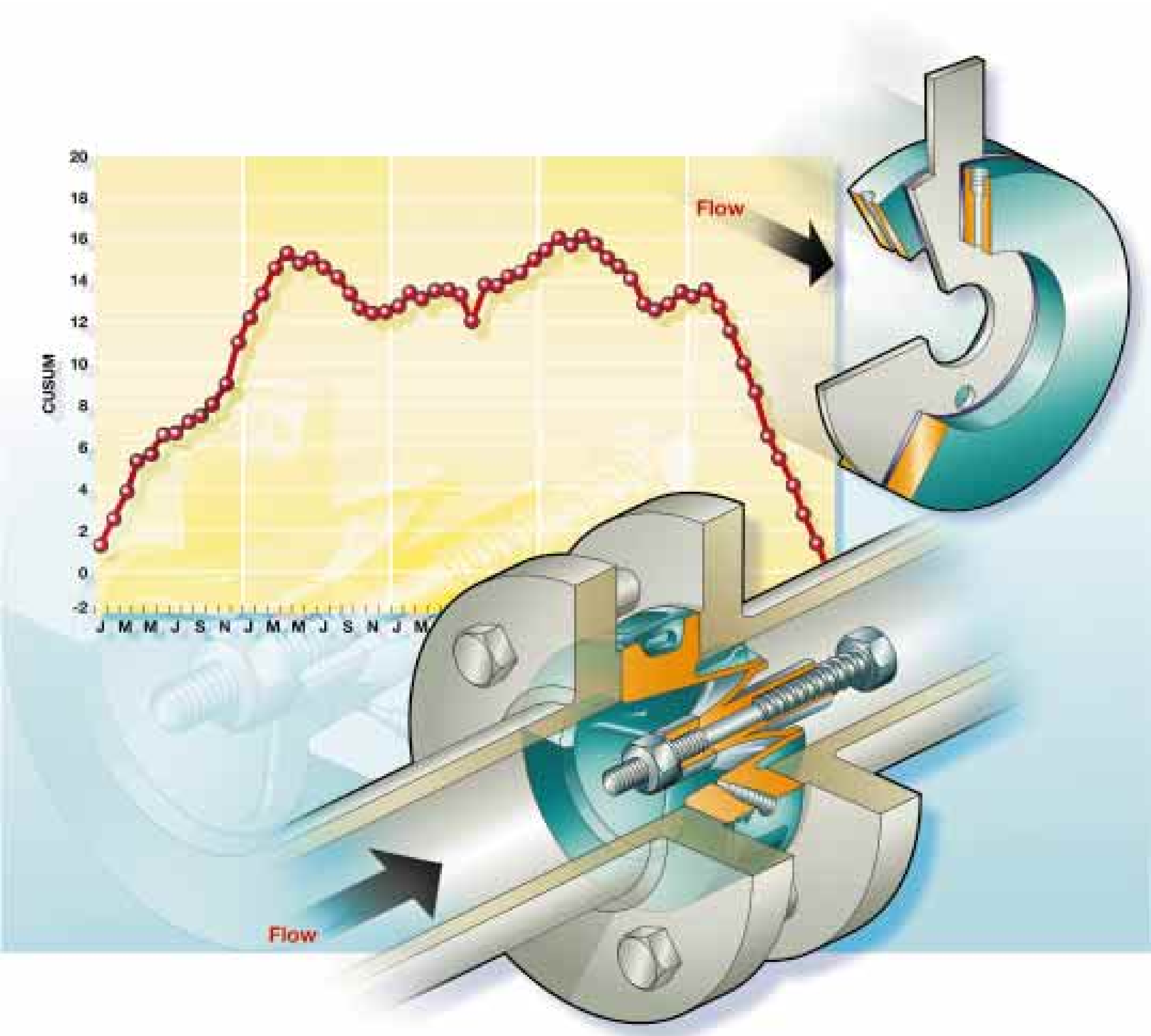
GOOD PRACTICE GUIDE 18

Reducing energy consumption costs by steam metering



ENERGY EFFICIENCY

BEST PRACTICE
PROGRAMME

REDUCING ENERGY CONSUMPTION COSTS BY STEAM METERING

This Guide is No. 18 (revised) in the Good Practice Guide series and is aimed at those who are seriously considering how they can reduce operating costs through metering their steam consumption.

The writers would like to thank all those who have provided information used in the preparation of this Guide. A list of equipment suppliers is given in Section 12.

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First published 1991: Revised and reprinted February 2000

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FOREWORD

This Guide is part of a series produced by the Government under the Energy Efficiency Best Practice Programme. The aim of the programme is to advance and spread good practice in energy efficiency by providing independent, authoritative advice and information on good energy efficiency practices. Best Practice is a collaborative programme targeted towards energy users and decision makers in industry, the commercial and public sectors, and building sectors including housing. It comprises four inter-related elements identified by colour-coded strips for easy reference:

— *Energy Consumption Guides:* (blue) energy consumption data to enable users to establish their relative energy efficiency performance;

— *Good Practice Guides:* (red) and *Case Studies:* (mustard) independent information on proven energy-saving measures and techniques and what they are achieving;

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1. INTRODUCTION

Steam has been used since the 18th century to supply power and heat to industrial and commercial organisations. Historically, however, because of relatively low fuel costs, the cost of steam constituted only a small proportion of overall production costs. As a result, apart from very large steam users such as power stations and major chemical plants, most enterprises saw little need to measure rates of steam flow.

After the first oil crisis in 1973 fuel prices rose rapidly and this, combined with fiercer competition for market share, resulted in a drive towards greater efficiency. A reduction in energy costs was recognised to be an essential part of this drive.

The first step in checking efficiency is measurement.

Lord Kelvin once said:

> “When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.”

Many industrial and commercial businesses have now recognised the value of energy cost accounting, energy conservation, and Monitoring and Targeting (M&T) in achieving greater energy efficiency. All require good metering systems.

The purpose of this Good Practice Guide is to increase the knowledge base of managers involved in steam-using operations so that reliable measurement systems giving credible results can be developed. The Guide is also intended to be of use to those steam users planning to improve or upgrade existing metering systems.

Any operation spending £30,000/year (equivalent to a gas consumption of approximately 100,000 therms, or 260,000 litres of medium fuel oil) or more on fuel for steam-raising should consider installing steam metering. Furthermore, the principle applies whether the steam is used for space heating, for the production of domestic hot water or for process heating. Since these uses are characteristic both of many sectors of industry and of public sector buildings, offices, hospitals etc., steam metering is applicable in a wide range of situations.

The Guide is structured to provide basic information on the subject of steam metering. Consideration is given to the nature of steam and to the characteristics of steam flow in pipes. The reasons for metering steam are examined, together with the criteria for meter selection. The main types of meter available are described and assessed, and considerable attention is paid to the practicalities and details of system design. The Guide offers a basic guide to maintenance requirements and techniques, and consideration is given to the subject of data handling. A number of case studies are presented, both to highlight problems experienced by existing metering systems and to illustrate good practice. The knowledge gained from these case studies has been incorporated into the main body of the Guide.

2. WHAT IS STEAM?

When water is heated its temperature will rise. The heat added is called *sensible heat* and the heat content of the water is termed its *enthalpy*. The usual datum point used to calculate enthalpy is 0°C.

When the water reaches its boiling point, any further heat input will result in some proportion of the water changing from the liquid to the vapour state, i.e. changing to steam. The heat required for this change of state is termed the ‘latent heat of evaporation’ and is expressed in terms of a fixed mass of water. Where no change in temperature occurs during the change of state, the steam will exist in equilibrium with the water. This equilibrium state is termed ‘saturation conditions’. Saturation conditions can occur at any pressure, although at each pressure there is only one discrete temperature at which saturation can occur.

If further heat is applied to the saturated steam the temperature will rise and the steam will become ‘superheated’. Any increase in temperature above saturated conditions will be accompanied by a further rise in enthalpy.

The relationship between steam pressure, saturated temperature, superheated temperature and the enthalpies and densities of water and steam have been tabulated and can be found in Steam Tables. These are commonly presented in two parts, the first dealing with saturation conditions and the second with superheated steam. An extract from the Steam Tables is given in Table 1. This shows that for discrete values of absolute pressure there are corresponding saturation temperatures, water enthalpies, latent heats of evaporation, steam enthalpies and steam specific volumes. The enthalpies are expressed in terms of a mass of water and are known as ‘specific enthalpies’.

Table 1 Extract from Steam Tables

Absolute pressure bar	Saturation temperature °C	Specific enthalpies			Specific volume m^3/kg
		Water kJ/kg	Evaporation kJ/kg	Vapour kJ/kg	
0.5	81.3	340.5	2305.5	2646.0	3.241
1.0	99.6	417.5	2258.2	2675.7	1.693
1.5	111.4	467.1	2226.6	2693.7	1.159
2.0	120.2	504.7	2202.1	2706.8	0.885
3.0	133.5	561.4	2163.9	2725.3	0.605
4.0	143.6	604.7	2133.7	2738.4	0.462
5.0	151.8	640.1	2108.3	2748.4	0.374
6.0	158.8	670.4	2086.0	2756.4	0.315
8.0	170.4	721.0	2047.5	2768.5	0.240
10.0	179.9	762.6	2014.7	2777.6	0.194
12.0	188.0	798.4	1985.6	2784.0	0.163
15.0	198.2	844.4	1946.7	2791.1	0.132
20.0	212.4	908.6	1890.0	2798.6	0.0997

3. STEAM FLOW IN PIPES

A number of factors affect the characteristics of steam flow in pipes:

- velocity;
- viscosity;
- density;
- pipe diameter;
- pipe friction.

Under ideal conditions, where viscosity and pipe friction can be ignored, the flow profile in a pipe is uniform, i.e. at each point in the cross-section of a pipe the velocity is the same.

Under real conditions, however, the flow of steam near the surface of the pipe will be slower than within the body of the fluid, and the profile becomes convex. The Reynolds equation (Re) accounts for all the factors affecting flow and generates a dimensionless number expressing the ratio between dynamic and viscous forces.

$$Re = \frac{DV\rho}{\mu}$$

where D = internal pipe diameter (m)
V = mean fluid velocity (m/s)
ρ = density (kg/m^3)
μ = viscosity (kg/ms)

At low *Reynolds Numbers* (4,000 and below) viscous forces will reduce the velocity at the pipe walls, and the highest velocity will occur at the centre of the pipe. The flow profile is parabolic in shape, and the flow is laminar in that all of the motion occurs along the axis of the pipe.

At Reynolds Numbers above 4,000 the flow breaks up and becomes turbulent. The velocity profile flattens and lateral motion occurs within the steam.

Steam formation in the boiler will be turbulent with a high degree of water entrainment. To reduce this entrainment, most boilers are designed with disengagement spaces and steam separators at the outlet. The efficiency of the separation process, however, will never be complete, so conditions of the outlet will be ‘wet’, i.e. containing entrained moisture.

The problem of entrained moisture is increased when the boiler is operated at less than the design pressure. At lower pressures, steam velocities will be increased, as will the degree of entrainment possible. Typically, if a boiler is operated at a pressure of 791 kPA compared with a design pressure of 1,136 kPA, the actual velocity will be 50% greater than design velocity, and separator efficiency will be reduced.

Depending on the velocity profile of the steam, condensate will occur either as an annular film of liquid running down the pipe surfaces or as fully entrained water droplets dispersed within the steam. An intermediate situation can occur with both annular and dispersed flow existing at the same time. The velocities of each phase will be different. However, if the condensed phase is allowed to build up, it can flow in ‘slugs’ along the pipe at the same velocity as the steam, creating water hammer.

The aim of any steam distribution system is to minimise the overall quantity of entrained condensate and to obtain the fully dispersed flow of such condensate as remains, in the form of small water droplets distributed randomly within the vapour. This is particularly important if meters have been or are to be installed. No meters exist which can simultaneously measure two phases with differing velocities. Furthermore, water hammer can permanently damage meters. The use of steam traps will remove most of the annular film, while separators installed upstream of the more important meter elements will remove some of the entrained droplets and reduce the size of the remainder.

4. STEAM METERING

The installation of steam-metering equipment enables steam users to measure one of the elements that contribute to the overall cost of their operations.

4.1 Reasons for Metering Steam

There are two main reasons for metering steam:

- to check on the cost of heat supply to all or to certain parts of the operation;
- to check on the efficiency of both steam production and steam utilisation (efficiency calculations also require data on fuel input and heat requirements).

Furthermore, the information obtained by using a purpose-designed steam-metering system to monitor costs and efficiency on a period basis can be used in several ways:

- to give priority in setting targets to those areas of a site where steam costs are high;
- to provide guidance for management in any decisions entailing changes in steam requirements;
- in contributing to decisions on the future direction of a business in situations where energy is a significant part of operating costs.

4.2 The Justification for Steam Metering

For many companies, steam measurement provides information about the performance of boilers and boiler plant. For boilers, the boundary line for fuel input and steam output is drawn around the boiler itself. For boiler plant, the boundary is drawn around the boilerhouse. The efficiency measured will be less in the latter case because it will take into account fuel and water heating, ancillary plant losses and other minor items. A method of calculating boiler efficiency is given in Appendix 2.

Steam metering at the boiler plant boundary is particularly valuable. Accurate measurement at that single interface allows both boiler plant and consumer system efficiencies to be derived. In addition, it provides a cross-check on sub-meter accuracy.

A site with a single boiler plant export meter is, however, likely to encounter difficulties in pinning down areas of site steam loss. If the energy bill is small and the site is believed to operate reasonably efficiently in terms of steam consumption, then a single meter may be acceptable. But if there are suspicions about operational efficiency, the location of the inefficiencies must be established.

The measurement of steam supply to each individual building or process gives information only about that particular user and cannot always readily be justified. Senior management usually need convincing of the potential for savings before sanctioning any investment in this kind of additional sub-metering. However, the benefits in terms of reduced consumption can only be assessed after the areas of excess usage have been identified. Fortunately, the dilemma can be resolved in several ways:

- by the employment of expert advisers to assess where the inefficiencies exist;
- by the short-term installation of a hired temporary meter system;
- by reference to numerous case histories of successful M&T schemes.

Experience with M&T systems has shown that fuel cost savings of 5 – 10% can be achieved with no capital expenditure other than the meters themselves. Where fuel bills range from £40,000 to

£500,000/year, this indicates minimum savings of between £2,000 and £25,000/year. The capital invested in steam metering will depend on the savings likely to be achieved and on the payback required (Table 2). This investment will determine whether a company installs only a single boiler plant export meter, an export meter plus one or two sub-meters, or a full metering system. Typically, a figure of £2,000 will only allow the purchase and installation of one small meter; £5,000 would buy two or three meters (depending on their size) and £50,000 – £100,000 would probably purchase a complete metering and M&T system.

Table 2 Capital investment in relation to savings/year and payback

Savings/year	**Payback period (years)**			
£	**1**	**2**	**3**	**4**
2,000	2,000	4,000	6,000	8,000
25,000	25,000	50,000	75,000	100,000

In summary, the implementation of M&T will maximise the benefits of steam metering. The data supplied will enable management to:

- improve existing steam operation;
- maintain that improvement;
- target further projects that will reduce steam consumption;
- determine costings for individual elements of the operation;
- make appropriate decisions on future expansion or changes in operating procedures.

4.3 The Importance of Data Analysis

Not only must the reasons for installing a metering system be clearly defined before equipment type or system design is considered, but users must be both aware of and committed to the collection and analysis of data and to subsequent action. Installing meters and collecting data only to have them filed away is of no value at all. Nevertheless, this is what happened in many businesses during the 1980s, wasting both time and capital.

To be of value, data must be collected and, where necessary, cross-checked on a regular basis – usually weekly or monthly. One of the main reasons why metering systems fall into disuse is that the data are sometimes not credible. A means of cross-checking the values recorded is therefore essential if confidence in the system is to be established and the information provided is to be used effectively.

