

◀

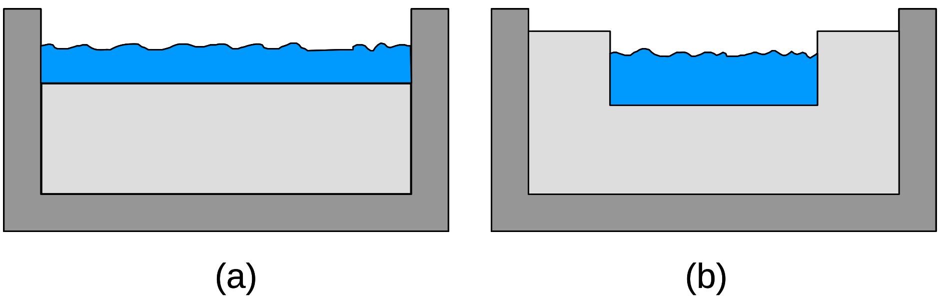


Figure 9.3. Rectangular weir (a) with no contraction; and (b) with lateral contraction.

Generally, this means that for a 1 % change in flow, there will be a 0.7 % change in the level.

A problem with rectangular weirs without contraction is that the air supply can become restricted and the nappe clings to the crest. In such cases a contracted rectangular weir (Figure 9.3 (b)) is used where end contractions reduce the width and accelerate the channel flow as it passes over the weir and provides the needed ventilation.

▶ In this case the discharge equation of such a restriction, with end contractions, becomes:

$$q = k\ (L - 0.2\ h)\ h^{1.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(9.2)}$$

where: q = flow rate;
k = constant;
L = length of crest; and
h = the head.

◀

The rectangular weir can normally handle flow rates in the range of 1:20 from about 0 - 15 ℓ/s up to 10 000 ℓ/s or more (3 m crest length).

9.2.2 Trapezoidal (Cipolletti) weir

In the trapezoidal type of weir (Figure 9.4) the sides are inclined to produce a trapezoidal opening. When the sides slope one horizontal to four vertical the weir is known as a Cipolletti weir and its discharge equation (head vs. flow rate) is similar to that of a rectangular weir with no end contractions:

$$q = k\,L\ h^{1.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(9.3)}$$

The trapezoidal type of weir has the same flow range as a rectangular weir.

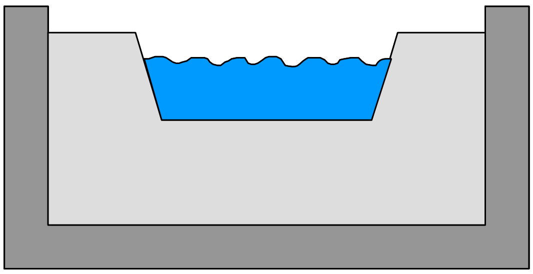


Figure 9.4. The trapezoidal or Cipolletti weir.

9.2.3 Triangular or V- notch weir

The V-notch weir (Figure 9.5) comprises an angular v-shaped notch – usually of 90° – and is particularly suited for low flows.

A major problem with both the rectangular and trapezoidal type weirs is that at low flow rates the nappe clings to the crest and reduces the accuracy of the measurement. In the V-notch weir, however, the head required for a small flow is greater than that required for other types of weirs and freely clears the crest – even at small flow rates.

▶ The discharge equation of the V-notch weir is given by:

$$q = k\,h^{2.5} \quad \text{...(9.4)}$$

where:

q = flow rate;
k = constant; and
h = the head.

This equates to a 0.4 % change in height for a 1 % change in flow. ◀

V-notch weirs are suitable for flow rates between 2 and 100 ℓ/s and, for good edge conditions, the flow range is 1: 100. Higher flow rates can be obtained by placing a number of triangular weirs in parallel.

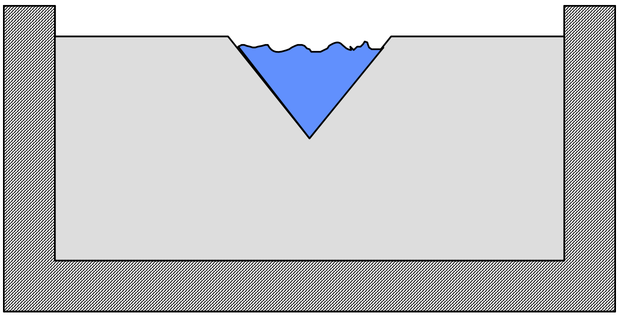


Figure 9.5. The Triangular or V- notch weir.

9.2.4 Application Limitations

There is a high unrecoverable pressure loss with weirs, which may not be a problem in most applications. However with the operation of a weir, it is required that the flow clears the weir on departure. If the liquid is not free flowing and there is back pressure obstructing the free flow, then the level over the weir is affected and hence the level and flow measurement.

Advantages

- Simple operation.
- Good Rangeability (for detecting high and low flow).

Disadvantages

- Pressure loss.
- Accuracy of about 2%.

9.3 The flume

The second class of primary devices in general use is the flume (Figure 9.6). The main disadvantage of flow metering with weirs is that the water must be dammed, which may cause changes in the inflow region. Further, weirs suffer from the effects of silt build-up on the upside stream. In contrast, a flume measures flow in an open channel in which a specially shaped flow section restricts the channel area and/or changes the channel slope to produce an increased velocity and a change in the level of the liquid flowing through it.

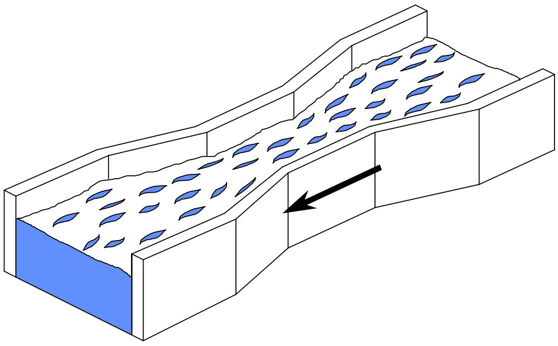


Figure 9.6. Basic flume in which a specially shaped flow section produces an increased velocity and a change in the liquid level.

Major benefits offered by the flume include: a higher flow rate measurement than for a comparably sized weir; a much smaller head loss than a weir; and better suitability for flows containing sediment or solids because the high flow velocity through the flume tends to make it self-cleaning.

The major disadvantage is that a flume installation is typically more expensive than a weir.

9.3.1 Flume flow considerations

An important consideration in flumes is the state of the flow. When the flow velocity is low and is due mainly to gravity, it is called tranquil or sub-critical. Under these conditions, it is necessary to measure the head in both the approach section and in the throat in order to determine the discharge rate.

As the flow velocity increases and the inertial forces are equal to or greater than the gravitational force, the flow is termed critical or supercritical. For both critical and supercritical states of flow, a definitive head/discharge relationship can be established and measurement can be based on a single head reading.

9.3.2 Venturi flume meter

The most common flume is the Venturi flume (Figure 9.7) whose interior contour is similar to that of a Venturi flow tube with the top removed: normally consisting of a converging section, a throat section, and a diverging section.

The rectangular venturi flume, with constrictions at the side, is the most commonly used since it is easy to construct. In addition, the throat cross section can also be trapezoidal or U-shaped. Trapezoidal flumes are more difficult to design and construct, but provide a wide flow range with low pressure loss. A U-shaped section is used where the upstream approach section is also U-shaped and gives higher sensitivity – especially at low (tranquil) flows.

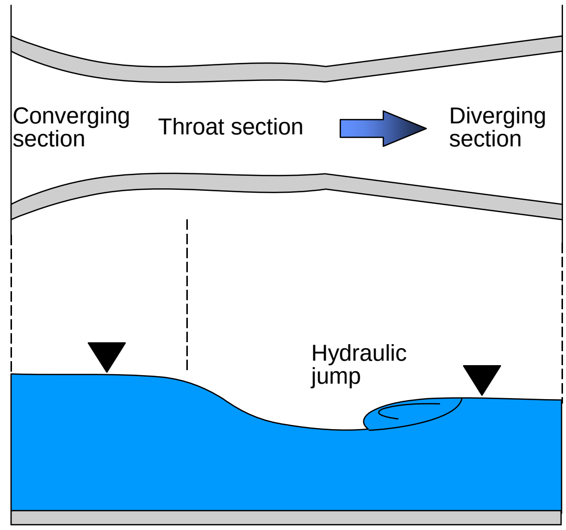


Figure 9.7. Rectangular venturi flume with constrictions at the side.

▶ Although the theory of operation of flumes is more complicated than that of weirs, it can be shown that the volume flow rate through a rectangular Venturi flume is given by:

$$q = k\,h^{1.5} \qquad (9.5)$$

where:

q = the volume flow;
k = constant determined by the proportions of the flume; and
h = the upstream fluid depth.

◀

9.3.3 Parshall venturi flume

The Parshall Venturi Flume (Figure 9.8) differs from the conventional flat bottomed venturi flume in that it incorporates a contoured or stepped floor that ensures the transition from sub-critical to supercritical flow. This allows it to function over a wide operating range whilst requiring only a single head measurement. The Parshall Venturi flume also has better self-cleaning properties and relatively low head loss.

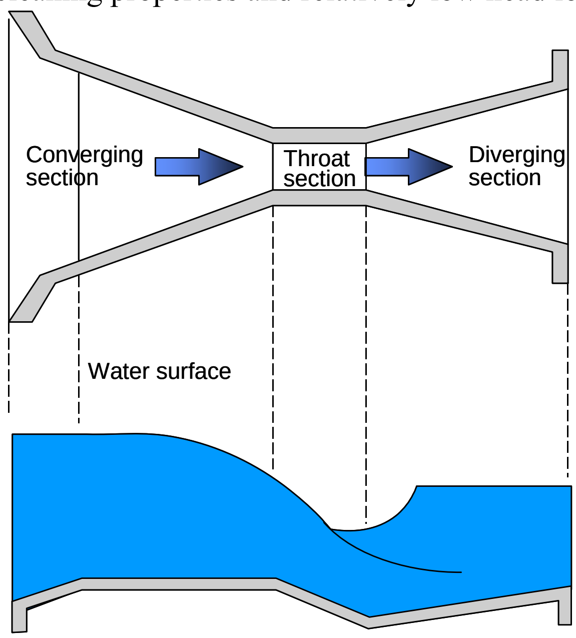


Figure 9.8. The Parshall Venturi Flume incorporates a contoured or stepped floor.

Parshall Venturi flume are manufactured in a variety of fixed sizes and are usually made of glass fibre reinforced polyester. The user need only install it in the existing channel.

▶ Because of its slightly changed shape, the discharge equation of the Parshall Venturi flume changes slightly to:

$$q = k\,h^n \qquad (9.5)$$

where:

q	=	flow rate;
h	=	the head; and
k and n		constants determined by the proportions of the flume.

Generally, the exponent n varies between 1.522 and 1.607, determined mainly by the throat width. ◀

Application Limitations
Providing excellent self cleaning properties, the venturi flume has replaced the weir in most applications, and the Parshall flume is, at present, possibly the most accurate open channel flow measuring system with flow ranges from 0.15 to 4000 ℓ/s.

Advantages include: reliable and repeatable measurements; no erosion; insensitive to dirt and debris; low head pressure loss; and simple operation and maintenance. However it is more expensive than the rectangular venturi flume and more difficult to install.

9.3.4 Palmer Bowlus

The Palmer Bowlus flume (Figure 9.9) was also developed in the USA in 1936 for use in waste water treatment and its name derives from the inventors, Messrs. Palmer and Bowlus. As shown it comprises a U-sectioned channel having a trapezoidal throat section and a raised invert. Its main advantage is its ability to match up to circular pipes and it can be fitted inside existing pipes in special applications. Flow ranges from 0.3 to 3500 ℓ/s.

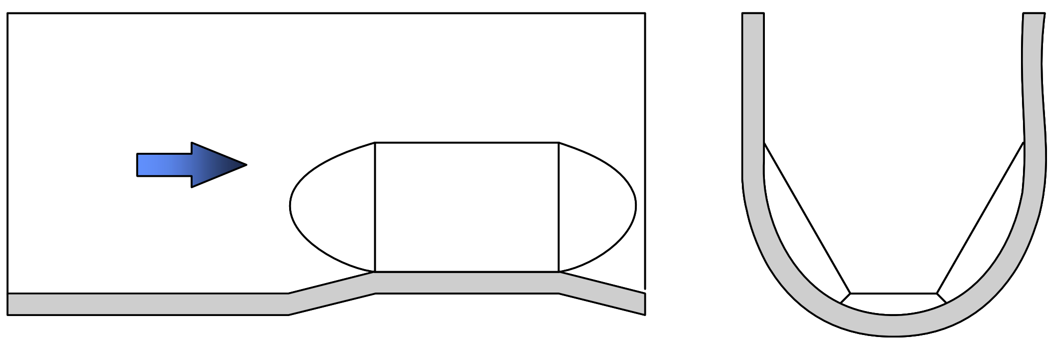


Figure 9.9. The Palmer Bowlus flume comprises a U-sectioned channel having a trapezoidal throat section and a raised invert (courtesy Neuplast).

9.3.5 Khafagi flume

Similar to the venturi flume the Khafagi flume (Figure 9.10) does not have a parallel throat section. Instead, the throat section is that point at which the inlet section meets the curve of the divergent discharge section. The floor is horizontal throughout its length. The flow range is from 0.25 to 1500 ℓ/s.

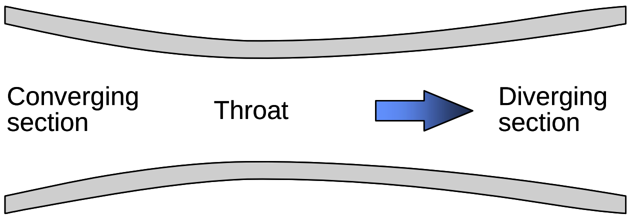


Figure 9.10. The Khafagi flume does not have a parallel throat section.

9.4 Level measurement

Whilst a weir or a flume restricts the flow and generates a liquid level which is related to the flow rate, a secondary device is required to measure this level. Several measuring methods exist:

9.4.1 Float measurement

Float measurement is a direct measurement method in which the height of the float is proportional to the water level (Figure 9.11). This height is mechanically transmitted via either a cable and pulley or a pivoting arm, and converted into an angular position of a shaft that is proportional to liquid level. Alternatively, the mechanical movement may be electrically linearised and converted to a standardised output signal.