Once credible data are available, they must be analysed for presentation in a readily understandable form. A useful first step is to produce steam consumption figures per unit of fuel used, per unit of production or per degree day[1]. More sophisticated statistical techniques can also be used where necessary and these are readily available in many computer software packages. However, such systems depend on regular information being available so that a characteristic can be developed for the process, e.g. the variation in steam consumption with changing conditions of boiler load, production level, product mix or air temperature.

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[1] See Fuel Efficiency Booklet No. 7, *Degree days*, available through the Helpline on 0800 585794.

5. CRITERIA FOR METER SELECTION

A company will always want to purchase the correct equipment for the job at the best possible price. Its choice of equipment will be determined by site conditions and by the objectives of meter installation which, in turn, will determine the relative importance of criteria such as turndown ratio, accuracy and repeatability. Accuracy, for instance, may be less important than repeatability for an M&T system, but the reverse may be true where the performance of an item of equipment such as a boiler needs to be assessed. As accuracy costs more than repeatability, the choice must be made carefully in order to make best use of the capital invested.

A further consideration is that it may be cheaper to measure a flow rate other than steam and still achieve acceptable results. Such a situation might occur where it proves impossible to justify steam metering on a cost/benefit basis, where site energy costs are small, or where turndown requirements are such that a steam metering system would be very expensive. In such cases it may be possible to adopt a ‘second-best’ approach, measuring, for instance, the feed water input to the boiler rather than the steam output.

The three characteristics of a meter that are most commonly used as criteria for meter selection are its turndown ratio, accuracy and repeatability.

Turndown Ratio

The turndown ratio of a meter can also be expressed as the effective range or the rangeability. It is a means of describing the span of flow rates over which a meter will work within the given tolerances of accuracy and repeatability. For example, if a meter can measure flow rates from a minimum of 1.25 kg/s to a maximum of 12.5 kg/s, then the effective range or turndown ratio would be 10:1.

As the actual flow rates are often completely unknown prior to fitting a meter, it makes sense to choose a meter with a large turndown or rangeability. This will ensure that the meter will not be operating outside its capability.

Accuracy

Accuracy describes the quality of the instrument and the ‘truthfulness’ of the readings. Manufacturers may express the accuracy of their meters in one of two ways:

- **As a percentage of measured value or actual reading.** If a meter has an accuracy of ±4% of actual flow rate and gives a reading of 12.5 kg/s, then the true flow rate would be between 12.0 kg/s and 13.0 kg/s. Similarly, at an indicated flow rate of 6.75 kg/s the true rate of flow would lie between 6.48 kg/s and 7.02 kg/s.
- **As a percentage of Full Scale Deflection (FSD).** If a meter has an accuracy of ±4% of FSD and the maximum flow rate that the meter can handle is 12.5 kg/s then, at an indicated flow rate of 6.75 kg/s, the true value could lie between 6.25 kg/s and 7.25 kg/s, i.e. 6.75 ±4% of 12.5. These boundary values would equate to an accuracy of ±7% for a 6.75 kg/s flow using the measured value method defined above.

Users should ascertain which of these methods has been employed as the meanings differ significantly.

Repeatability

The repeatability of a meter is its ability to indicate the same value for an identical flow rate on two or more successive occasions. For many processes, however, the true value of the flow rate is of secondary importance to the trends in the readings recorded.

6. TYPES OF METER

This Section examines the various types of meter currently available and discusses their principles of operation.

Three different categories of meter are on offer from the various suppliers:

- momentum meters;
- volumetric and mass flow meters;
- others.

6.1 Momentum Meters

Momentum meters sense the momentum of the flow and normally rely on the measurement of a differential pressure across the metering element. They are the most common type of meter used in industry for general flow measurement and have been successfully adapted for measuring steam.

Momentum meters work on the principle that, if a constriction is placed in a closed channel carrying a stream of fluid, there will be an increase in velocity and hence an increase in kinetic energy at the point of constriction. From *Bernoulli's Theorem* (essentially a statement of the conservation of energy applied to the flow of fluids) this increase in kinetic energy is accompanied by a corresponding reduction in pressure energy.

The rate of discharge can be calculated from the measured pressure reduction, the known area at the constriction, the density of the fluid and the coefficient of discharge of the constriction. The coefficient of discharge is the ratio of actual flow to theoretical flow and makes allowance for constructional and frictional effects. Steam density alters as it passes from a high to a lower pressure, so an additional factor has to be included in the equation to account for this change in density.

The volumetric flow rate is proportional to the square root of the differential pressure. Thus, with a knowledge of the density of the fluid at the measured conditions and the geometry of the pipe, it is possible to determine the velocity or mass flow rate. The square root proportionality implies that if the meter is to measure flows of x:1, then the cell measuring differential pressure must have a range of x^2:1.

Working from first principles it can be shown that:

$$V = C.E \left[\frac{m^2}{1 - m^2}\right]^{1/2} \left[\frac{2dp}{\rho}\right]^{1/2}$$

where V = velocity in pipe upstream of the orifice
m = d^2/D^2 (d = diameter of orifice, D = diameter of pipe upstream)
E = expansibility factor
C = coefficient of discharge
dp = differential pressure
ρ = density of fluid at upstream pressure

Differential Pressure Cells
Most momentum meters require connection to a Differential Pressure Cell (DPC) so that the differential pressure signal generated can be used to derive a value for the flow rate. Exceptions are target meters and the target-type of variable-area meter.

Most modern DPCs work on the principle of differential capacitance where a tensioned metal diaphragm is used as one electrode of the capacitor (Fig 1). This metal diaphragm moves with the change in pressure, the amount of movement being directly proportional to the pressure difference. The capacitance of the system depends on the separation between the moving electrode and the stationary electrode of the cell body, the inter-electrode space being filled with a dielectric oil. This differential capacitor is switched to an AC bridge. The voltage of the bridge is rectified, amplified and converted to a load-dependent direct current of 4 – 20 mA. For DPCs used for flow measurement, a square root characteristic may be applied to the signal such that there is a linear relationship between the output signal and volumetric flow.

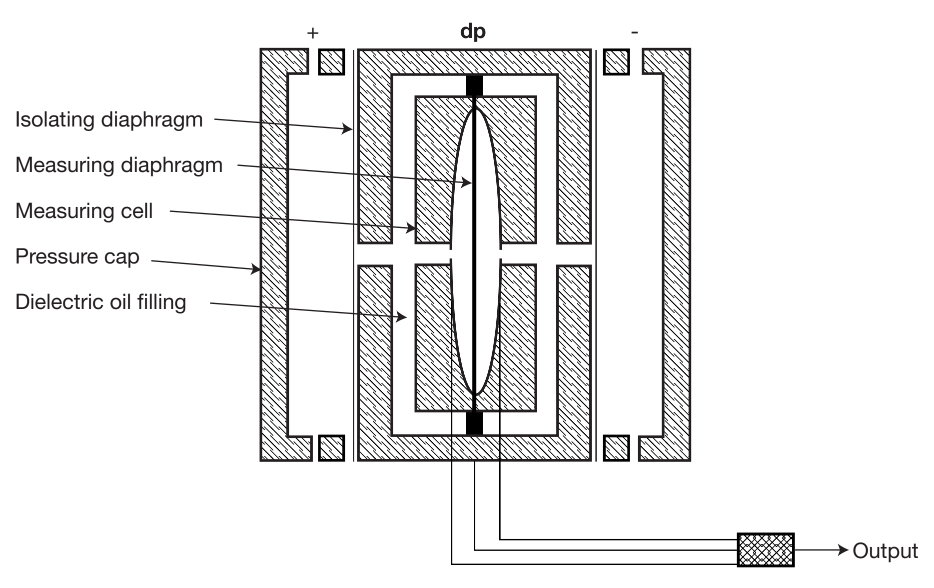

Fig 1 Schematic of differential pressure cell

The momentum range of meters includes:

- orifice plates;
- nozzles;
- wedge-type meters;
- averaging pitot tubes;
- variable-area meters.

6.1.1 *Orifice Plates*

This type of meter consists of a precision machined plate which is inserted into the flow stream and clamped between two flanges (Fig 2). It is superficially simple to construct and is also easy to install. It is not surprising, therefore, that the orifice plate is or has been the most frequently used device for measuring flow rate.

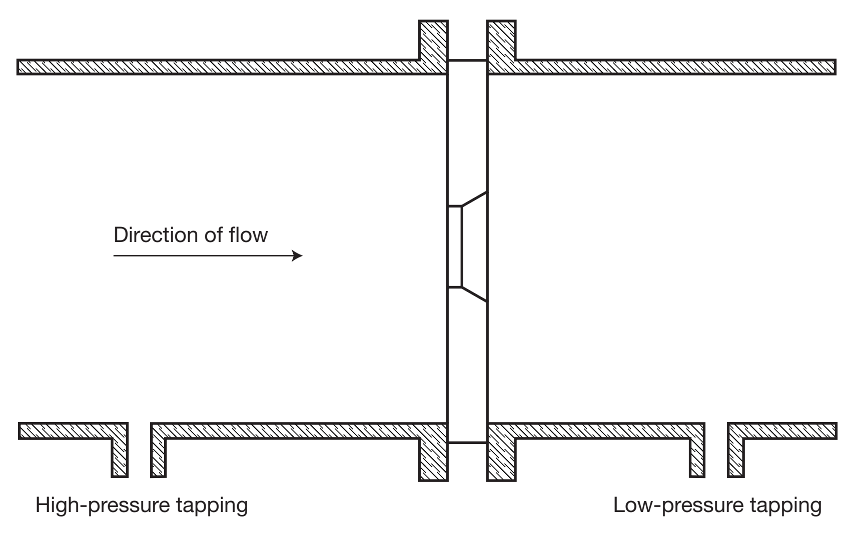

Fig 2 Schematic of orifice plate

The orifice plate itself is the primary element of the meter. The resulting differential pressure is measured via impulse lines filled with condensate connected from the pressure tappings of the orifice plate to the DPC which is mounted below the steam line. This converts the pressure reading into an analogue or digital signal which can be processed prior to being displayed.

The pressure tappings can be located in the pipeline upstream and downstream of the orifice plate. Alternatively, orifice plates can be supplied with corner or flange pressure tappings as part of a plate carrier ring assembly. Variation in the performance of the various tapping point locations can be encompassed in formulae used to determine the coefficient of discharge.

The location of the orifice plate in the pipe run is also important. Because the differential pressure measurement is sensitive to swirl and to other fluid effects, the orifice plate should be located a certain distance downstream and upstream of any pipe fitting. The British (BS 1042) and international (ISO 5167) standards provide details of the dimensions required. Manufacturers should, however, advise on standard requirements, and reference to the published standards is therefore unnecessary for most purchasers.

All proprietary orifice plates contain bleed holes to prevent the build-up of liquid on the upstream face of the plate when steam is at or near conditions of saturation.

The major advantage of the orifice plate is its rugged construction and ease of installation. Its turndown ratio, however, is limited compared with other meter types (figures quoted lie between 4:1 and 5:1). The plate is also susceptible to erosion because of the two-phase nature of steam flow. This alters the coefficient of discharge and can lead to a loss of accuracy over time. The sharpness of the upstream edge of the orifice is paramount to the accuracy of measurement. Even a very slight radius will cause the meter to under-read significantly. Serious problems can be prevented by regular inspection and by recalibration of the orifice plate whenever necessary.

6.1.2 *Nozzles*

Nozzles are similar in design and construction to orifice plates but consist of a short cylinder with a flared inlet approach rather than a drilled and machined hole in a plate (Fig 3). As with the orifice plate, the nozzle requires only limited space for its installation and can be clamped between existing flanges. The nozzle cross-section can be elliptical or conical. The straight portion of the throat will, in general, be about half one pipe diameter in length.

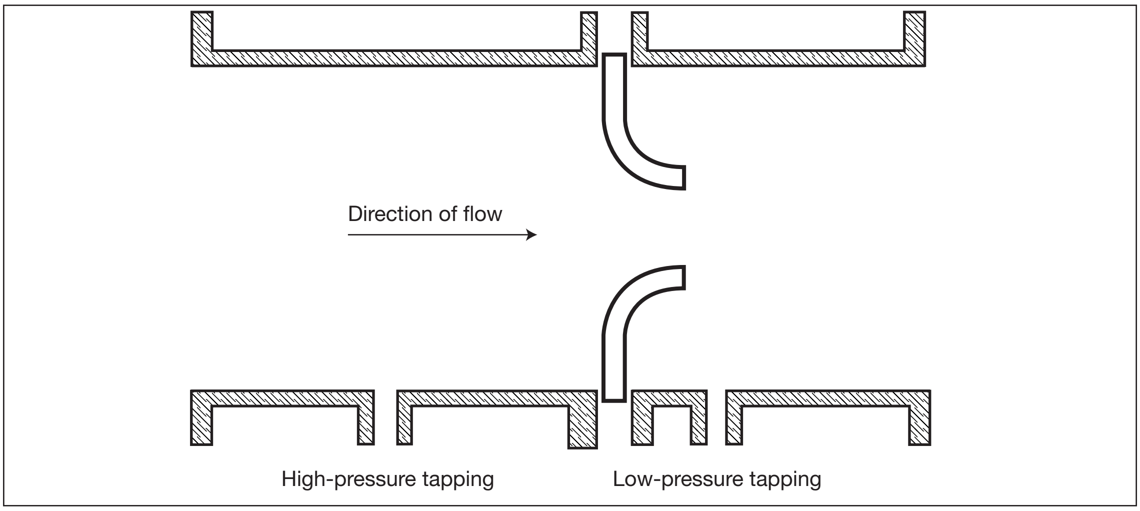

Fig 3 Schematic of nozzle

As with orifice plates, the nozzle is merely the primary element used to generate the pressure drop. In order to measure the flow rate, the user will need to install a DPC together with transmission/display devices. The flow equation is the same as for orifice plates although the formulae used to determine the coefficient of discharge will vary.

The main advantage of nozzles is that they are more stable than orifice plates under high temperature and high velocity conditions. Furthermore, they are more resistant to erosion and less susceptible to damage from water or steam hammer.

6.1.3 *Wedge-type Meters*

With wedge-type meters, the restriction is achieved using a wedge-shaped obstruction in the pipe (Fig 4). Differential pressure measurements are made across this restriction and the normal square root pressure difference proportionality applies. Manufacturers claim that this type of meter is accurate at low Reynolds Numbers, that it is resistant to erosion and that maintenance requirements are low.

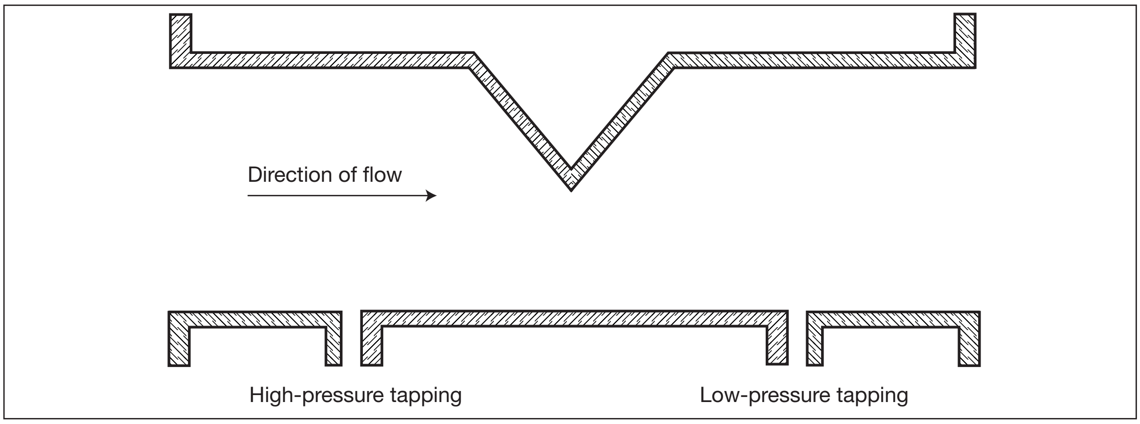

Fig 4 Schematic of wedge-type meter

6.1.4 *Averaging Pitot Tubes*

Unlike other momentum meters which impose a constriction on the flow and then measure the consequent loss of pressure, the pitot tube detects the difference between the impact (dynamic) pressure and the static pressure of the moving fluid. Typically, it consists of a tube with one or more holes facing into the stream to detect the impact pressure, plus one or more sidewall or downstream holes to detect the static pressure (Fig 5). If only one impact hole is used then the device measures only the localised velocity. As this is unlikely to be representative of the average flow in the pipe, the error is reduced by using a number of holes, located at set distances apart. The separation will depend on the total number of holes, the aim being for each hole to cover an equivalent annular area of flow.