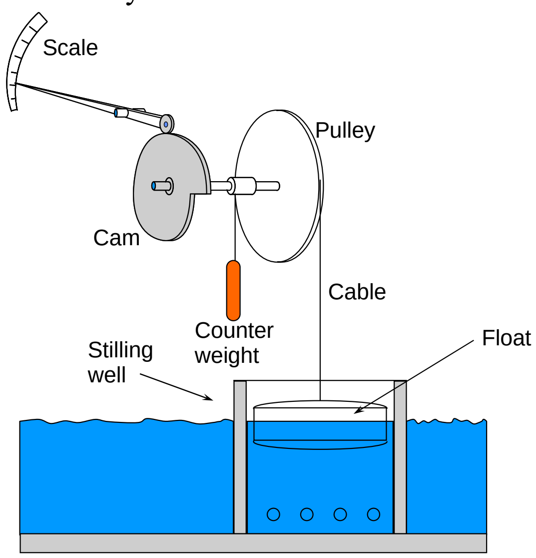


Figure 9.11. Float-operated flow meter (Courtesy Isco Inc.)

Floats are not only affected by changes in ambient air temperature, but are also subject to build up of grease and other deposits that can alter the immersion depth of the float and thus affect the measured value. Floats generally require the use of a stilling well and, since this method has moving parts that are subject to wear, periodic maintenance and repair is required.

9.4.2 Capacitive

The principle of capacitive level measurement is based on the change in capacitance between an insulated probe immersed in the liquid and a grounding plate or tube which is also in contact with the liquid (Figure 9.11). The probe forms one plate of a capacitor; the grounding plate, together with the conductive liquid, form the other plate; and the PVC or Teflon coating forms the dielectric. As the liquid level changes, it alters the size of the plate and, therefore, its capacitance. By measuring the capacitance a reading can be obtained that can be directly related to level and the flow.

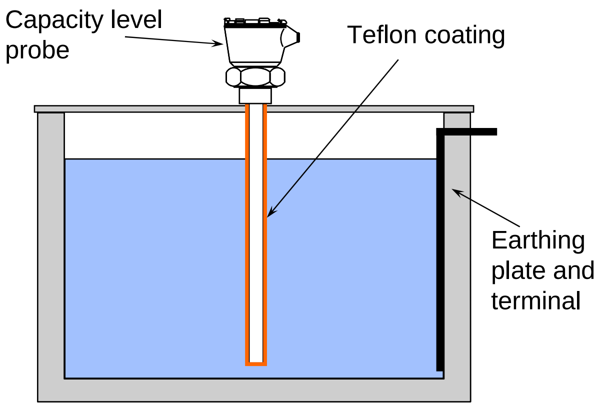


Figure 9.11. Insulated probe and grounding plate form a capacitor – with the liquid acting as the dielectric (Courtesy Endress + Hauser).

The main advantages of this system are that there are no moving parts; no mains power is required at the measuring point; and the distance between the probe and the control room can be up to 3000 m.

The main disadvantage is that accuracy is affected by changes in the characteristics of the liquid. Further, despite the very smooth surface of the Teflon or PVC coating, waste water containing grease can still lead to deposits on the measuring probe and affect the measured value.

9.4.3 Hydrostatic

This method makes use of a submerged sealed pressure transducer to measure the hydrostatic pressure of the liquid above it (Figure 9.12). The hydrostatic pressure is the force exerted by a column of water above a reference point and is proportional to the height.

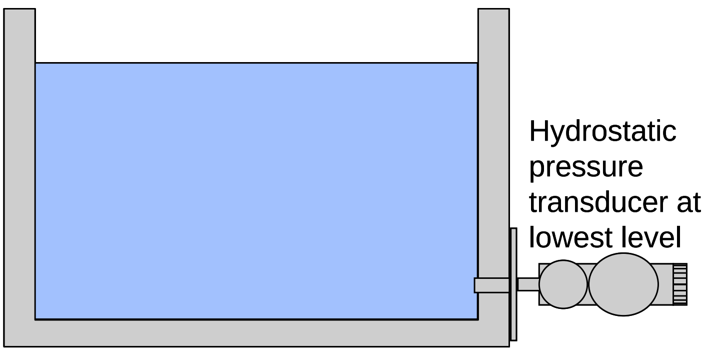


Figure 9.12. Hydrostatic pressure measurement uses a submerged sealed pressure transducer to measure the hydrostatic pressure of the liquid above it.

The transducer comprises a membrane which is firmly attached to the channel wall – with an oil fill transmitting the pressure on the membrane to a capacitive metering cell.

Submerged pressure transducers are not affected by wind, steam, turbulence, floating foam and debris, or by deposits or contamination.

However, because they are submerged, the transducers may be difficult to install in large channels with high flow, and may require periodic maintenance in flow streams with high concentrations of suspended solids or silt. Further, accuracy may be affected by changes in the temperature of the process medium.

9.4.4 Bubble injection

Like the submerged pressure transducer, the bubble injection method or 'bubbler' measures the hydrostatic pressure of the liquid (Figure 9.13). The system comprises a pressure transducer connected to a 'bubble tube' which is located in the flow stream and whose outlet is at the lowest point.

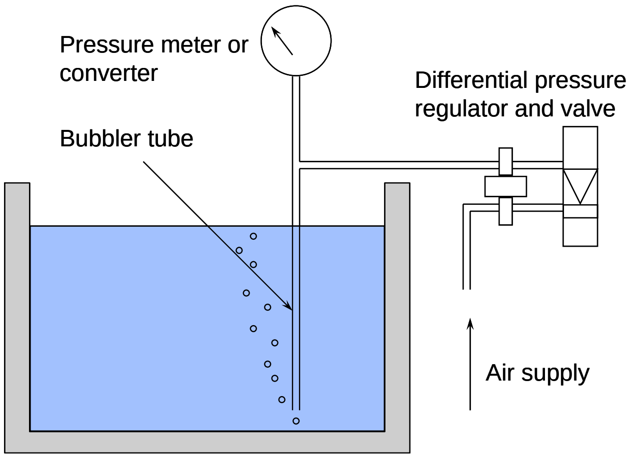


Figure 9.13. Bubble injection system (Courtesy Bailey-Fischer + Porter).

Air or other gas, at a constant pressure, is applied to the tube so that bubbles are released from the end of the bubble tube at a constant rate. The pressure measured by the transducer, which is required to maintain the bubble rate, is proportional to the liquid level.

Because the pressure transducer is not in contact with the fluid, it is not subject to chemical or mechanical attack. Additionally the cost for providing explosion proof protection is minimal.

When used in channels with high concentrations of grease, suspended solids, or silt, bubblers may require occasional maintenance – although periodic air purges of the bubble tube often minimise this problem. Additional maintenance is also required to regenerate desiccators that prevent moisture from being drawn into the air system of a bubbler.

9.4.5 Ultrasonic

Ultrasonic level measurement makes use of a transducer, located above the channel, which transmits a burst of ultrasonic energy that is reflected from the surface of the water (Figure 9.14). The time delay from the transmitted pulse to the received echo is converted into distance and hence determines the liquid level. That you are all the are' like history is it to do the things you exactly how popular

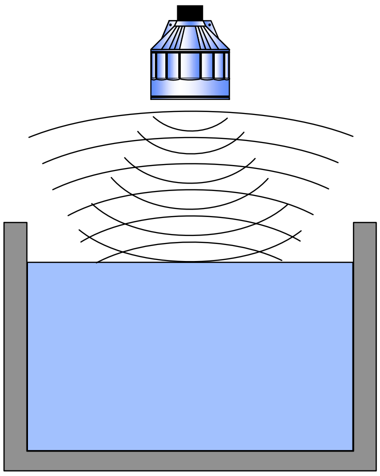


Figure 9.14. Ultrasonic level measurement uses a transducer mounted above the channel, which transmits a burst of ultrasonic energy that is reflected from the liquid surface (Courtesy Milltronics)

Ultrasonic sensors have no contact with the liquid; are easy to install; require minimal maintenance; and are not affected by grease, suspended solids, silt, and corrosive chemicals in the flow stream.