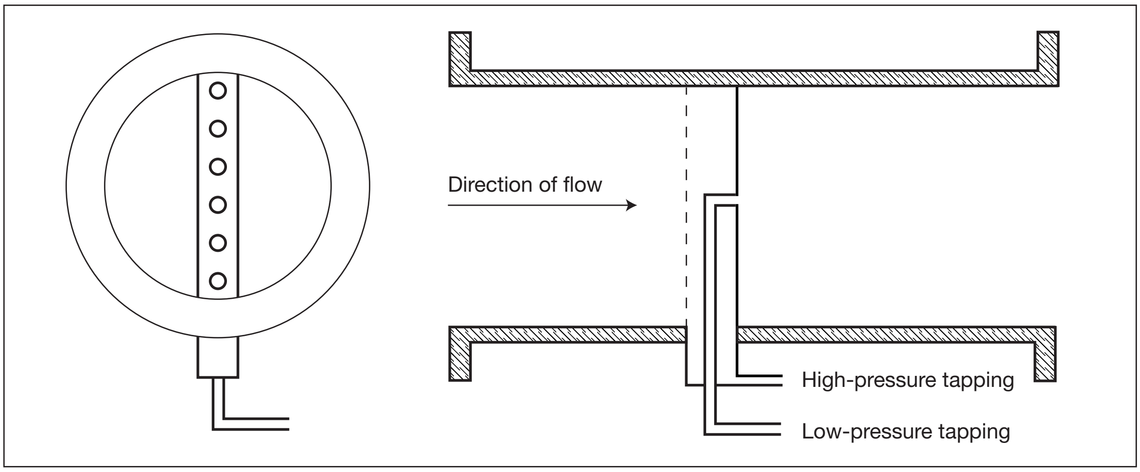

Fig 5 Schematic of averaging pitot tube

The pitot tube is sensitive to the angle of attack and thus to swirl effects. It is, therefore, recommended that flow is stabilised over a length of pipe of upwards of 50 pipe diameters. If this is not possible, then the use of straightening vanes is desirable.

One advantage of the pitot tube is that it presents very little resistance to flow. Turndown, however, may be limited to around 4:1.

When a pitot tube is used to measure steam flow, care should be taken to ensure that the lowest holes do not become blocked with water. This can be achieved by positioning the meter so that the pipework in which it is located is inclined slightly upward. Any condensate formed will then collect away from the pitot element.

6.1.5 *Simple Variable-area Meters*

Whereas all the meter types detailed above work on the principle of constant area and variable differential pressure, with the simple variable-area (VA) type of rotameter or tapered tube meter (Fig 6), the reverse effect occurs. Because it is balanced by the weight of the float, the differential pressure is kept constant, whilst the area of the aperture is allowed to increase with the flow rate. Sensing the flow rate is achieved by determining the displacement of the plug/target through mechanical or magnetic coupling. Generally, this type of meter is more suited for liquid or gas measurement, but devices suitable for steam use incorporating a metal tube are now available. A disadvantage is that they generally have to be installed with the direction of flow vertically upwards. Turndown is usually in the region of 10:1.

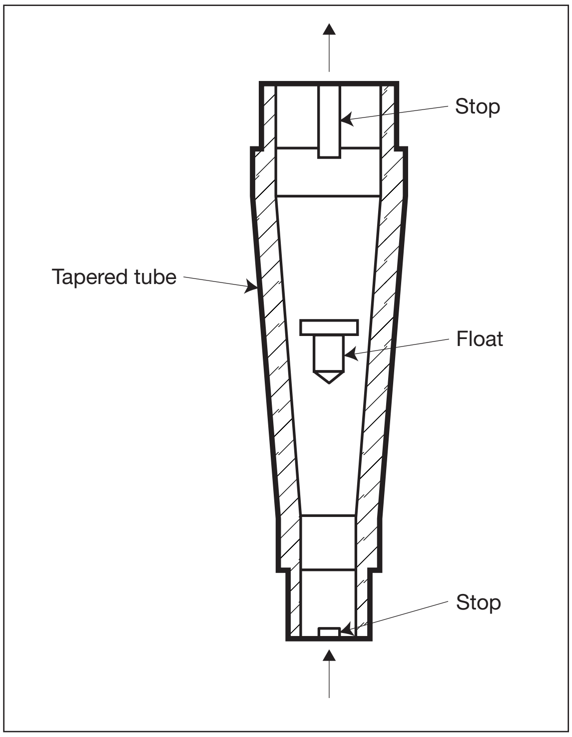

Fig 6 A simple variable area meter

6.1.6 *Spring-loaded Variable-area Meters*

The spring-loaded variable-area (SLVA) meter (Fig 7) is, in effect, a hybrid between the simple differential pressure flow meter (e.g. the orifice plate) and the VA flow meter. A spring is used to press together the two members forming the variable aperture, so that, as the flow rate increases, both the aperture and the force tending to close the aperture – and hence the differential pressure across it – must increase together. This means that the flow through this type of flow meter has two degrees of freedom, which gives it an outstanding wide rangeability. The flow rate can be determined either by measuring the differential across the device using a DPC or by measuring the displacement of the moving member.

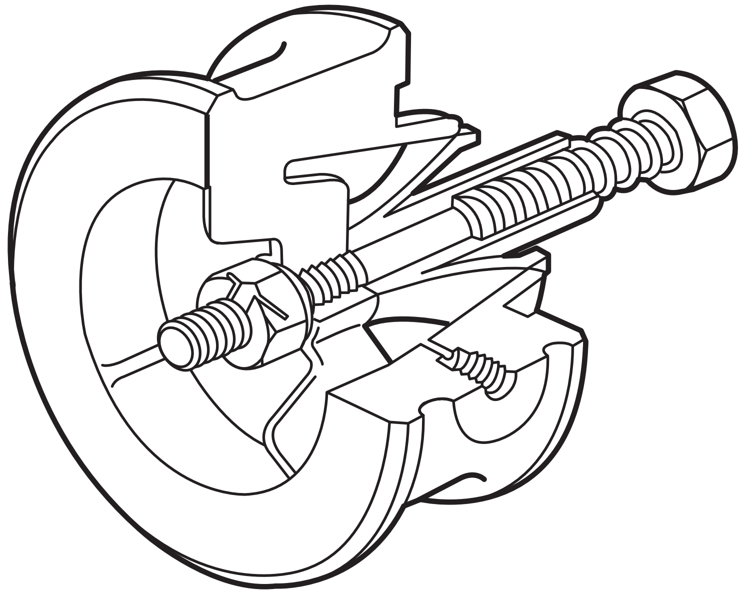

Fig 7 Spring-loaded variable-area meter with differential pressure output
(with acknowledgement to Spirax-Sarco Ltd)

This type of meter tends to be less sensitive to upstream and downstream pipe configurations than some of the others described previously. Manufacturers quote upstream lengths of six pipe diameters and downstream lengths of three pipe diameters. The major advantage of the SLVA meter is that it offers a very high turndown ratio.

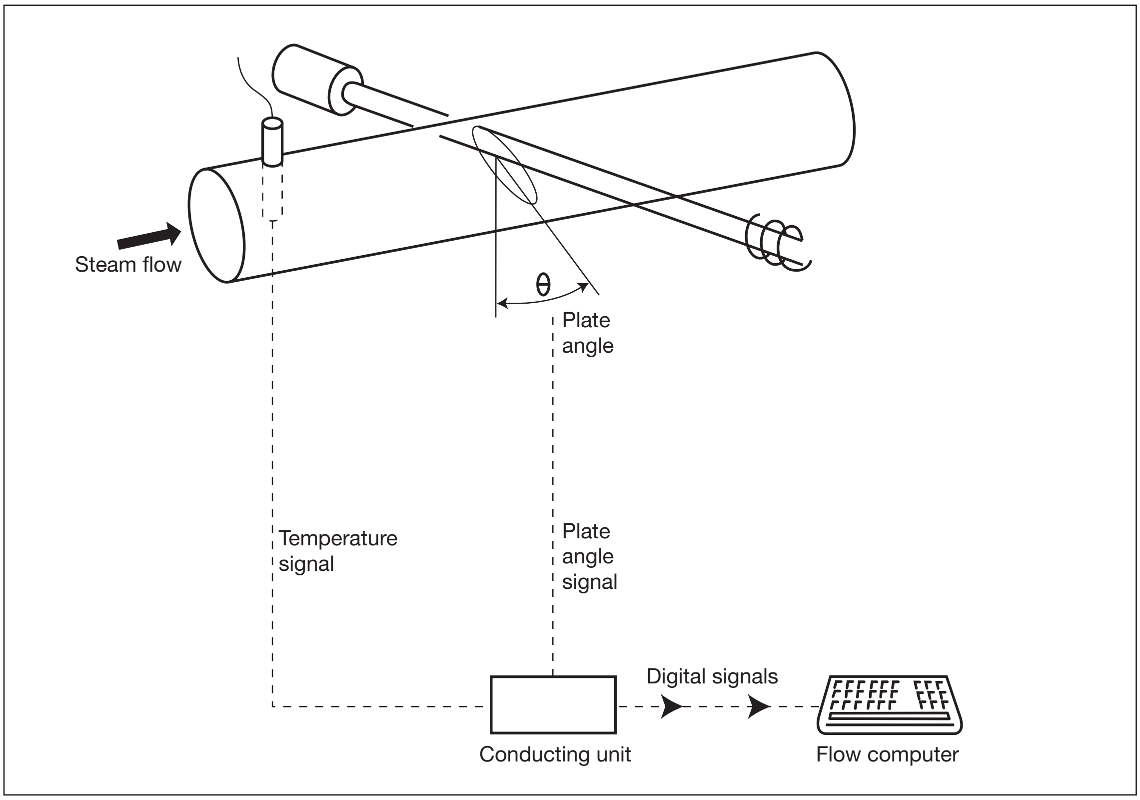

Fig 8 Schematic of target-type variable-area meter
(with acknowledgement to Spirax-Sarco Ltd)

6.2 Volumetric and Mass Flow Meters

While momentum meters derive the volumetric flow from a differential pressure, other types of meter rely on the volumetric and mass properties of the fluids involved to provide a direct measurement of volumetric or mass flow. Such meters include:

- turbine meters;
- vortex shedding meters.

6.2.1 *Turbine Meters*

Turbine meters consist of a freely rotating propeller or screw located within the pipe (Fig 9). Provided that bearing drag is minimised and the blades are well designed, then the process stream will exert a torque on the turbine causing it to rotate at a velocity proportional to the fluid flow rate. If a magnetic coil or optical device is placed in the meter housing, a voltage pulse can be induced with each pass of a turbine blade. This pulse rate will be proportional to the rate of flow and the total number of pulses can be integrated to give the volume which has passed the meter. The response of this type of meter is approximately linear. However, at low flow rates the drag effects of the bearings become significant and may cause a departure from linearity. This can readily be overcome by incorporating a calibration curve into the system which converts the signal pulse into a flow rate.

The turbine meter is affected both by swirl and by upstream disturbances. Under most conditions, therefore, the installation of flow straighteners is recommended. Bearing wear is also a major consideration and may necessitate frequent recalibration. However, if this is carried out, a turndown ratio of around 10:1 will be possible with a corresponding accuracy of ±0.5% of actual value. Generally, this type of meter is used on superheated steam applications.

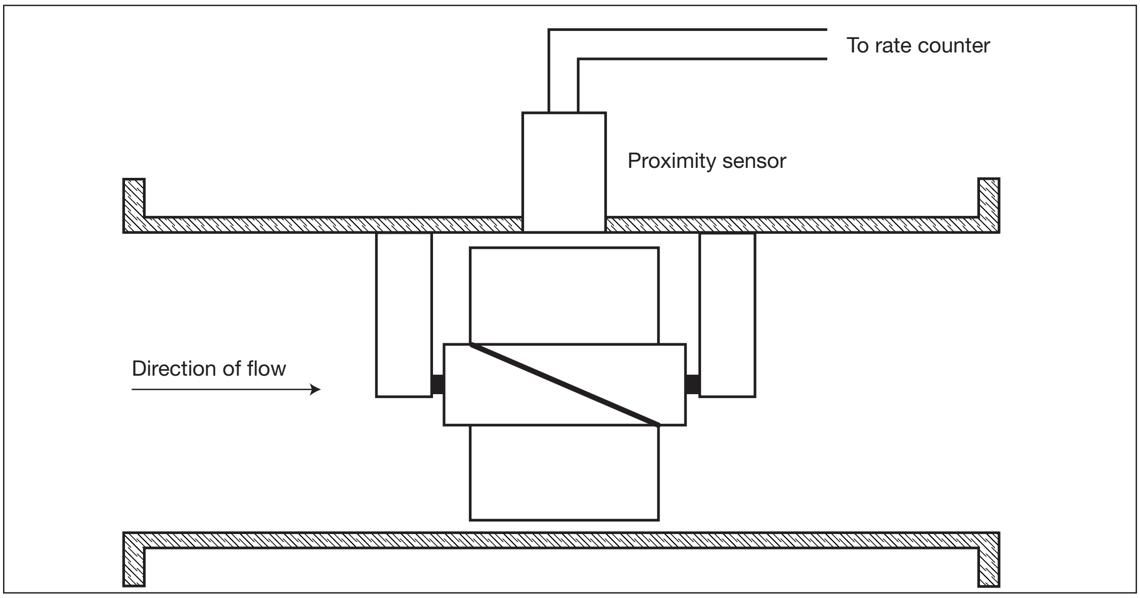

Fig 9 Schematic of turbine meter

6.2.2 *Vortex Shedding Meters*

The vortex shedding meter operates on the principle that when a fluid stream flows around a bluff body (the vortex 'shedder'), viscosity-related effects produce vortices downstream (Fig 10). The most common body shapes used in such meters approximate to a rectangle or a triangle. The vortices are shed sequentially from either side of the bluff body at a frequency proportional to the flow velocity (v) divided by the bluff body width (d). A dimensionless multiplication factor – the Strouhal Number – is also part of the equation:

$$f = St \, . \, v/d$$

where f = frequency (Hz)
St = Strouhal Number
v = flow velocity (m/s)
d = bluff body width (m)

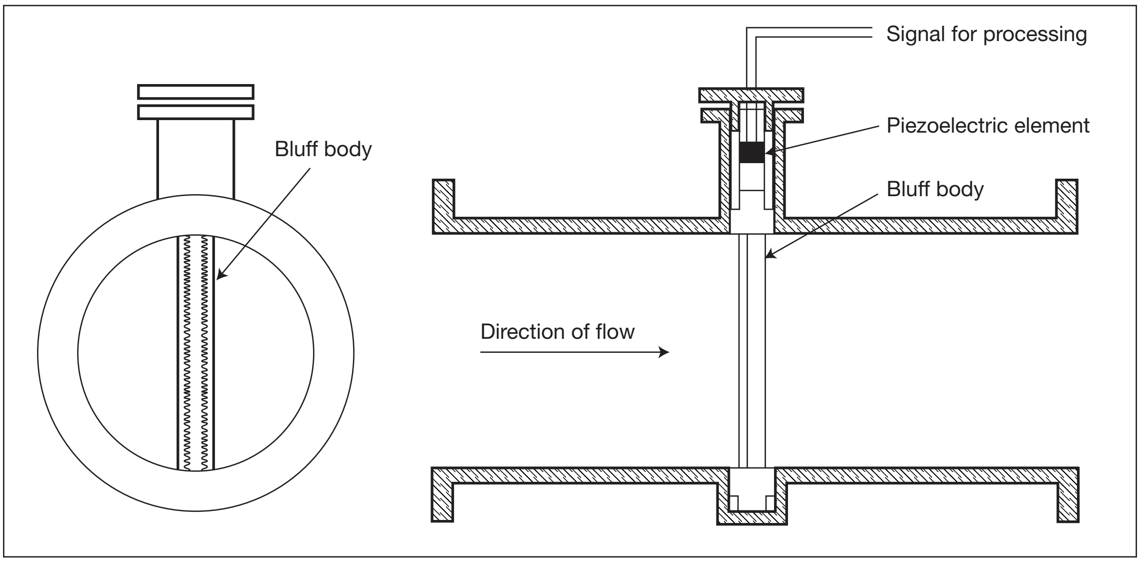

Fig 10 Schematic of vortex shedding meter

For a wide range of Reynolds Numbers the Strouhal Number remains constant. This implies that the shedding frequency will be directly proportional to the flow velocity and will remain unaffected by changes in fluid density or viscosity.