Modern ultrasonic systems are also capable of providing very high level measuring accuracies (down to ± 0.25%).

9.5 Linearization

Open channel flow measurement does not end with the measurement of level, since it still remains to convert the measured liquid level into a corresponding flow rate. This conversion or linearization must be carried out according to the level-flow rate relationship for the primary measuring device being used and can be accomplished in several ways:

9.5.1 Non-linear scale

The simplest method, where readout on an analog meter is sufficient, is to calibrate the scale according to the calculated values. Apart from its obvious inaccuracy, this method is not suitable for applications where the flow signal is required for process purposes.

9.5.2 Mechanical cam

In this method a mechanical cam is rotated by the level measuring device. The profile of the cam is contoured according to the specific level-flow rate relationship of the primary measuring device being used and thus the position of the cam follower is then proportional to flow rate.

9.5.3 Software

In modern level measuring instruments, linearization is usually carried out in software in which a wide range of different compensating curves are stored in the instrument's memory. During commissioning of the system, users may then access the correct curve – dependent on the type and dimensions of the weir or flume.

Chapter 10. Common Installation Practices

Industrial Flow Measurement

Chapter 10

Common Installation Practices

10.1 Introduction

In non-fiscal and non-custody transfer applications, flowmeters are rarely calibrated and are often left in situ for 10 or more years without any thought to their accuracy. Further, in too many instances, the initial installation is often so poorly undertaken, without any regard to basic installation practices, that it is highly unlikely that the meter in question ever met the manufacturer's stated accuracy. The data supplied by most manufacturers is based on steady flow conditions and installation in long straight pipes both upstream and downstream of the meter. In practice, most meter installations rarely meet these idealised requirements – with bends, elbows, valves, T-junctions, pumps and other discontinuities all producing disturbances that have an adverse effect on meter accuracy.

Both swirl and distortion of the flow profile can occur – either separately or together. Research has shown that swirl can persist for distances of up to 100 pipe diameters from a discontinuity whilst in excess of 150 pipe diameters can be required for a fully developed flow profile to form.

10.2 Environmental influences

The most important feature of a flow meter is that it should be sensitive to flow and as insensitive to environmental influences as possible. The most important environmental influences include:

10.2.1 Fluid temperature

The temperature range of the fluid itself will vary considerably depending on the industry in which it is to be used:

- food industry 0 to 130 °C to withstand CIP (clean in place);
- industrial steam, water, gases – 0 to 200 °C;
- industrial superheated steam – up to 300 °C;
- industrial outdoor usage – down to -40 °C; and
- cryogenics – down to -200 °C.

10.2.2 Pressure pulsations

Pressure pulsations can be a problem when measuring liquids since, after they are created, they travel a long way down the pipeline without being significantly damped. In vortex meters, for example, such symmetrical pulsations could be detected as a vortex signal. The insensitivity to such 'common mode' pressure fluctuations should, therefore, be at least 15 Pa. Differential pressure flow measurement systems can be susceptible to common mode pressure variations if the connection systems on either side of the differential pressure cell are not identical and as short as possible.

10.2.3 Vibration

Vibration is present on any piece of pipework in industry and is of particular significance in Coriolis and vortex meters. The vortex frequencies for gas, for example, lie in the range 5 to 500 Hz. Consequently, vibration induced signals in this range cannot be fully filtered out. Where possible, therefore, the sensor itself should be insensitive to pipe vibration.

10.3 Flow conditioning

While the effect of most flow disturbances can be overcome through the use of sufficient straight pipe length, upstream of the meter, this is not always practical. In such cases use can be made of one of a number of flow conditioners or straightening vanes or pipes. (Figure 10.1). Straighteners are effective in eliminating swirl and helping to restore grossly distorted flow profiles. However they cannot, generally, provide the mixing action of fluid layers required to normalise a velocity profile and some length of straight piping is still required downstream of the conditioner to provide the necessary mixing action.

For example, a Vortab Flow Conditioner is 3 diameters long, and requires 4 diameters of straight pipe between it and the meter. This reduces the total upstream pipe run (including the flow conditioner) to just 7 diameters for any upstream disturbance.

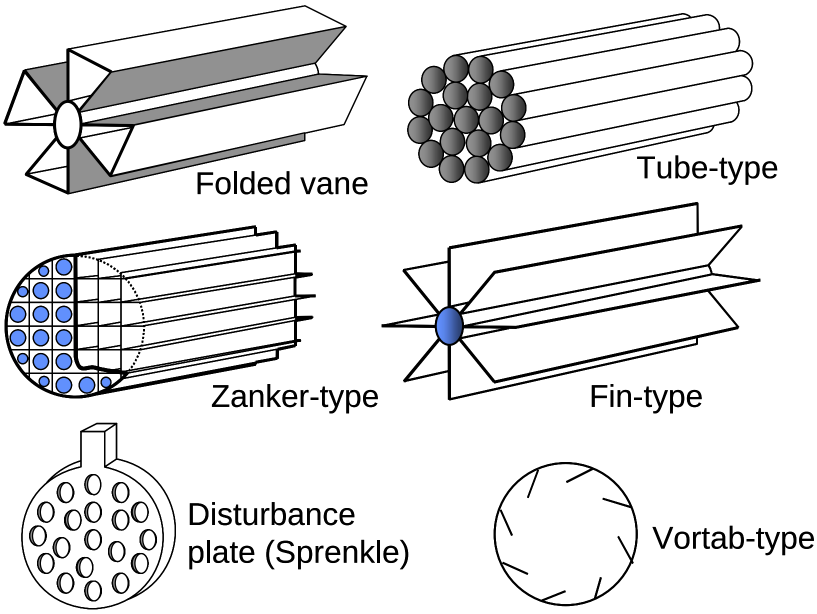


Figure 10.1. A number of flow conditioners or straighteners are available for use in the upstream line in order to minimised the effects of disturbances.

Folded vane and fin type straightening vanes are normally used on gases whilst the tubular type is normally used on steam or liquids. It is usually recommended that vanes be installed only in extreme cases after all other alternatives have been exhausted.

There is always a danger of straightening vanes coming loose in the flow line and causing serious damage to expensive equipment. They should be installed as securely as possible and should be used only for applications where moderate line velocities, pressures and temperatures exist.

10.4 General installation requirements

One To ensure reliable flowmeter operation, the following check-list will minimise problems:

- Install the meter in the recommended position and attitude.
- Ensure the measuring tube is completely filled at all times.
- When measuring liquids, ensure there is no air or vapour in the liquid.
- When measuring gases, ensure there are no liquid droplets in the gas.
- To minimise the effects of vibration support the pipeline on both sides of the flowmeter.
- If necessary, provide filtration upstream of the meter.
- Protect meters from pressure pulsations and flow surges.
- Install flow control or flow limiters downstream of the meter.
- Avoid strong electromagnetic fields in the vicinity of the flowmeter
- Where there is vortex or corkscrew flow, increase inlet and outlet sections or install flow straighteners.
- Install two or more meters in parallel if the flow rate is too great for one meter.
- Allow for expansion of the pipework.
- Make sure there is sufficient clearance for installation and maintenance work.
- Where possible provide proving connections downstream of the meter for regular in-situ calibrations.
- To enable meters to be removed for servicing without station shutdown, provide a by-pass line.