The method of sensing the vortices produced will depend both on the manufacturer and on various physical parameters. A common method is to use a piezoelectrical cell located in the bluff body support spindle. Shedding of the vortices creates lift in the bluff body, which in turn causes small movements to the spindle. Each movement causes compression of the cell, thereby generating a small electric current. Other methods use ultrasonics which are modulated by the vortices, or involve the detection of the small pressure waves that accompany the shedding of the vortices.

Claims for the operating range vary but, typically, a 10:1 turndown should be achievable at an accuracy of ±1.5% of the rate. The turndown ratio is, however, limited by the strength and stability of the shed vortices at low Reynolds Numbers. This size range is also limited: as the bluff body width increases, the frequency of shed vortices is reduced to the point where it is too slow to obtain a reasonable response.

The length of straight flow upstream and downstream of the vortex shedder should be the same as recommended for an orifice meter (ASME MFC6-M-1987, ISO 5167, BS 1042), with which it is directly comparable. Typically, the vortex shedding meter will have an area ratio equivalent to a β value of 0.8 (where β is the diameter of the orifice divided by the upstream pipe diameter) and a pressure drop that is broadly the same as that of an orifice plate.

While the use of orifice plates is supported by a mass of data collected over the years for a variety of fluids and conditions, the same claim cannot be made for vortex shedding meters. However, as a class, they have a number of significant advantages, notably linearity of response, a direct electrical output and a wide range of operability. They are also of rugged construction with only the bluff body being exposed to the flow. Nevertheless, they can be sensitive to upstream flow distortion and erosion, and installation must be carried out carefully with reference to the manufacturer’s instructions.

6.3 Other Meter Types

6.3.1 *Thermal Flow Meters*

Thermal flow meters involve the application of heat to the fluid under consideration. The associated rise in temperature will be proportional to the mass flow rate for the particular fluid. For this type of measurement to be successful, the variation of heat capacity with pressure and temperature must be known. Modern signal-processing computers can have such physical properties mapped within them.

The thermal flow meter consists of an upstream means of fluid temperature measurement, a heater and a downstream temperature sensor. Some proprietary devices incorporate all temperature measurement within a single probe, thereby minimising the number of intrusions that need to be made into the stream.

These devices should only be installed after consultation with the manufacturer. They provide only a spot measurement of mass flow rate, so variations in the fluid, e.g. a laminar flow profile, will result in inaccuracies in the measurement. Similarly, any entrained moisture impacting on the device may cause spurious readings if not actual physical damage. For this reason it is recommended that separators are installed upstream of the device.

The advantage of the thermal flow meter is that it can be used to measure low flow rates and has a high turndown ratio. However, unless temperature and pressure compensation is built into the signal-processing equipment, inaccuracies may result from fluctuations in steam pressure.

6.3.2 *Rotary Shunt Meters*

Rotary shunt meters are a form of turbine meter (Fig 11). An orifice plate is placed across the main flow: part of the flow passes through the orifice plate and the remainder is diverted. The diverted flow is directed onto the blades of a turbine via nozzles and is then returned to the mainstream flow downstream of the orifice plate.

The diverted flow rate is proportional to the mainstream flow rate, and the speed of turbine rotation is, therefore, a measure of the flow rate in the pipeline. The turbine is prevented from overspeeding by the use of a linked damper fan rotating in a liquid. Two systems of measurement are possible: either the rotor can drive a totalising meter or the speed of rotation can be measured using magnetic sensors to give the instantaneous flow rate.

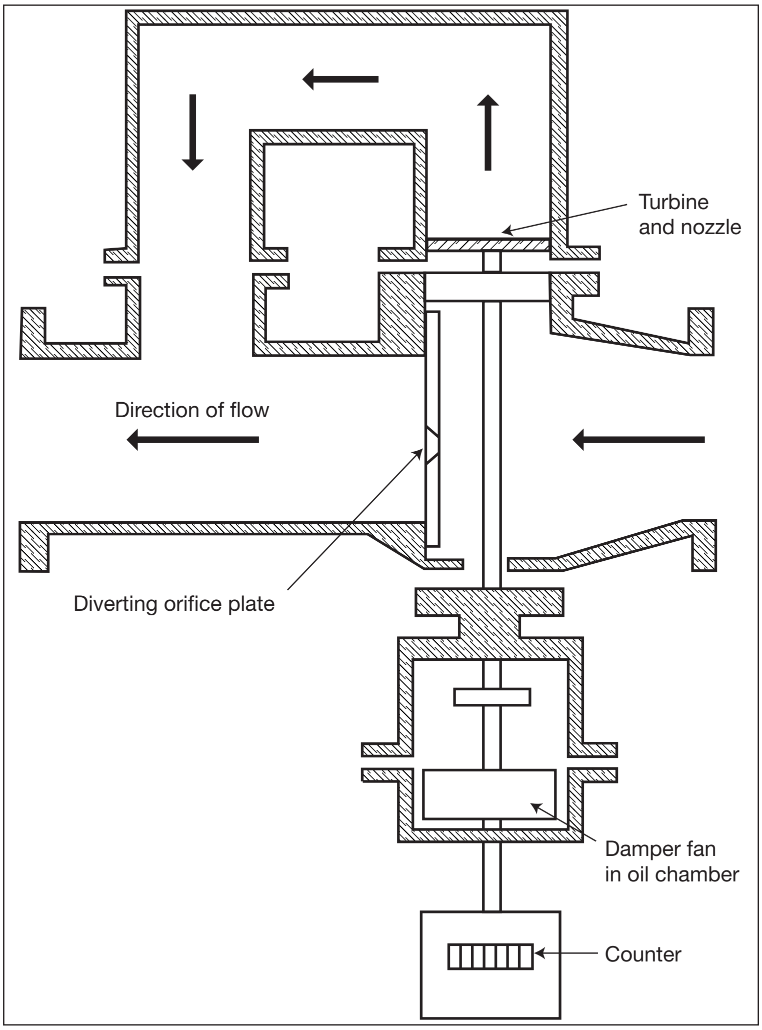

Fig 11 Schematic of rotary shunt meter

If a rotary shunt meter is used to measure steam flow in mains with a diameter greater than 100 mm, a bypass installation will be required. In this instance, an orifice plate is inserted in the main pipe to divert a proportion of the flow to the bypass in which the meter is placed (Fig 12). In the bypass location, the shunt meter's orifice plate is replaced by a blanking plate so that all the bypass flow is directed via the meter. The installation of this blanking plate means that the normal approach criteria for installation are ignored and accuracy suffers.

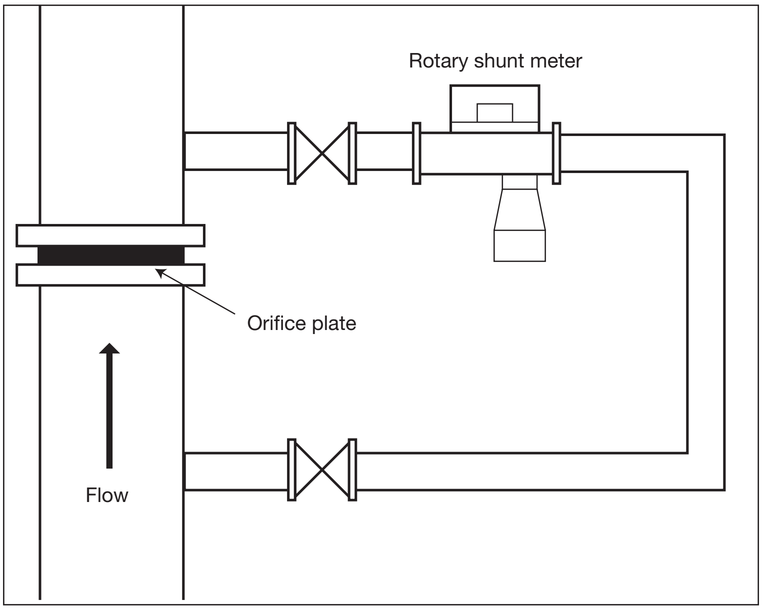

Fig 12 Rotary shunt meter in bypass application

Swirl affects this meter for both in-line and bypass situations in the same way as discussed above for turbine meters. Rotary shunt meters are also susceptible to damage on start-up if steam valves are opened too quickly.

As with both orifice plates and turbine meters, two-phase flow can often lead to inaccuracies. Manufacturers quote accuracies of ±2% of metered value for a 7:1 turndown ratio. If turndown is taken to 10:1, accuracy is ±4% of metered value. Meters are calibrated to read correctly at the pressure and temperature specified by the user. Any variation in those conditions will result in errors, although correction formulae can be supplied. When rotary shunt meters are used under conditions of varying pressure and temperature, compensation will be required.

6.4 Summary

The principal characteristics of the various types of meter discussed above are summarised in Table 3. The values given are guidelines only and individual meters may differ slightly.

Table 3 Meter comparison

	Orifice	Nozzle	Pitot	Wedge	Var. area	Turbine	Vortex	Thermal	Rotary shunt
Maximum temperature (°C)	500	500	500	500	450	150	400	200	260
Maximum pressure (bar)	60	60	20	60	20	40	10	10	20
Minimum Reynolds No	5000	10000	1000	10000	500	10000	10000	10	10000
Maximum kin. viscosity	0.01	0.01	0.01	0.01	0.001	0.0003	0.0001	–	0.0003
Accuracy	0.75	0.75	1.50	1.0	1.0	0.50	0.50	1.0	2.0
Repeatability	0.25	0.25	0.50	0.25	0.25	0.05	0.15	0.25	–
Scale	SQR	SQR	SQR	SQR	LIN	LIN	LIN	LOG	LIN
Turndown ratio	<10:1	<10:1	5:1	10:1	<100:1	10:1	<10:1	10:1	5:1
Pressure losses	H	M	L	M	M	L	L	L	H
Ease of installation	E	ME	ME	ME	E	NE	E	NE	ME
Purchase cost	L	H	L	L	M	H	M	H	M
Installation cost	M	M	L	L	M	M	L	L	M
Maintenance cost	H	M	L	M	M	L	L	L	L
Operating cost	L	M	L	L	L	M	L	M	M

Pressure losses: H - High
M - Moderate
L - Low

Scale: SQR - Squared
LIN - Linear
LOG - Logarithmic

Ease of installation: NE - Not easy
ME - Moderately easy
E - Easy

Cost: H - High
M - Moderate
L - Low

7. SYSTEM DESIGN CONSIDERATIONS

This Section introduces the basic elements of system design. It offers a structured approach to steam metering which, if adopted, should result in an optimised metering system at minimum cost. Consideration is given to the number and layout of the meters required, to factors influencing meter selection, and to the whole question of data collection and analysis. Finally, the importance of clearly defined structures for reporting and action is stressed.

7.1 A Structured Approach to Steam Metering

It is important to adopt a structured approach to steam metering from the start. This will help to ensure that:

- the design objectives are achieved;
- no elements of the design are omitted;
- the benefits are maximised;
- the financial outlay is kept to a minimum.

There are two main strands to such an approach.

The first involves consideration of the existing steam supply system. The user should identify any planned changes to the plant or process which might affect the installation of steam meters, and should consider whether the installation of the meters is likely to act as a catalyst for such changes. Alterations to the steam supply system, for instance, may involve blanking of redundant sections of steam main, re-routing steam pipework, or generally improving the condition of existing insulation. The costs incurred for these alterations may be offset in part by a reduced requirement for steam metering.

The second strand to the approach is the definition of design objectives, i.e. identifying the aim of installing the meters. Typically, one or more of the following design objectives will be defined:

- to provide information for accounting purposes, e.g. departmental allocation of costs;
- to facilitate ‘custody transfer’ – i.e. where a central generating station sells steam to a range of clients;
- to facilitate M&T;
- to determine levels of energy efficiency.

Each objective imposes different limitations on the design of the steam metering system.

If metering is to be used for accounting purposes or for custody transfer, it will be necessary to install a sufficient number of meters for consumptions to be assigned to the individual cost-accounting centres. If the product being sold is heat rather than steam, flow meters will also need to be installed on the condensate return system as this hot water will have an intrinsic value. For both applications, the highest possible standard of metering will be required, particularly with respect to accuracy, turndown ratio and repeatability. The system will also require adequate check metering so that consumptions can be proved to be correct. It should be noted that confidence in a steam metering system, once lost, is very difficult to restore.

A system should also include measurement of the system losses incurred as a result of supplying steam to a particular location. This implies that meters should be located as close to the boilerhouse as possible.

In M&T applications and in determining energy efficiency, the important metering criterion is repeatability. The user will be more interested in trends in consumption rather than in absolute values. Since less precise metering is required in these applications, full advantage should be taken of every existing alternative to steam metering.

7.2 Determining Meter Arrangements

Once the aims of the system have been defined, the number of meters required to achieve those aims can be determined. This requires consideration of the site as a whole as, in many instances, it may be possible to find cheaper alternatives to steam metering. Typical alternatives might include:

- measuring condensate from an enclosed vessel;
- measuring the flow rate and inlet-outlet temperatures of a process stream (this may be advisable where steady-state conditions prevail).

Fig 13 shows four different meter layout options for the same system.

In Option 1 the individual consumption to each area is measured directly except for area B which is obtained by difference. The disadvantage of this option is that the majority of the system losses will be included in area B's consumption.

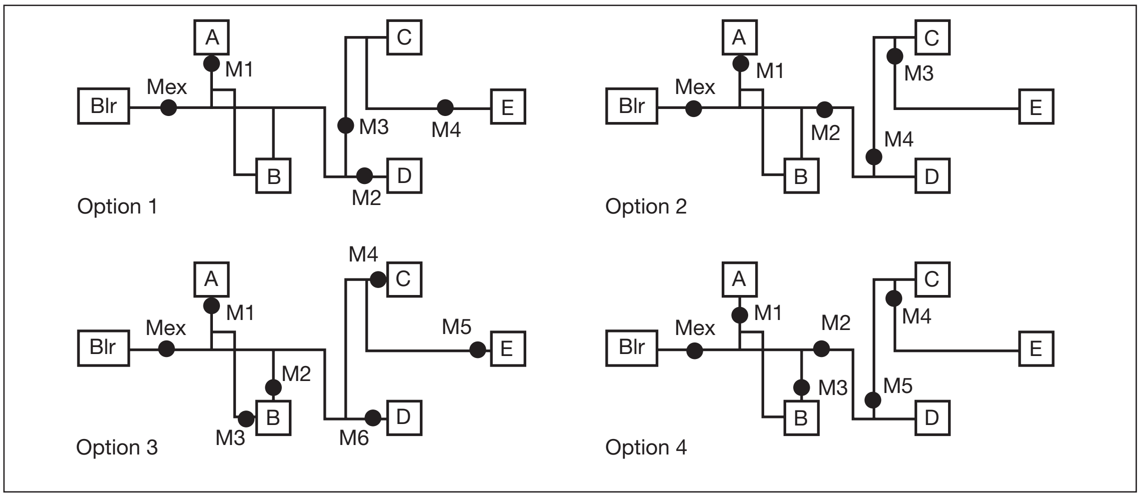

Fig 13 Meter layout options

Although Option 2 uses the same number of meters as Option 1, the meters are placed so that the system losses are more fairly divided between each area, since the losses metered are those inherent to each supply.