Figures 10.2 to 10.7 illustrate a number of recommended installation practices laid down specifically for electromagnetic flowmeters. The same principles also apply to most other flow metering devices.

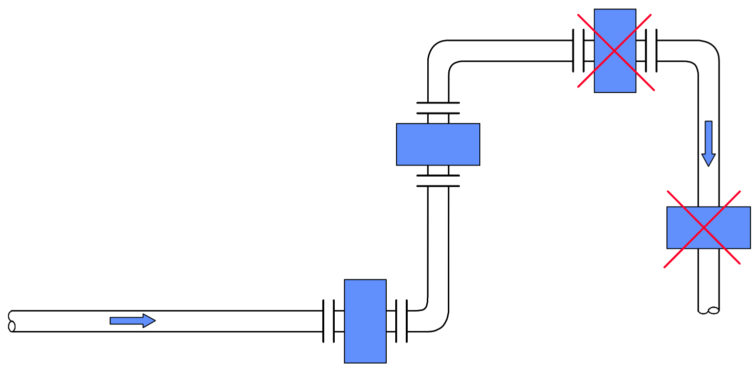


Figure 10.2. Preferred locations. Since air bubbles collect at the highest point on a pipe run, installation of the meter at this point could result in faulty measurements. The meter should not be installed in a downpipe where the pipe may be drained (courtesy Krohne).

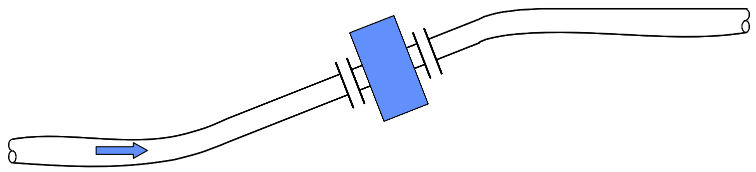


Figure 10.3. In a horizontal pipe run, the meter should be installed in a slightly rising pipe section (courtesy Krohne).

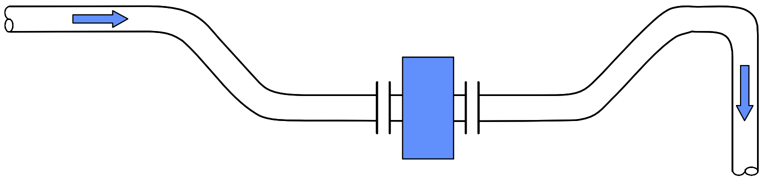


Figure 10.4. Where there is an open discharge, install the meter in a low section of the pipe (courtesy Krohne).

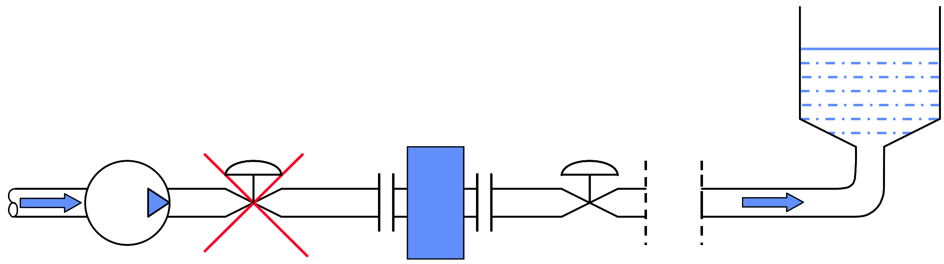


Figure 10.5. In long pipes, always install shutoff valves downstream of the flowmeter (courtesy Krohne).

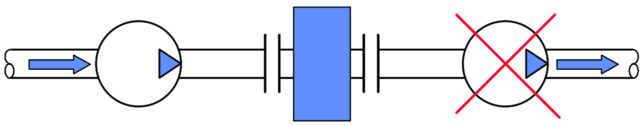


Figure 10.6. Never install a flowmeter on the pump suction side (courtesy Krohne).

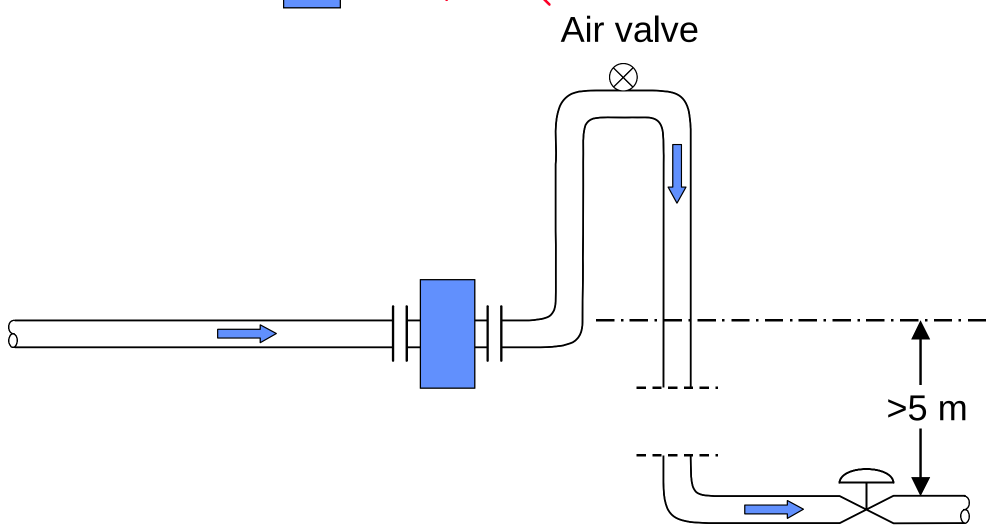


Figure 10.7. Where a downpipe is 5 m lower than the main inlet pipe, install an air valve at the highest point (courtesy Krohne).

10.5 Torquing

The role of a gasket is to form a sandwich between the flanges and ensure that the medium flowing through the meter is safely contained.

If the flange bolts are not tightened enough the gasket will leak. If over-tightened, the gasket may become deformed – resulting in a leakage. More seriously, many gaskets (for example, an O-ring) are recessed, as shown in Figure 10.8, and are normally tightened until a metal-to-metal contact occurs. In this case over-tightening can cause deformation of the flanges – leading to damage to the meter itself. Ceramic liners, in particular, have been prone to damage through over-tightening as their mechanical characteristics are quite different from metals.

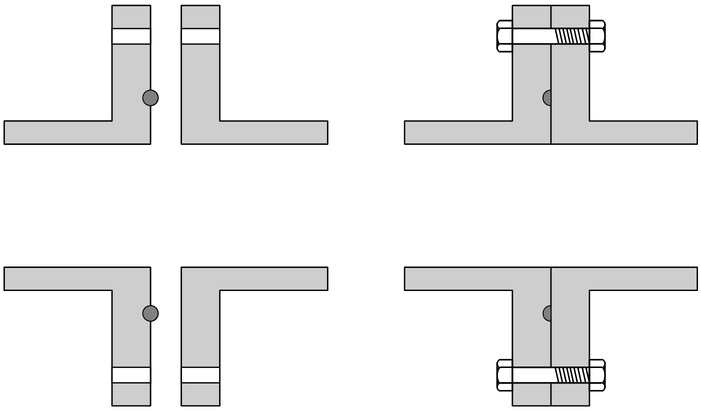


Figure 10.8. Recessed gaskets are normally tightened until a metal-to-metal contact occurs (courtesy Endress + Hauser).