In Option 3 the streams are metered as they enter each individual area and the losses are obtained by difference. This scheme uses two more meters than either of the first two options but provides a direct reading of flow rate in the individual steam mains.

Option 4 is a compromise between Options 2 and 3. It uses five meters yet allows flow rate in individual steam mains to be determined and allocates the distribution losses fairly.

The final arrangement chosen will depend on the purpose of the meters. As discussed in Section 7.1, if the meters are to be used for accounting purposes, they will need to be located so that the consumption of the individual accounting centres may be measured. Where only one or two large users operate on a site, it may be sufficient simply to have individual meters for each user. However, if meters are located at the boundary of each individual user or accounting centre's area, then system losses will not be measured. Under these circumstances, a meter should be installed at or in the boilerhouse so that losses can be determined and then charged either on a pro rata basis or within the charging structure.

Where consumption needs to be determined to a high or consistent level of accuracy, all opportunities for check metering should be exploited. The possible options will take the same form as the alternatives to steam metering, e.g. condensate measurement, heat input measurement by heat loss calculation etc. In addition, it may be possible to use the total from two sub-meters to act as a check on one main meter.

The most important cross-check to have in place is that on the main steam meter. Typically, this can be achieved by measuring total feed water flow to the boiler(s). Although the amount of blowdown will cause some degree of error, it is possible to carry out a final check by closing the blowdown for a short test period.

7.3 Selection of Meter Type

When selecting specific types of meter, the user should take four factors into consideration:

- technical factors – turndown ratio, accuracy, repeatability;
- practical considerations – installation limitations, maintenance requirements;
- properties of the fluids – pressure/temperature variations, dryness fraction;
- purchasing policy – single supplier, nominated supplier.

Table 3 (Section 6.4) offers a useful comparison of meter types.

7.3.1 *Technical Factors*

Depending on the ultimate use of the meter, the user will need to define acceptable limits of turndown ratio, accuracy and repeatability (Section 5).

The required turndown will depend on the user’s knowledge of the flow rates to be expressed within a particular steam leg. If temporary measuring instruments are not available, then the range will need to be estimated or calculated from the user’s own experience. Maximum load can be calculated on the basis of maximum process load and/or maximum space heating load, and meters can then be sized for these maximum expected flow rates, e.g. 12.5 kg/s. However, maximum flow rates may occur for only short periods during the year and, when operating away from these maximum rates, the effective range of the meter will be reduced, e.g. from 10:1 at 1.25 kg/s to 5:1 at 6.75 kg/s.

If the mean load is less than 25% of the maximum load, orifice plates cannot be used. Furthermore, even if the ratio between maximum and mean loads is only 2:1, the use of such plates would be inadvisable since, at the mean flow rate, the effective range of the meter would be reduced to 2:1. For example, if most of the steam flow occurs in the range 1.25 – 2.0 kg/s with a loading of 8.75 kg/s for peak hours during the winter months, and if the meters are sized for the maximum steam flow then, even with a turndown ratio of 5:1, they would not register flows below 1.75 kg/s within the accuracy specified. Under such circumstances it would, therefore, be better to use a meter which can achieve the required turndown. If, on the other hand, the flow varies with only a small range of, say, 6.75 – 8.75 kg/s, then orifice plates/nozzles would be both acceptable and probably cheaper than the other alternatives. The meter manufacturer will advise on suitability.

Selecting a meter with the same bore as the pipe in which it is to be fitted can be an error as, in many cases, steam mains are oversized for their eventual application. At low flow rates, therefore, the meter is likely to be operating at the low end of its effective range, at which point its accuracy will decline.

Similarly, it will normally be a mistake to size a metering installation for future expansion. Unforeseen circumstances may prevent this expansion from taking place and, even if development does occur, existing meters can often be recalibrated or new primary elements installed with relative ease.

Wherever there is uncertainty in the steam flows to be metered, the user will benefit from an accurate analysis of system operation. This may involve the installation of temporary metering and/or the employment of experts to assess flows.

A further consideration when specifying meter type is how the meter is to be used – for instance, whether it is to measure an instantaneous rate or to be able to totalise. Most modern meters are rate meters which have ‘add-on’ totalisers. Rotary shunt meters are the exception to this rule. They are designed as totalisers but can now be obtained with a ‘rate’ function. This uses a proximity sensor to measure the rotational rate of the damper fan.

7.3.2 *Practical Considerations*

Steam meters operate best with clean dry steam and at the design conditions of temperature and pressure. Any user should aim for these ‘ideal’ conditions when considering possible locations and ancillary equipment for the meter. For any particular location, consideration should be given to the questions outlined below.

- Do the minimum straight pipe lengths exist both upstream and downstream? BS 1042 gives minimum requirements for orifice plates and other differential pressure devices, and the topic is dealt with more fully in Section 8.4.
- Can the meter be installed at this location? Are the pipework supports adequate? Is there sufficient access for carrying out routine maintenance?
- Is the location in a horizontal or vertical section of pipe run? If vertical, is the steam flowing upwards or downwards? Certain meter types must be located in horizontal sections of pipework otherwise the vertical component will affect the equations used for the calculation of volumetric flow rate.
- Will steam flow be in one direction only, or is there a possibility of flow reversal? All meters are unidirectional and can, in some instances, be damaged by a reverse flow.
- Will the meter operate at a high or a low spot in the pipework system? All meters should be fitted with adequate air vents and, if necessary, steam traps and drains.

7.3.3 *Properties of the Fluids*

Most boiler systems operate on some form of ‘master pressure control’ under which the pressure at a selected part of the system, normally the steam main at the boilerhouse exit, is maintained at a fixed pressure. As the demand for steam varies, the pressure will either rise or fall, and the controller is designed to minimise these pressure variations by adjusting the firing rate of the boiler(s). Despite these adjustments, small fluctuations in pressure may be apparent adjacent to the boilerhouse. These are magnified further from the source, with the result that pressure at the geographical limits of the system may fluctuate wildly. Fluctuations in steam pressure cause variations in the density and dryness fraction of the steam.

Meters located in regions of fluctuating pressure can be equipped with pressure/temperature compensators if required. The extra cost involved, however, should only be considered if a high degree of metering accuracy is required.

The alternative is to have the meter calibrated at a mean pressure value and to accept that errors caused by low steam pressure will be counterbalanced by opposite errors at high steam pressure.

If compensation is considered, it may take the form either of an additional pressure tapping which measures the actual static pressure, or of a temperature probe mounted upstream of the meter. The disadvantage of both methods is that superheated steam (Section 2) cannot accurately be monitored. If superheated conditions exist then both a pressure tapping and a temperature probe will be required. Superheated conditions will generally occur downstream of a pressure reduction, so superheat compensation is only really justifiable where major consumers are involved. The extra cost of the compensation will need to be related to the savings potential, and that depends on an accurate knowledge of steam consumption.

Meters such as orifice plates and pitot tubes can be adversely affected by steam containing a high proportion of water droplets, i.e. steam with a low dryness fraction. The sharp edges of orifice plates will become eroded with time, causing a change in the discharge coefficient. With pitot tubes, one or more of the upstream pressure tappings may become flooded. Steam separators should be installed upstream of any meter location where entrained water vapour is likely to give rise to problems. Not only will these remove most of the entrained water droplets, but any droplets that remain will become more homogenised within the vapour fraction.

7.3.4 *Purchasing Policy*

Purchasing all meters from a single supplier has several benefits:

- the number of spares that the user needs to stock is reduced;
- maintenance staff expertise is restricted to one type of meter;
- the user becomes important to the supplier.

Single sourcing can, however, lead to a situation in which the meter supplied is over-specified for the application, e.g. variable-area meters might be used where orifice plates would be adequate.

7.4 Data Collection and Analysis

The next question to be considered is how the data are to be collected and analysed, and in this, there are three levels of sophistication:

- At the **manual** level, someone is assigned to record the meter readings manually. This may take place at each individual meter location or in a central control room to which readings are relayed.
- At the **semi-automatic** level, meter readings are fed manually into a computer used for data analysis.
- At the **fully automatic** level, meters are hard-wired back to an Energy Management System (EMS) or similar.

The last level has the particular advantage of eliminating human involvement and guaranteeing that the meters will be read at pre-determined intervals. It is, however, the most expensive option. A user coming new to metering is, therefore, probably advised to install a system that can be upgraded from manual to semi-automatic and, ultimately, to fully automatic if justifiable. Such a system will be based on a ‘pulsed output’ meter. The term ‘pulsed output’ describes the form of electronic signal provided by the meter and which can be interpreted using existing data-logging system hardware and software. Section 10 deals with data handling in greater detail.

Data collected should be analysed in sufficient detail to highlight any anomalies or trends in steam consumption. Readings may be compared with past results, or consumption may be related to other factors such as production output or the weather. In considering trends, for instance, while an individual week-on-week increase of, say, 2% might go unchallenged, continuing increases over a ten-week period could indicate a worsening situation.

7.5 Reporting

The corollary to data analysis is the establishment of clearly defined structures of reporting and action – ‘action pathways’. Fig 14 shows a typical action pathway. Such a structure will allow those who can influence steam usage to act on the results of the analysis. It is, however, important that the results of any such actions are collected and similarly analysed.

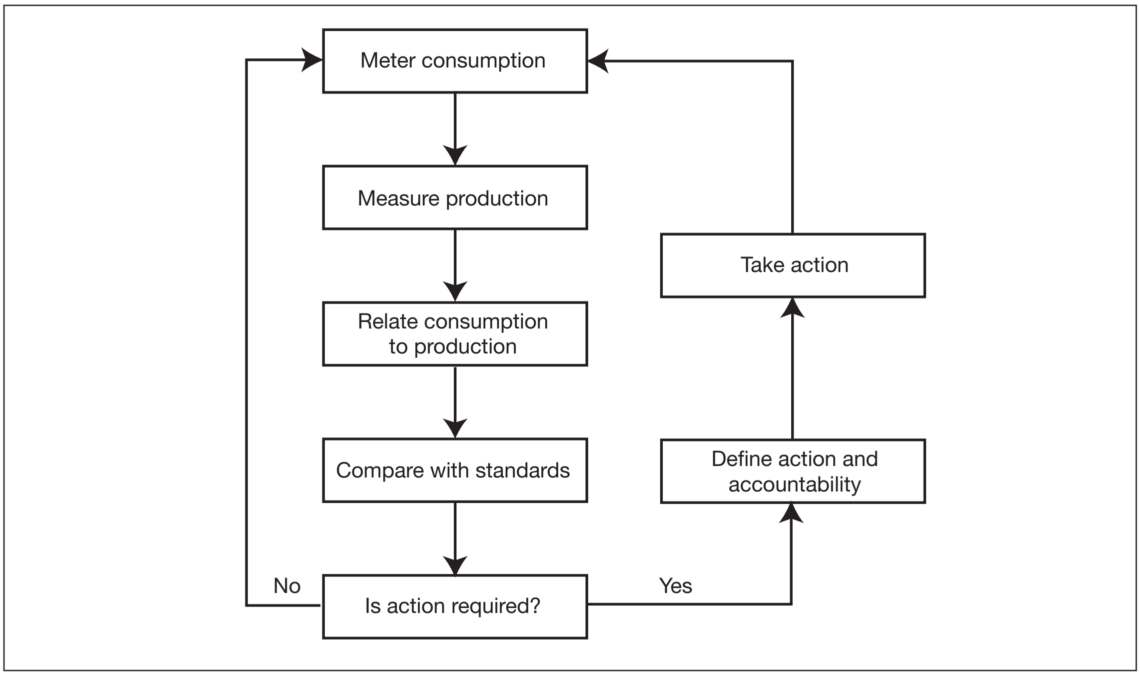

Fig 14 Typical action pathway

8. DETAILED STEAM METERING SYSTEM DESIGN

This Section examines the detailed design of steam metering systems. It considers the calculation of steam flow rates and velocities for both process and space heating situations, and examines the effects of varying Reynolds Numbers and of variations in steam pressure. Considerable attention is paid to sizing the meter for the application, as well as to the details of installation both of the meter and its associated equipment.

8.1 Calculation of Steam Flow Rates and Velocities

In order to select a meter of the appropriate size, the potential user must establish the range of steam flow rates and Reynolds Numbers to be measured by the meter. The aim is that the maximum capacity of the meter exceeds the maximum expected flow rate by as little as possible. Furthermore, the turndown ratio of the meter should be sufficient to allow the minimum expected flow rate to be measured. The range of flow rates expected can be calculated from known system parameters or can be estimated from the user's experience.

There are two principal uses for steam:

- process heating;
- space heating.

Either or both uses may occur within a particular site or area, and it is important when determining the maximum flow rate that the two types of load are calculated independently. The calculation will always take the form of a heat balance, as shown below.

8.1.1 *Process Load Calculation*

Flow and temperature conditions are obtained from design and operating conditions respectively.

Process fluid conditions:

Flow rate	10	kg/s
Specific heat capacity	2.4	kJ/kg °C
Heat exchanger inlet temperature	50	°C
Heat exchanger outlet temperature	150	°C

Heat supplied = 10 x 2.4 x (150-50)
= 2,400 kJ/s

Steam conditions:

Steam pressure (saturation conditions exist)	7.01	bar
Steam specific enthalpy	2,762.5	kJ/kg
Steam specific volume	0.277	m^3/kg
Condensate specific enthalpy	696.0	kJ/kg

(figures obtained from Steam Tables)

Heat released = 2,762.5 – 696.0 kJ/kg

= 2,066.5 kJ/kg

Steam flow rate = 2,400/2,066.5 kg/s

= 1.16 kg/s

This is equivalent to 4,176 kg/h
or 9,209 lb/h

If the steam pipework is 150 mm nominal diameter:

Flow cross-sectional area $= \frac{\pi}{4} \times (0.15)^2 \text{ m}^2$

$= 1.767 \times 10^{-2} \text{ m}^2$

Steam velocity $= (1.16 \times 0.277)/1.767 \times 10^{-2} \text{ m/s}$

$= 18.2 \text{ m/s}$

8.1.2 *Space Heating Calculation*

The load is determined by the addition of the design rating of all heat exchangers.

Heat load 1,000 kW
or 1,000 kJ/s

Steam conditions:

Steam pressure (saturation conditions exist)	7.91	bar
Steam specific enthalpy	2,768.0	kJ/kg
Steam specific volume	0.244	$\text{m}^3\text{/kg}$
Condensate specific enthalpy	718.7	kJ/kg

(figures obtained from Steam Tables)

Heat released = 2,768.0 – 718.7 kJ/kg

= 2,049.3 kJ/kg

Steam flow rate = 1,000/2,049.3 kg/s

= 0.488 kg/s

This is equivalent to 1,757 kg/h
or 3,874 lb/h

If the steam pipework is 75 mm nominal diameter:

Flow cross-sectional area $= \frac{\pi}{4} \times (0.075)^2 \text{ m}^2$

$= 4.418 \times 10^{-3} \text{ m}^2$

Steam velocity $= (0.488 \times 0.244)/4.418 \times 10^{-3} \text{ m/s}$

$= 26.95 \text{ m/s}$

8.1.3 *The Calculation and Effect of Reynolds Numbers*

Once steam velocities at maximum and minimum flow rates have been determined, the Reynolds Numbers for both conditions must be calculated. Using the steam specific volume instead of its density, the Reynolds equation becomes:

$$Re = \frac{Dv}{\mu S}$$

where D = pipe internal diameter (m)
v = mean fluid velocity (m/s)
μ = kinematic viscosity (kg/ms)
S = specific volume (m^3/kg)

At the minimum expected flow rate, the Reynolds Number should exceed 10,000. At lower values of Re where the flow regime is laminar or transitional, the pressure drop characteristic is directly proportional to the flow rate. When the flow regime is turbulent, the differential pressure becomes proportional to the square of the velocity. This implies that metering based on measurement of differential pressure would be highly inaccurate at low values of Re.