During commissioning or replacement of a meter, the flange bolts should be tightened only when the maximum process temperature is reached. Conversely, meters should be disconnected when the temperature is below 40 °C to avoid the risk of damaging the surface of the gasket.

If a flange connection leaks, despite the fact that the bolts are tight, then they should **NOT BE TIGHTENED ANY FURTHER**. Loosen the bolts opposite the leak and tighten the bolts by the leak. If the leak persists, then the seal should be checked for foreign objects trapped in between.

The torque values given in Table 10.1 are based on greased bolts and serve as guidelines only since they depend on the material from which the bolts are manufactured.

Table 10.1. Torque values based on greased bolts for various gaskets (Courtesy Endress + Hauser).

			Torque values DIN in Nm		
DN	**PN**	**Bolts**	**Klingerite**	**Soft rubber**	**PTFE**
15 20	40	4xM12 4xM12			15 25
25 32 40 50 65 80 l00 25 150 200	16	4xM12 4xM16 4xM16 4xM16 4xM16 8xM16 8xM16 8xM16 8xM20 12xM20	25 40 50 64 87 53 65 80 110 108	5 8 11 15 22 14 22 30 48 53	33 53 67 84 114 70 85 103 140 137
250 300 350 400 450 500 600 700 800 900 1000	10/16	12xM20 12xM20 16xM20 16xM24 20XM24 20XM24 20XM27 24xM27 24xM30 28XM30 28xM33	104/125 191/170 141/193 191/245 170/251 197/347 261/529 312/355 417/471 399/451 513/644	29/56 39/78 39/79 59/111 58/111 70/152 107/236 122/235 173/330 183/349 245/470	139/166 159/227 188/258 255/326 227/335 262/463 348/706

10.6 Grounding and earthing

To ensure measuring accuracy and avoid corrosion damage to the electrodes of electromagnetic flowmeters, the sensor and the process medium must be at the same electrical potential. This is achieved by earthing the primary head as well as the pipeline by any one or more of a number of methods including: earthing straps, ground rings, lining protectors and earthing electrodes.

Improper earthing is one of the most frequent causes of problems in installations. If the earthing is not symmetrical, earth loop currents give rise to interference voltages – producing zero-point shifts.

Figures 10.9 to 10.13 show the most effective earthing configurations.

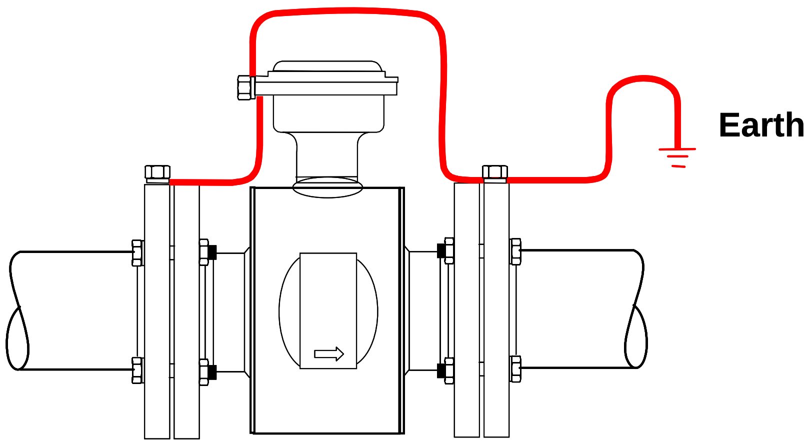


Figure 10.9. Earthing for conductive unlined pipe and conductive pipe with earthing electrode (courtesy Emerson).

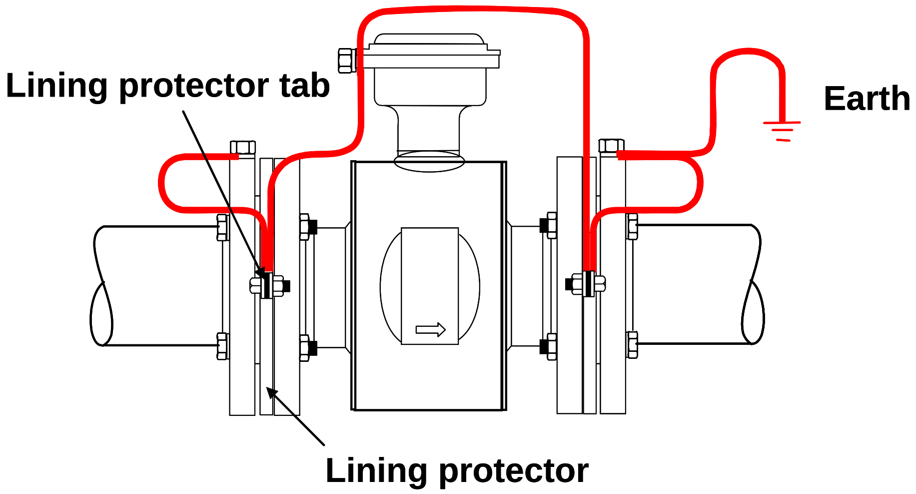


Figure 10.10. Earthing for conductive unlined and lined pipe with lining protectors (courtesy Emerson).

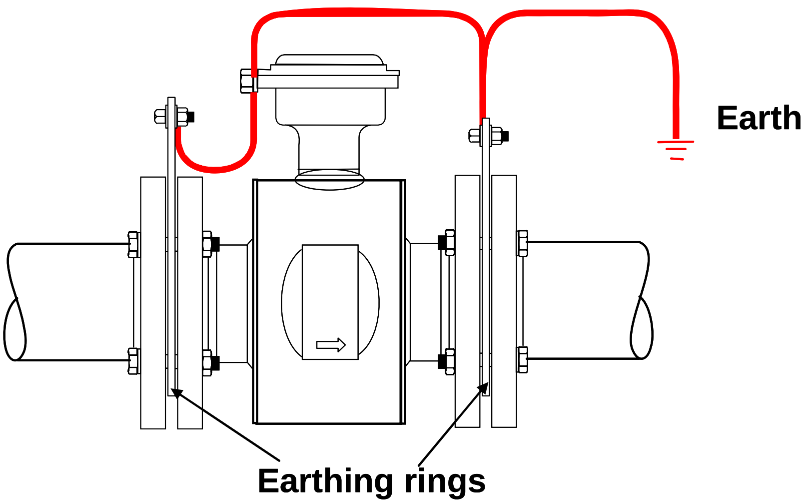


Figure 10.11. Earthing for non-conductive pipe with earthing rings (courtesy Emerson).

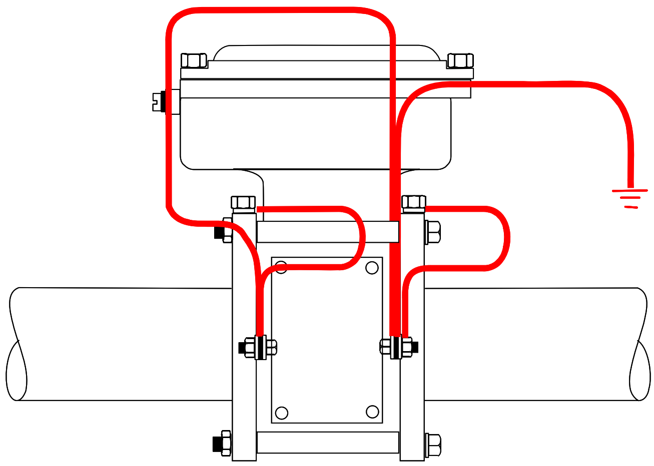


Figure 10.12. Earthing for conductive lined pipe with earthing rings (courtesy Emerson).

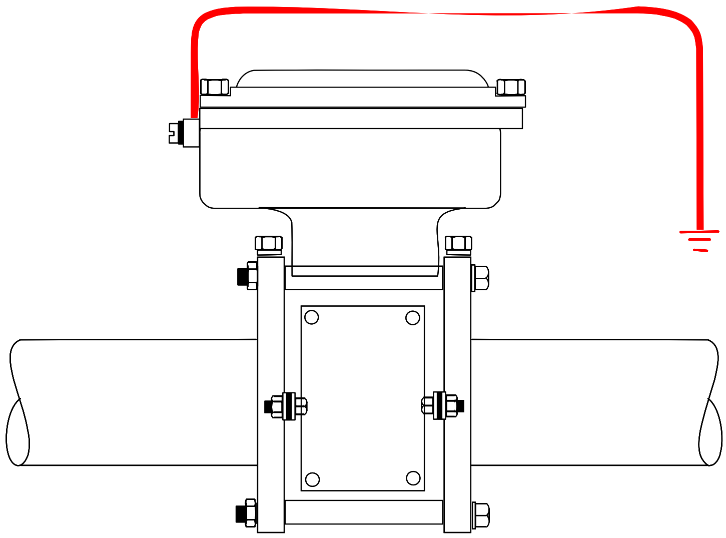


Figure 10.13. Earthing for non-conductive lined pipe with earthing electrodes (courtesy Emerson).

It is essential in cathodic protection installations to ensure that there is an electrical connection between the two piping runs using earthing rings or electrodes. It is also essential that ***no*** connection is made to earth.

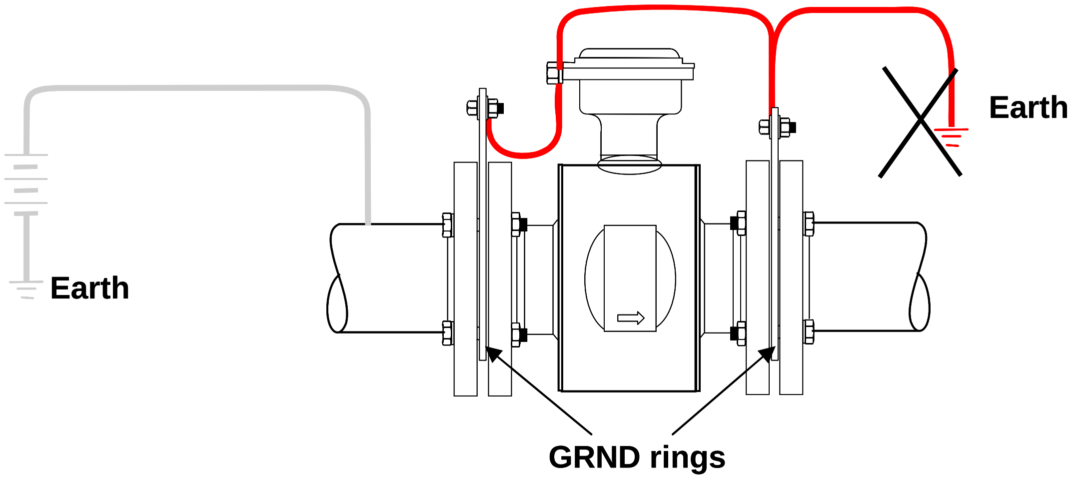


Figure 10.14. Cathodic protection installations (courtesy Emerson).