For ease of calculation, Tables 4 and 5 give values of Re for various pipe sizes and steam pressures at velocities of 5 and 40 m/s. Interpolation is permissible for velocities between these values which represent the range expected for the majority of steam systems. As can be seen, Re values vary between 5 x 10^6 and 3.1 x 10^4 – in both cases, well above the lower limit for turbulent flow.

Table 4 Reynolds Numbers for velocity = 5 m/s

			Reynolds Numbers for pipe nominal diameters (mm)					
P in psig	Visc. in Pa.s	Dens. kg/m^3	25	50	100	150	200	250
80	1.430E-5	3.430	31000	62000	124000	185000	249000	312000
90	1.460E-5	3.780	33000	66000	133000	200000	268000	337000
100	1.470E-5	4.120	36000	72000	144000	216000	291000	365000
110	1.480E-5	4.460	39000	77000	155000	232000	312000	392000
120	1.490E-5	4.800	41000	83000	166000	249000	334000	419000
130	1.500E-5	5.135	44000	88000	176000	269000	355000	446000
140	1.510E-5	5.470	47000	93000	187000	279000	375000	472000
150	1.515E-5	5.805	49000	98000	197000	296000	397000	499000
160	1.520E-5	6.140	52000	104000	208000	312000	419000	526000
170	1.545E-5	6.480	54000	108000	216000	324000	435000	546000
180	1.550E-5	6.820	57000	113000	227000	339000	456000	573000
190	1.560E-5	7.155	59000	118000	236000	354000	475000	597000
200	1.570E-5	7.490	61000	122000	246000	368000	494000	621000

Table 5 Reynolds Numbers for velocity = 40 m/s

			Reynolds Numbers for pipe nominal diameters (mm)					
P in psig	Visc. in Pa.s	Dens. kg/m^3	25	50	100	150	200	250
80	1.430E-5	3.430	247000	492000	988000	1480000	1989000	2498000
90	1.460E-5	3.780	266000	531000	1067000	1598000	2147000	2697000
100	1.470E-5	4.120	288000	575000	1155000	1730000	2324000	2919000
110	1.480E-5	4.460	310000	618000	1242000	1860000	2499000	3139000
120	1.490E-5	4.800	331000	661000	1327000	1988000	2671000	3355000
130	1.500E-5	5.135	352000	702000	1410000	2113000	2839000	3566000
140	1.510E-5	5.470	372000	743000	1492000	2236000	3004000	3773000
150	1.515E-5	5.805	394000	786000	1579000	2365000	3177000	3991000
160	1.520E-5	6.140	415000	829000	1664000	2493000	3350000	4208000
170	1.545E-5	6.480	431000	861000	1728000	2589000	3478000	4369000
180	1.550E-5	6.820	452000	903000	1813000	2716000	3648000	4583000
190	1.560E-5	7.155	471000	941000	1890000	2831000	3803000	4777000
200	1.570E-5	7.490	490000	979000	1966000	2944000	3956000	4969000

If, at the minimum flow rate, the Reynolds Number is below 10,000 the pipe diameter will need to be reduced. The equation can be used to specify the maximum pipe diameter such that the Re number will always exceed 10,000. Where pipe reducers are used they should be eccentric since this will avoid the trapping of pools of condensate (Fig 15).

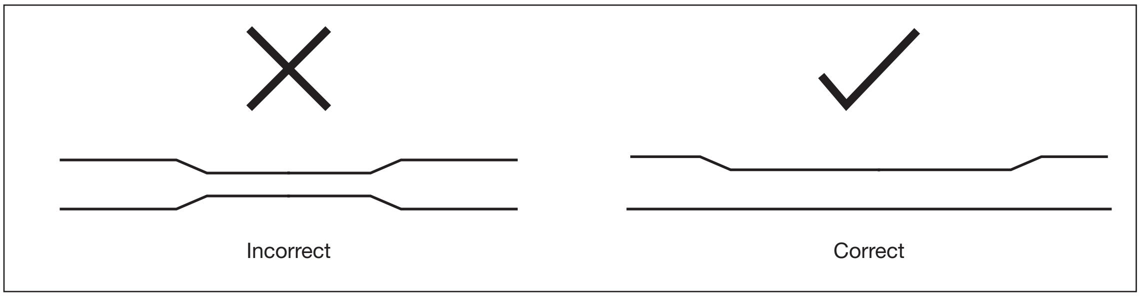

Fig 15 Correct use of pipe reducers

8.2 The Effect of Variations in Steam Pressure

Steam meters should be sized for the minimum operating pressure, i.e. largest volumetric flow rate. If pressures differ from design conditions and pressure and temperature compensation is not used, errors will be introduced. Such errors can be significant, as illustrated below.

If a differential pressure type meter has been designed to operate at 6 bar but is operating at 4.5 bar:

Differential pressure is proportional to $\frac{v^2}{2\,S}$

where v = velocity of the fluid (m^3/s)
S = steam specific volume (m^3/kg)

Hence, for equal values of differential pressure, the ratio of velocities will be equal to the square root of the ratio of specific volumes:

$$\frac{v_2}{v_1} = \left[\frac{S_2}{S_1}\right]^{1/2}$$

At 6.0 bar $S_1 = 0.315\ m^3/kg$

At 4.5 bar $S_2 = 0.418\ m^3/kg$

The velocity at 4.5 bar is, therefore, 15% greater than at 6 bar

The mass flow rate $Q = a\ \frac{.v}{S}$ kg/s

where a = the cross-sectional area over which the flow is taking place

So $\frac{Q_2}{Q_1} = \frac{v_2\,S_1}{v_1\,S_2}$

Hence, substituting for v_2

$$\frac{Q_2}{Q_1} = \left[\frac{S_1}{S_2}\right]^{1/2}$$

the error is equivalent to 13%.

This example clearly illustrates the errors that can result from comparatively small changes in pressure.

8.3 Sizing the Meter for the Application

Once maximum and minimum flow rates have been calculated, the user can refer to a range of manufacturers' literature to select the correct meter for any particular application. Most manufacturers/suppliers will include either selection tables or monographs showing the minimum and maximum flow rates that each individual meter can handle. If manufacturers offer no such tables or graphs, they should undertake to size the meters themselves based on information supplied by the user regarding steam flow at the measuring point:

- maximum flow rate through the meter;
- mean steam temperature;
- mean steam pressure;
- the number of straight pipe diameters upstream and downstream of the proposed meter location;
- the location of any pressure reducing, control or isolating valves likely to affect the meter;
- the percentage dryness of the steam.

The normal procedure when choosing a meter is to select the one for which the maximum specified flow rate is equal to, or slightly greater than, the maximum flow rate expected, irrespective of the actual size of meter involved. It is a common mistake to select a meter of the same size as the pipeline in which it is to be installed. This can lead to a meter being oversized for the range of flows expected and to a reduction in the meter's overall effective range.

It is important to check the assumptions on which the maximum capacity of a meter is based. For instance, a number of manufacturers of vortex shedding flow meters have specified a maximum meter capacity corresponding to a velocity of 80 m/s or to a Reynolds Number of 7×10^6. A typical steam supply system, however, is designed for a maximum velocity of 40 m/s for saturated steam, experience having shown that this value offers the best compromise between initial capital cost, operating cost and the erosive effects of saturated steam. If 40 m/s is adopted as a maximum viable velocity for a vortex meter of the capacity described, its effective operating range is halved from 10:1 to 5:1 – a level which can be obtained by using orifice plates or similar types of meter.

The potential turndown ratio of the vortex shedding meter can be maximised by using pipe reducers to increase the flow velocity at the meter to 80 m/s. The benefits gained will, however, be at the expense of increased pressure drop over the metering section and of a greater potential for erosion of the vortex shedding bar. The consensus of manufacturers' opinions is that erosion could be minimised by using a bluff body shape designed for this duty, i.e. a round-edged rather than a sharp-edged body. Regular recalibration would then minimise the effects of any erosion that did occur. The erosive effects of the steam can also be reduced by installing a steam separator upstream of the meter.

Once an appropriate meter has been selected for the maximum velocity criterion, it is important to check whether the minimum specified flow rate is below the minimum expected. If not, two options are available:

- selecting a meter with a greater range;
- considering the use of two meters in parallel.

8.4 Aspects of Meter Installation

There is no British Standard that specifically addresses steam metering, although BS 1042 relates to square-edged orifices, nozzles, vented tubes and pitot static devices for measuring fluid flow. BS 1042 is in two parts: Part 1 deals with pressure differential devices; Part 2 deals with velocity area methods of measurement and relates to the use of pitot static tubes. The international equivalents to BS 1042 are given overleaf.

British Standard	**Equivalent International Standard**
BS 1042 Part 1.1	
Part 1.2	ISO 5167
Part 1.4	
Part 1.5	

These standards are interpreted as equal although differences in wording do occur.

Part 2.1	ISO 3966
Part 2.2	ISO 7145
Part 2.3	ISO 7194

These standards are the same.

8.4.1 *Location of Equipment*

Meters need to be installed in defined lengths of straight pipe to ensure accurate and repeatable performance. These pipe lengths are usually described in terms of the number of pipe diameters upstream and downstream of the meter. For example, an orifice plate meter may need ten pipe diameters of straight pipe upstream and five downstream. If the pipe diameter is 150 mm, this is equivalent to 1.5 metres upstream and 750 mm downstream.

If the meter is to be located downstream of, say, two right-angled bends in different planes, then the minimum straight length required upstream of the meter is 34 pipe diameters. This can be difficult to achieve, particularly in fairly complex pipework systems, and there may not be a location that allows these criteria to be met. In these circumstances, the use of flow straighteners is recommended. If these are installed immediately downstream of the swirl-inducing pipework, the straight-length requirement can be reduced.

The characteristics of steam impose different requirements on a flow meter than, say, a pure gas or liquid. For metering devices based on orifice plates, nozzles etc. the minimum requirements laid down in BS 1042 should be adopted (Table 6). Most steam meter manufacturers have, in fact, adopted these requirements.

Table 6 Minimum straight length requirements upstream:
BS 1042 Part 1 recommendations

Area ratio	Single 90 bend	Two 90 same	Two or more diff. plane	Reducer 2D-D	Expander 0.5D-D	Globe valve fully open	Gate valve fully open	Downstream
<0.2	10	14	34	5	16	18	12	4
0.25	10	14	34	5	16	18	12	4
0.30	10	16	34	5	16	18	12	5
0.35	12	16	36	5	16	18	12	5
0.40	14	18	36	5	16	20	12	6
0.45	14	18	38	5	17	20	12	6
0.50	14	20	40	6	18	22	12	6
0.55	16	22	44	8	20	24	14	6
0.60	18	26	48	9	22	26	14	7
0.65	22	32	54	11	25	28	16	7
0.70	28	36	62	14	30	32	20	7
0.75	36	42	70	22	38	36	24	8
0.80	46	50	80	30	54	44	30	8

Note: Figures given are for an uncertainty of 0%.
Values may be halved for an additional uncertainty of 0.5%.

Manufacturers of the spring-loaded variable-area meters state within their specifications that straight lengths of six pipe diameters upstream and three downstream are sufficient. The manufacturers of vortex meters and rotary shunt meters adopt the requirements of BS 1042.

Where the meter selected is of a smaller cross-sectional area than the pipework into which it is to fit, it is necessary to use eccentric pipe reducers to ensure that there are no areas in which condensate can collect (Fig 15). It is important to remember when installing such a reducer that the minimum straight length upstream of the meter must be maintained: the reducer should not, for instance, be installed within five pipe diameters of the meter.

Where possible, a steam meter should not be located downstream of a partially open flow control valve. The pressure drop caused by the valve may cause *adiabatic expansion* of the steam and result in superheated conditions immediately after the valve. The quality of the pipework insulation will influence how far downstream these conditions extend. If the steam meter has both temperature and pressure compensation, no errors will occur. If, however, only temperature compensation is present, errors will result.

The orientation of the metering element within the pipework and the location of the differential pressure transmitter are both important. Certain types of meter need to be installed in horizontal pipe runs (e.g. the Kent rotary shunt meter) or to have the sensing element horizontal within the pipe (e.g. the Fisher and Porter vortex flow meter). For differential pressure transmitters, however, the impulse lines should be full of condensate and the transmitter should, therefore, be located below pipe level.

BS 1042 also stipulates the location of the pressure tapping points used for differential pressure measurement. Normally, the upstream tapping point will be located one pipe diameter and the downstream point half a pipe diameter from the meter element. However, the standard also allows for tapping points located within the carrier ring of orifice plates/nozzles etc., or for flange tappings. A proprietary meter such as the Gilflo, for instance, has pressure tappings located within the mounting flanges. All pressure tappings should be located in a position where they are not readily blocked by stray pieces of dirt within the fluid stream.

If meters are to operate under variable steam pressure conditions it is advisable to consult the meter manufacturer for advice.

Where thermocouple pockets are used for temperature/pressure compensation they should be located at least five pipe diameters upstream of the meter element if the pocket diameter is less than or equal to 0.03 pipe diameters, or 20 pipe diameters upstream if it is between 0.03 and 0.13 diameters.

Certain types of meter have electronic housings attached to the meter element. Sufficient space should be available both to install the whole meter and to ensure adequate access for maintenance procedures to be carried out. If the meter is large or heavy, lifting beams may be required to facilitate its removal for repair or recalibration.

8.4.2 *Differential Pressure Cells and Impulse Lines*

Certain types of meter use a DPC to convert the pressure signal to an electrical (e.g. 4 – 20 mA) or electronic (e.g. variable frequency pulse) signal. The DPC is connected to the pressure tapping points of the meter via 10 mm impulse lines.

The DPC should be located below the primary element, and there should be an equal change in height from the high and low pressure tappings to the DPC to avoid the creation of a base differential pressure and the possibility of reduced meter accuracy. Alternatively, the DPC can have an offset zero.

The impulse lines should be filled with a continuous column of condensate, and condensate chambers, if necessary, can be located at the high point of the impulse lines to ensure that this condition is met. The large surface area per unit volume of the condensate chamber ensures that any steam reaching the chamber rapidly condenses, a factor of particular importance in the measurement of superheated steam.

Since the impulse lines provide a static column of incompressible liquid there is the risk that, in external applications, the condensate will freeze. Should this happen, the associated expansion will destroy the DPC. This can be prevented in two ways:

- the impulse lines can be filled with a glycol solution, the concentration of the mixture depending on the level to which protection is required;
- the impulse lines can be insulated and trace-heated.

Because the impulse lines will commonly provide the high point for the metering system, they should be provided with air vents. The optimum location for these is at the top of the condensate chambers. During start-up, the impulse lines should be 'blown through' to ensure that no air is trapped.

Isolating valves on the impulse lines, close to the primary element, ensure that the DPC can be isolated from the steam pressure whenever it needs recalibrating. Such valves also allow a ready check of the zero point of the meter. Fig 16 shows the various elements of the impulse line connection to the DPC.

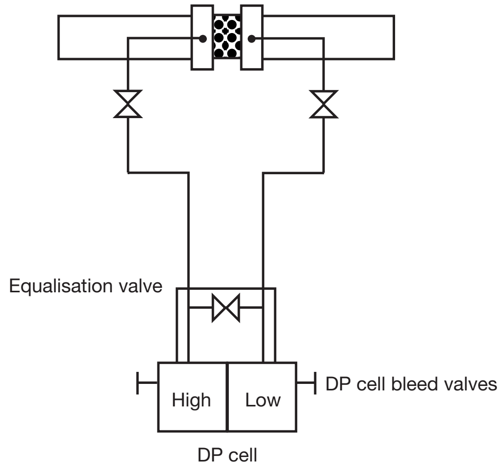

Fig 16 Connections from impulse line to DPC

8.4.3 *Separation and Trapping*

Steam meters operate most effectively with clean dry steam since it is under these conditions that its behaviour most closely models that of a gas. Unfortunately, this situation rarely occurs in practice. Heat losses in the distribution system can result in the build-up of a film of condensate on the inside surface of the pipework with dispersed water droplets within the steam itself.

If condensate levels are allowed to rise unchecked, two problems occur which can result in meter failure:

- the rate of erosion will increase;
- 'slugs' of condensate may form within the pipe, travelling at the same velocity as the steam – if these impinge on the meter the element can be destroyed.

Condensate can be removed by adequate steam trapping within the distribution system. However, if high levels of metering accuracy are required, a steam separator should be installed upstream of the meter. This comprises a large baffled chamber, the volume of which reduces steam velocity and ensures that the larger droplets fall out of entrainment. The baffles create swirl within the steam flow and this causes the smaller condensate droplets to impinge on the chamber walls. Only the smallest water droplets will remain entrained and the swirl environment of the chamber will ensure that they are completely mixed. The separator vessel should be fitted with a steam trap for removal of the condensate collected.

The causes of high water content in steam should be established before separators are installed. Common causes include poor insulation, faulty or inadequate steam traps, or poor boiler water treatment. It may be more economical to cure the cause than to overcome the symptoms.

8.4.4 *Isolation*

If maintenance or repairs are to be undertaken with the steam supply system in operation, some form of isolation will be required so that the work can be undertaken safely. Furthermore, a distinction is necessary between isolation of the primary element, e.g. the orifice plate, and isolation of the secondary element, e.g. the DPC.

Many users make no provision for isolating the primary element of their steam meters. The assumption is that failures are unlikely and that all maintenance can be undertaken during an annual shutdown. Failures are more common in DPCs and transmitters, and after repair these elements will require recalibration – hence the requirement for isolating valves to be installed on impulse lines.

Where the primary element is to be isolated, the provision of a bypass leg should be considered to eliminate downtime in other parts of the system. If no bypass exists, all pipework downstream of the isolating valve will be ‘dead’ during periods of repair/replacement of the element. Fig 17 shows a typical meter train incorporating a bypass and isolation of the primary element.

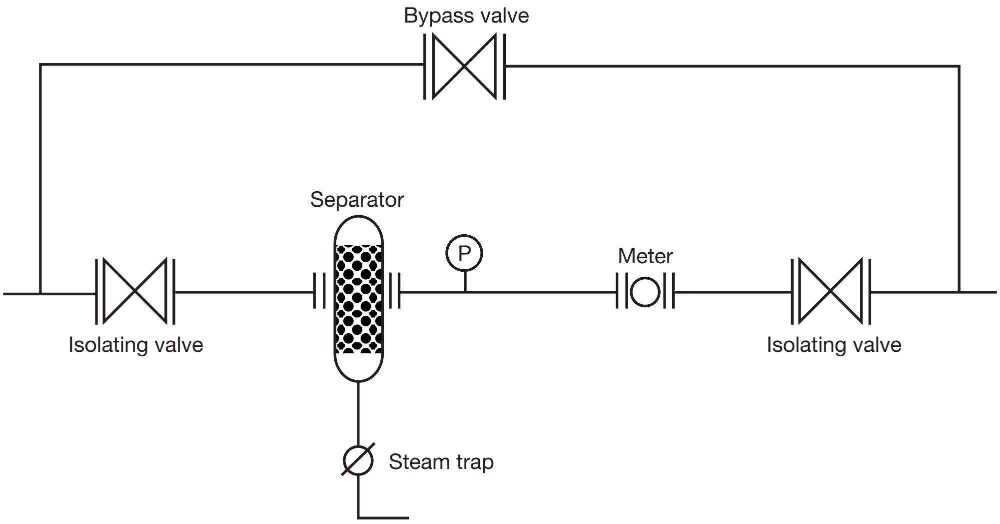

Fig 17 Typical meter installation

Where a section of pipework can be isolated it should be fitted with a local pressure gauge and drain valves so that there is a local indication when the section is pressurised. When depressurising, the drain valve should be opened from about 1 bar to allow the pressure to fall quickly and to ensure that no vacuum builds up.

The various stages involved in the design and selection of the correct size and type of steam meter, and the order in which they should be addressed, are summarised in Fig 18.

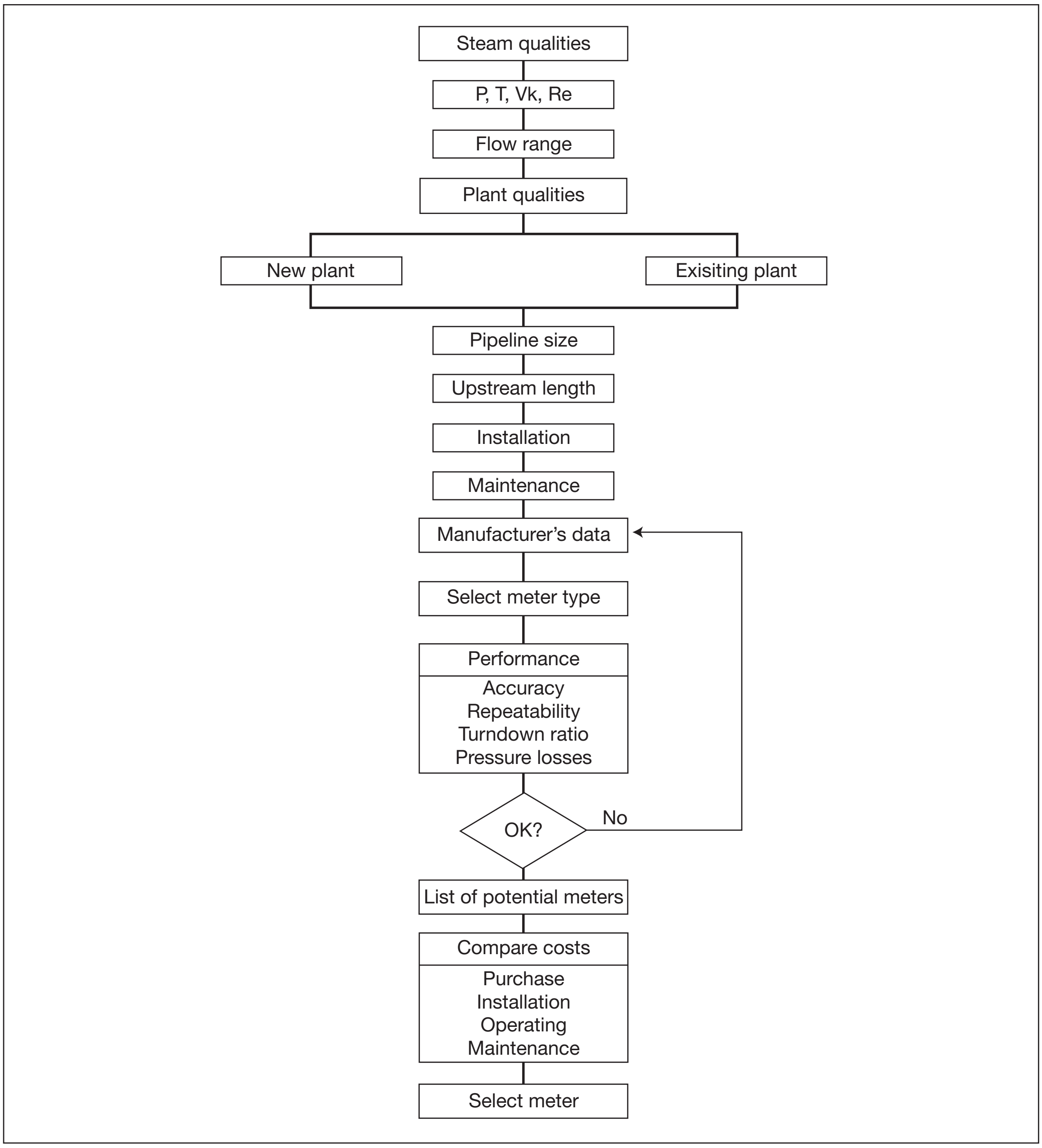

Fig 18 Meter selection flow chart

9. OPERATION AND MAINTENANCE

Metering systems will operate efficiently only if they are well maintained and regularly recalibrated. This Section provides a basic guide to maintenance requirements and techniques. It covers maintenance of both the primary elements and any ancillary differential pressure cells or electronics. However, it is in no way a substitute for the more detailed instructions available in the literature from manufacturers' which should always be used as the basis for a maintenance system. It is not possible to give the specific requirements for individual manufacturers' equipment in a document of this type.

The Section is divided into three parts dealing respectively with the safety aspects of maintenance, routine checks, and fault-finding and troubleshooting.

9.1 Safety During Maintenance

Maintenance work can be hazardous for several reasons:

- the steam in the system will be at elevated pressures and temperatures;
- steam meters and their associated equipment may be connected to a low voltage power supply;
- there is a risk of spark-initiated explosions in certain types of atmosphere unless power supplies are interrupted prior to work being carried out.

It should, therefore, be mandatory to work to a system using ‘permits to work’.

Before work is begun, someone in authority should assess each meter application to determine the precautions that need to be taken. Such precautions might include, for instance, isolating and powering down a DPC, or depressurising the whole distribution main.

If any part of the system is to be isolated, it should be depressurised and allowed to cool before work commences. The impulse line or meter train isolating valves should also be closed. Closure of valves is not in itself a guarantee of complete pressure isolation as valves can develop leaks. Where possible, separate pressure gauges should be installed to allow the fall-off in pressure to be monitored, and small-bore drain valves with drain lines piped to *tundishes* would allow any remaining pressure to be vented safely to drain.

Correctly sized spanners should be used to loosen nuts, as the use of adjustable wrenches or Stilson wrenches can result in damaged nuts, broken studs or stripped threads.

Gaskets, once removed, should be renewed rather than refitted. They should be fitted so as not to intrude into the pipe stream. Such intrusion can create swirl effects and vortices which will reduce the accuracy of some metering elements.

If the user is unsure about any item of equipment, a specialist should be contacted.

9.2 Routine Checks

The routine checks to be carried out have two main aims:

- to ensure that the existing equipment is functioning both safely and correctly;
- to maintain the highest possible level of steam quality.

Routine checks on existing equipment will include examination of:

- all valves;
- steam traps/separators;
- the primary meter element;
- the DPC and transmitter.

It can be assumed that if the equipment is operating correctly, then steam quality will be maintained at the best possible level.

9.2.1 *Valves*

Valves should be checked to see if they are in the correct position – either fully open or fully closed (Section 8.4, Figs 16 and 17). Under normal operating conditions valves should be in the position indicated below.

- Inlet and outlet isolating valves – fully open
- Bypass valve – fully closed
- Impulse line isolating valves – fully open
- Equalisation valve – fully closed
- Air vents and DPC bleed valves – fully closed

The inlet isolating valve is of particular importance. This valve, if partially closed, may create a sufficient pressure drop for superheated conditions to occur through the meter. If no compensation is built into the meter, inaccuracies will occur in the readings.

Valves should be checked for gland leaks and, where these are found, the gland nuts should be tightened equally until the leakage stops. If there is no further travel left on the gland nuts then, at the first available shutdown, the packing should be replaced.

The checks described above should be undertaken immediately after start-up of the system and subsequently at quarterly intervals.

9.2.2 *Steam Traps and Separators*

The function of the steam trap is to discharge concentrate while retaining live steam. It will be fitted at the condensate outlet of the steam separator. One of two problems can arise if the trap malfunctions: either live steam is discharged instead of retained or, if the trap fails to open, there is waterlogging of the steam separator and a consequent carryover into the metering system. Such a carryover, if neglected, may develop into water hammer. The steam trap should, therefore, be checked for correct operation.

There are several methods of checking the operation of steam traps.

- Installation of a sight glass downstream of the trap. If blast-action traps are used, the sight glass should be at least 1 m downstream of the trap. This method has the disadvantage that the window of the glass is susceptible to deposits which can render it useless.
- Checking the pipe-wall temperature at or after the trap. This is of questionable benefit since both condensate and live steam will be at, or close to, the saturation temperature. This method can, therefore, only be used to determine if the trap is blocked. If it is blocked, the pipework downstream of the trap will be appreciably colder than that upstream.
- Sound checks. Thermodynamic steam traps have a distinctive ‘audio fingerprint’ which allows operational failure to be detected simply. Under normal circumstances, the thermodynamic trap will give a regular ‘click’ as the condensate is blasted through.
- Measurement of the electrical conductivity of the condensate. The conductivity of steam is different from that of the condensate, allowing ready differentiation. This method can, however, be quite expensive.

If the trap fails in the closed position, the fault will readily become apparent from the erratic nature of the meter readings.

9.2.3 *The Primary Element*

Access to the primary element will usually only be possible during plant shutdown. The erosive effects of saturated steam on the primary elements of the heating system have already been noted in several Sections of this Guide, and it is, therefore, important that during the annual shutdown these elements should be removed and their dimensions checked against the specification. If there are serious discrepancies, or if the element is showing visible signs of erosion, it should be replaced. The meter and DPC must then be recalibrated. If the damage is not too severe, the element can be recalibrated and a new coefficient of discharge calculated. This value is then fed into the flow computer.

9.2.4 *The Differential Pressure Cell and Transmitter*

Checks on the DPC and transmitter can be carried out more frequently than checks on the primary element.

If compression fittings have been used to pipe the impulse lines back to the transmitter, these should be checked for steam leaks and tightened if necessary. This check should be carried out at quarterly intervals or whenever the readings appear to be in error. At the same time, the DPC tapping points and impulse lines should be checked to ensure that they are clear. The sequence of operations is given below.

- Check that the DPC equalisation valve is shut. This should be the case if the meter is in operation.
- Check that the impulse line isolating valves are open. Again, this should be the case if the meter is in operation.
- Open, in turn, the high- and low-pressure DPC bleed valves. If the lines are clear, a continuous stream of condensate will emerge. If it does not, then the lines and DPC tappings must be cleared.

Every six months the zero point on the transmitter should be checked. Referring back to Fig 16, the sequence of operations is given below.

- Close the impulse line isolating valves and check that they are shut.
- Open the DPC equalisation valve.
- Check that the indicator is reading a zero flow rate and/or the transmitter output is at 4.0 mA.
- If the indicator does not read zero, close the DPC equalisation valve and check to see if the DPC impulse lines and tapping points are blocked.
- If the lines and points are clear, close the impulse line isolating valves, open the DPC equalisation valve and adjust the zero point on the transmitter accordingly.

9.3 Fault-finding and Troubleshooting

Meter faults are of four types:

- the meter reads inaccurately;
- the meter does not read zero at zero flow;
- the meter reads more than 100% flow;
- the meter reads between 0 and 100% at 100% flow.

Provided that a structured approach to fault-finding is adopted, the cause of the failure can usually be rapidly identified. The suggestions that follow are of a general nature and the user should at all times refer to the manufacturer’s data provided with the meter. These data are normally of a high standard and may include fault-finding charts.