Chapter 11. Selection charts

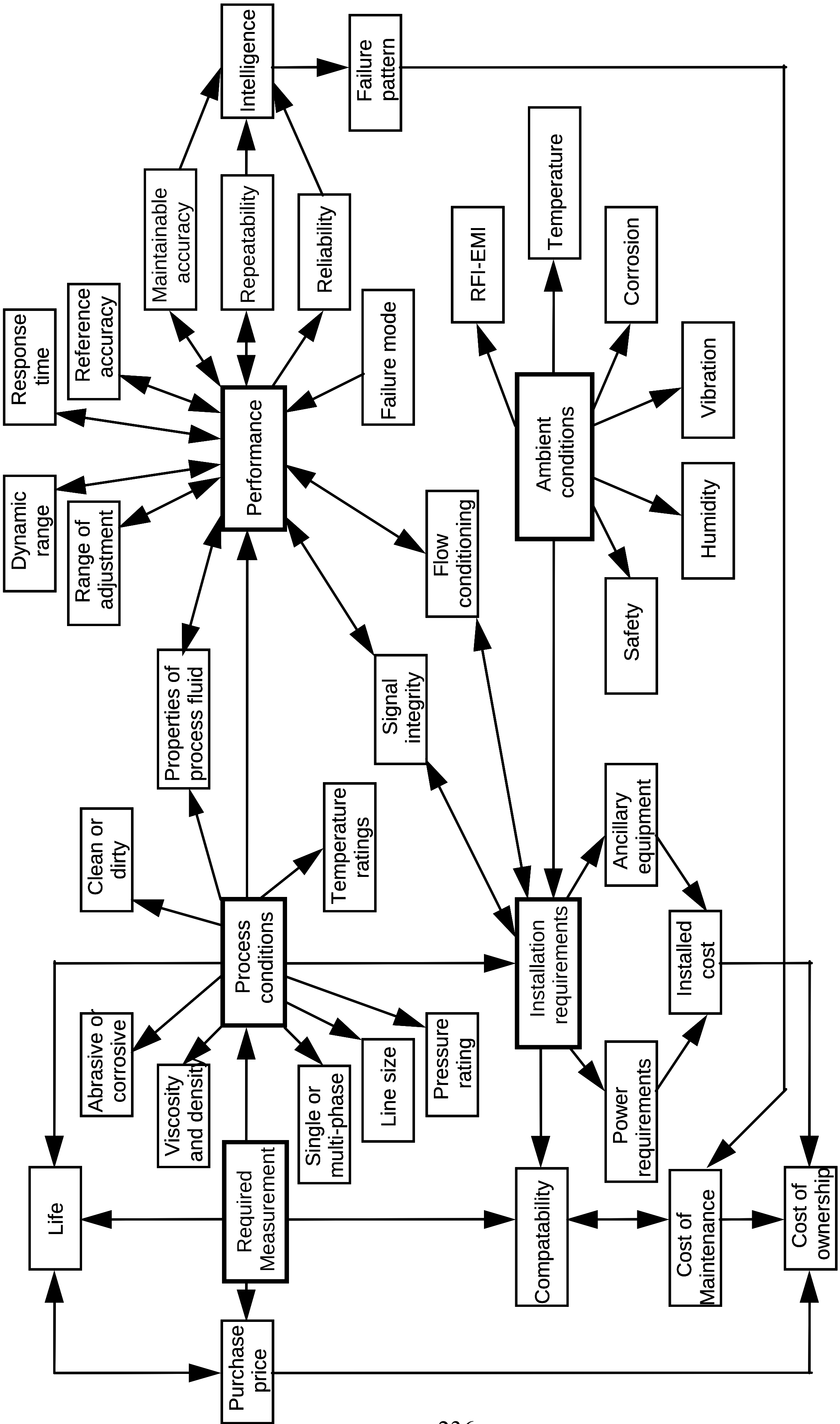
Industrial Flow Measurement

Chapter 11

Selection charts

Measuring technology	Clean liquids	Dirty liquids	Corrosive liquids	Low conductivity	High temperature	Low temperature ( )	Low velocity	High viscosity	Non-newtonian	Abrasive slurries	Fibrous slurries	Gas	Steam	Semi-filled pipe	Open channel
Coriolis	●	●	●	●	◎	●	●	●	●	◎	●	●	○	○	○
Electromagnetic	●	●	●	○	◎	○	●	◎	◎	●	●	○	○	◎	◎
Flow nozzles	●	◎	◎	●	◎	◎	◎	◎	◎	◎	◎	●	●	○	○
Fluidic	●	◎	●	●	◎	◎	○	●	○	○	○	●	◎	○	○
Flumes	●	●	●	●	◎	○	●	○	○	◎	◎	○	○	●	●
Orifice plate	●	◎	●	●	●	●	●	◎	◎	○	○	●	●	○	○
Pitot	●	◎	●	●	◎	◎	◎	◎	○	○	○	●	●	○	○
Positive displacement	●	○	◎	●	◎	●	●	●	◎	○	○	●	◎	○	○
Target	●	●	●	●	◎	◎	◎	●	◎	◎	○	●	●	○	○
Thermal mass	●	◎	◎	●	◎	○	●	◎	◎	◎	◎	●	●	○	○
Turbine	●	○	◎	●	◎	●	◎	◎	○	○	○	●	●	○	◎
Ultrasonic – Doppler	○	●	◎	●	○	○	◎	◎	◎	◎	◎	○	○	○	○
Ultrasonic – Transit time	●	◎	◎	●	○	◎	◎	◎	○	○	○	●	○	○	◎
Variable area	●	◎	●	●	●	○	◎	◎	○	○	○	●	◎	○	○
Venturi tubes	●	●	◎	●	◎	◎	◎	◎	◎	◎	◎	●	●	○	○
Vortex shedding	●	●	●	●	●	●	○	◎	○	○	○	●	●	○	○
Vortex precession	●	◎	◎	●	◎	○	○	◎	○	○	○	●	●	○	○
Weirs	●	●	●	●	◎	○	●	○	○	◎	◎	○	○	●	●

● Very suitable ◎ Applicable under certain conditions ○ Not suitable



Parameters to consider when choosing a flowmeter (*courtesy ABB-Kent*)

Chapter 12. Measurement of steam

Chapter 12.
Measurement of steam

Water converts from its liquid phase to its vapour phase (steam) at its boiling point of 100 °C at atmospheric pressure, rising as the system pressure increases.

Steam that is fully vaporised, but has not been heated to a temperature above the boiling point temperature, is called ***saturated steam***. Steam that is fully vaporised and heated to temperature above the boiling point is called ***superheated steam***.

Steam that is not fully vaporised is called ***wet steam***. The percentage, by weight, of the water droplets in wet steam is known as the percentage moisture, and subtracting the percentage moisture from 100 gives the percentage quality of the steam.

The measurement of 'wet' low quality steam is possible with a vortex meter – depending on the distribution of the liquid phase within the steam. Ideally, the secondary phase should be homogeneously dispersed within the primary phase (Figure 12.1). This tends to be the case with low amounts of secondary phase due to the high velocities and turbulence produced by the meter.

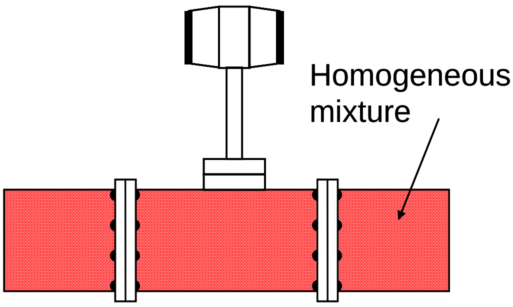


Figure 12.1. Homogeneous distribution of 'wet' low quality steam (courtesy Krohne).

However, for low quality steam the distribution of the liquid phase, within the steam, may be stratified. In horizontal pipes the water phase travels continuously along the bottom of the pipe and the vapour phase travels as a continuous stream along the top. Here, the best installation for the vortex meter would be in a horizontal line with the shedder positioned in the horizontal plane (Figure 12.2).

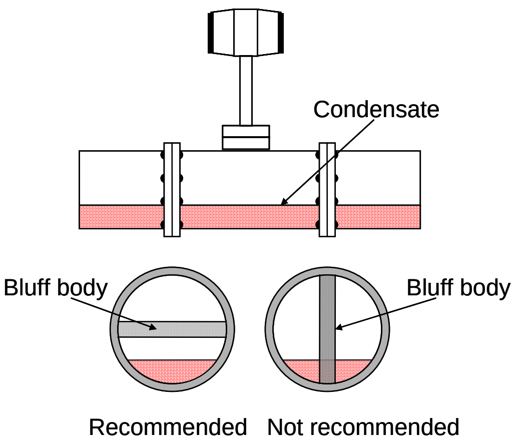


Figure 12.2. Recommended installation for 'wet' low quality steam with stratified flow in horizontal pipes (courtesy Krohne).

In vertical pipes the trend is towards 'slug' flow in which the water phase travels as discontinuous slugs down the pipeline, suspended between the vapour phase (Figure 12.3)

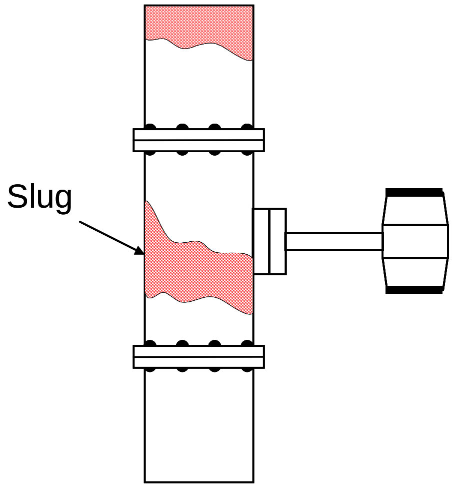


Figure 12.3. 'Slug' flow in vertical pipes (*courtesy Krohne*).

Again, however, users should be aware that the meter will, at best, measure the total volume and performance will not be to standard specifications. Most meters cannot make a measurement if slug flow exists and many meters will be destroyed by slug flow.

Chapter 13. Standards organisations

Chapter 13.
Standards organisations

A large number of organisations who are not normally involved in the field of instrumentation have been involved in the field of flow measurement. Such organisations have been involved specifically in determining the limits for custody and fiscal management; to cover the requirements for safety; and to the cover the requirements for environmental protection.

Some of the organisations involved are shown in Table 13.1

Table 13.1. Some of the organisations involved in setting standards for the measurement of flow in an industrial environment.

Abbreviation	Organisation
AChI	American Chemical Institute
AGA	American Gas Association
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BSI	British Standards Institute
DIN	Deutsches Institit für Normung
EIA	Electronic Industries Alliance
HSE	Health and Safety Executive
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical & Electronic Engineers
ISA	International Society for Automation (formerly Instrument Society of America)
ISO	International Organisation for Standards
NEMA	National Electrical Manufacturers Association
OSHA	Occupational Safety and Health Administration
TIA	Telecommunications Industry Association