- If the meter is reading inaccurately:
  - Check that it has been installed correctly. Many meters are supplied with flow direction arrows cast onto the body, yet are still installed with the arrow pointing upstream. Ensure that the wiring to the meter is correct and that the impulse lines are correctly connected.
  - Ensure that no steam is bypassing the meter. If the system is fitted with a bypass valve, ensure that this is fully closed. If the system is fitted with a steam separator and steam trap, ensure that the trap is functioning correctly and is neither passing steam nor causing waterlogging.
  - If the meter is not compensated for pressure and temperature, ensure that the operating conditions are those for which the meter was calibrated. If the meter is compensated, ensure that those quantities used for compensation are being read correctly.
  - If the meter is a differential pressure type, ensure that the impulse lines are clear, that the equalisation valve is shut, that all air vents and drains are shut and that any compression fittings used are pressure-tight. Then check that the zero point adjustment is correct. If everything is in order, the meter will need recalibrating.
- If the meter does not read zero at zero flow, check the zero adjustment of the transmitter.
- If the meter reads more than 100%, first ensure that the meter installed is as specified and that the range of flows expected has not been exceeded. If the flow is believed to be within the range of the meter, then the span will require recalibration. For this, reference should be made to the manufacturer.
- The same reasoning should be adopted if the meter reads less than 100% at 100% flow.

10. DATA HANDLING

Steam metering is not cheap, and having invested the thought and effort to select the right meter and install it properly, it is important to discover as much as possible of what the meter can tell you from the data generated.

To install most kinds of steam meter, to check them or to relocate a poorly sited meter, it is necessary to break into the steam pipe. Many engineers are reluctant to do this because of potential unforeseen difficulties in putting the piping back together. A common problem, therefore, is that you may meet resistance to installing all the meters required, or may be constrained to work with data from existing meters that are not ideally located, are suspected of being unreliable or cannot be calibrated. These are not an insurmountable handicap. Data analysis can distinguish meter characteristics from process or building characteristics, and techniques are available which enable steam use to be related to more than one variable, so a single meter with more sophisticated analysis can often serve where two or three might have been ideal. Also, it is only some inferences made from meters that demand absolute calibration.

General guidance on the analysis and use of data in energy management is provided in Good Practice Guide 112 *Monitoring and Targeting in Large Companies*. The intention here is to indicate the broad scope of the data analysis techniques and demonstrate their use with real data.

10.1 Boilerhouse Metering

A steam meter fitted to the output of a boiler serves two functions. By comparison of the boiler output with fuel use you can establish the efficiency of the boiler (or boilers) and monitor performance. If data on steam inputs to a process are combined with data on production, you can appraise the efficiency of a process and monitor its performance, or the steam supplied to a building can identify faults in the heating system, appraise the heat balance of the building and monitor the building. This makes the meter that measures both the output of the boilerhouse and the supply to the rest of the site the most important. The example used here and in Appendix 2 is based on real data taken from such a meter.

10.2 Relating Energy to Output

For data in equal interval time series, which is the way steam meter readings accumulate and most of the other information with which they will eventually be combined tends to accrue, the commonest relationship between steam and the variable on which it depends (production, degree days, boiler fuel) is a straight line with an intercept. It can be shown from physics that this applies to:

- steam output from a boiler compared to fuel input;
- steam requirements for a process compared to production, where the same material is subject to the same process transformation;
- steam input and power output of a generator (also known as the Willans line);
- steam input compared to a measure of the weather called degree days, for a building with good temperature control (and for an intermittently heated building controlled by optimum start strategies) and constant ventilation rate.

This can be formulated mathematically as

$$\text{steam} = m\,x + c$$

where x can be production, power, degree days or boiler fuel in the same time interval. The intercept c can be positive or negative; it is rare for c to be zero. An example of a boiler which shows a very small positive intercept is shown in Appendix 2. A graph from a textile finishing works with a small negative intercept using data from the same meter is shown in Fig 19.

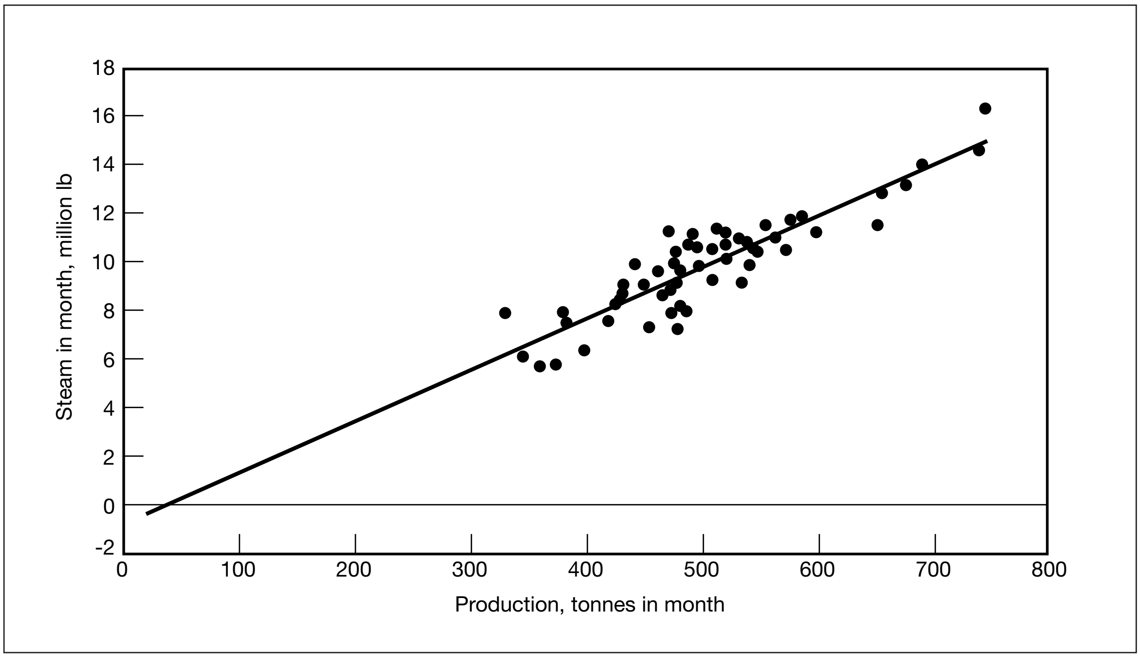

Fig 19 Steam vs production, all data

The straight line with an intercept is important for three reasons:

- The straight line is derivable from physics and this provides a quantitative interpretation of the main features of the graph.
- If such a graph has a non-zero intercept, then the graph of specific steam consumption (y/x, for example, steam per unit of production vs production) against x cannot be a straight line. It is a curve that starts at high (+ve x) or low (–ve x) specific energy and tends towards horizontal with increasing x. Fitting a straight line to specific energy vs production can never achieve high resolution and carries a risk of being misleading (in the middle of the production range steam use will tend to be better than expected but can become impossible at the ends of the range), even if the curvature is not visible to the naked eye.
- There are mathematical techniques (called linear regression) amenable to computation in computer software that can establish the numerical values of the coefficients m and c and enable these to be used for setting a control standard for monitoring, but this only works for straight lines.

In a graph where steam vs production, degree days, electric power or fuel input is a straight line:

- The slope quantifies the heat balance efficiency of the process, generator, boiler or building:
    - in boilers, processes and generators it measures the efficiency (which, to be reliable, requires the meter to have been calibrated);
    - in buildings it measures the ventilation rate.
- In buildings, if the line is not straight this is an important indicator of possible heating faults.
- The intercept:
    - A *positive* intercept on the steam axis indicates and measures the steam which is unrelated to production, weather or power output. These are usually standing losses from the process plant or distribution system, or uses of energy that do not vary with the weather, such as catering in buildings. In a boiler, the same applies to an intercept on the fuel axis.
    - A *negative* intercept on the steam axis, which is sometimes better interpreted as an intercept on the production or degree day axis, indicates energy that is coming from outside the boundary of the metered system – such as recovered heat in processes, or internal heat generated in a building through office or electrical machinery. In a boiler, the same applies to positive intercepts on the steam axis.

- The scatter is a measure of either the control of the process or building, or the influence of other factors not taken into account in the analysis. Scatter is reduced if these are taken into account.

Fuller details of the interpretation of these features are given in GPG112.

10.3 Monitoring

Monitoring of steam consumption usually means tracking the scatter by charting the differences between the actual steam (consumption for a process, generation for a boiler) and the expected value from the line of best fit over time. Such a chart is called a control chart. Fig 20 shows the control chart for the textile works.

The point at which a single difference can be identified as due to something other than natural random scatter is called the *resolution* of the monitoring system. In this case it is 3.25% (which is average for this industry but 0.2% is achievable in some sectors). Because this is based on a standard determined with the same meter, it does not depend on the calibration accuracy of the meter and so the resolution of monitoring can be better than the calibration accuracy. The resolution can be applied as a control level, outside which differences would be a subject for investigation.

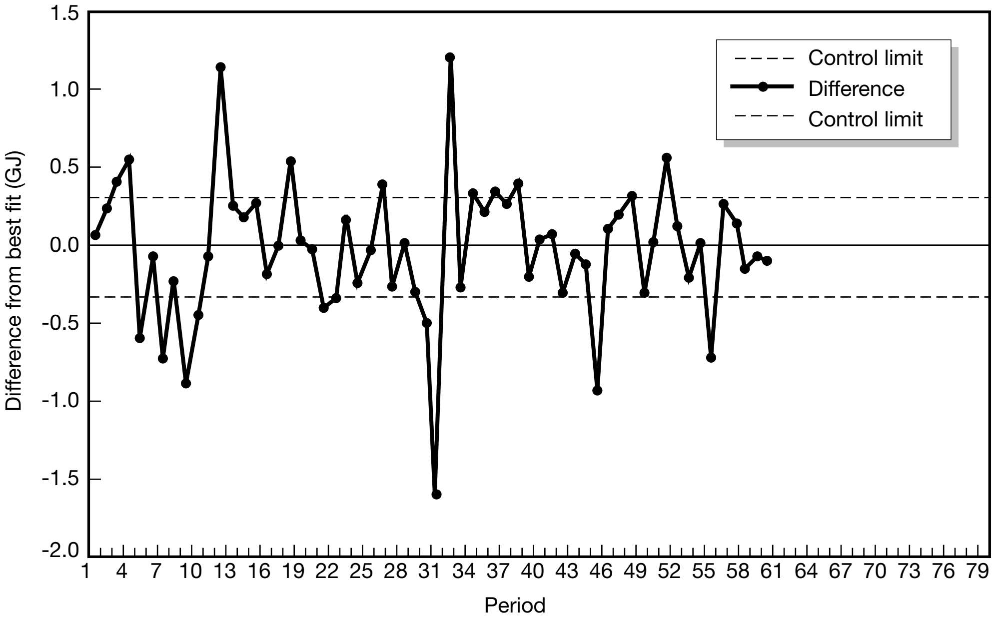

Fig 20 Textile works control chart

10.4 More Detailed Analysis

There are four kinds of exceptional variation. Apart from data errors and sporadic (those that show in only one data interval) events:

- other factors affecting the measured steam consumption that have not been taken into account in calculating the expected consumption;
- an event may change the underlying pattern from that used to calculate the expected consumption.

Other factors can be accommodated by comparing the differences with the variables associated with them (residuals analysis) or by computing the line of best fit by regression using more than one independent variable (multivariate regression).

Multivariate regression can be used to relate consumption to more than one product or to production and buildings simultaneously. This provides a means to use analysis to compensate for fewer meters than would be desirable.

Changes in the pattern over time are accommodated using CUSUM. CUSUM means CUmulative SUM of differences and is the sum of the differences over time. A graph of CUSUM against time, Fig 21, comprises a series of straight segments separated by kinks, each kink represents an event that changed the pattern, the data in the straight segments represent the process or building operating to a consistent pattern.

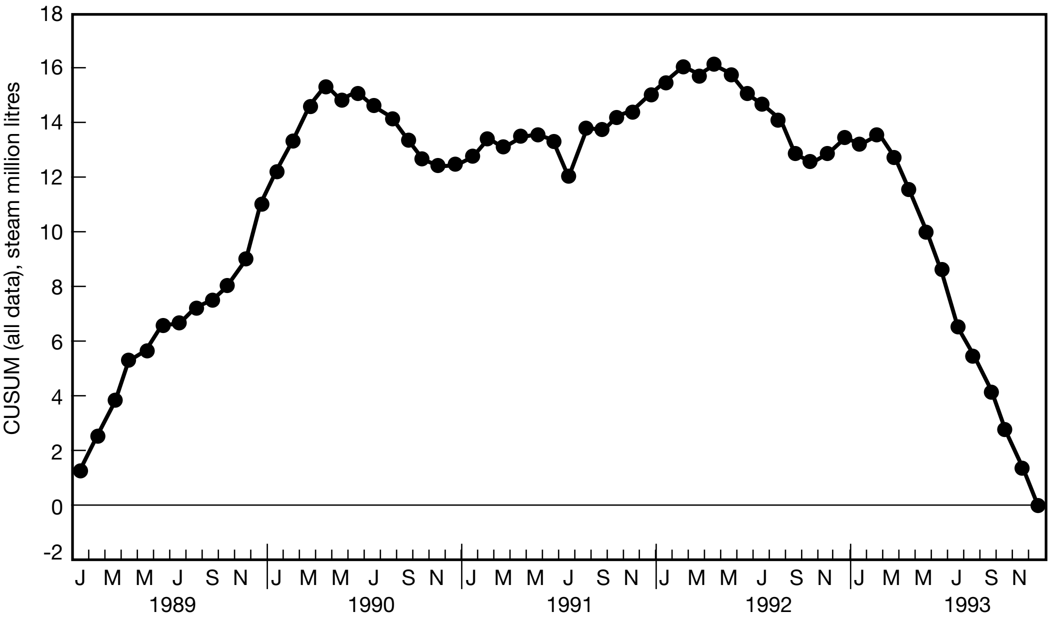

Fig 21 All data parametric CUSUM steam consumption

CUSUM has several uses. After an energy-saving intervention it provides the evidence that the intervention has had an effect and quantifies the savings. It also enables the identification of those, and *only* those, data that represent the process, building or boiler since the last event and so better enables characterisation of the *current pattern.* Analysis of the data between each event (kink) in the CUSUM chart enables a better quantification and characterisation of the natural scatter.

In the case of the textile finishing works, for example, a combination of CUSUM and residuals analysis provides a control limit of better than 3% to be established, quantifies the variation in the recovered heat and identifies a fault in the operation of the space heating.

10.5 Software for Data Analysis

Dedicated monitoring software is only necessary for installations with very large numbers of meters. Computer software in general tends to have four data handling capabilities – summary (reducing a large number of data to fewer, by averaging and totalling), organisation (filing and retrieving information), presentation (converting numerical information into graphs and tables) and analysis (establishing relationships between data and making inferences, such as identifying faults). Most proprietary monitoring and targeting software tends to give priority to the summary, organisation and presentation of data. It is important to consider how far the analysis routines supplied with the software are capable of resolving the features important in a particular application. Some data analysis may be necessary ‘off-line’ in a spreadsheet. However, none of the key analysis techniques are difficult with even quite modest spreadsheet skills.

11. CASE HISTORIES

During the period of background research for this Guide, visits were made to a number of sites to ascertain how typical users approached the problem of steam metering. Examples were selected according to steam use, i.e. whether predominantly for process use, for a mixture of process/space heating, or predominantly for space heating. A summary of each case history is presented in this Section, while the overall lessons learnt have been incorporated, where appropriate, into the main text.

Case History 1: Chemical Company (Yorkshire)

System Design
The site spends approximately £500,000/year on oil purchases for its three boilers. The steam produced is for process use and the system is controlled via a Trend Energy Management System.

The metering system was designed to monitor the 12 main production areas and it also provides the basis for Trend plc’s control of the boilers. Thirteen meters have been installed.

Detailed Design
The steam supplied to the site is saturated and the load in individual production areas can vary. Vortex meters were chosen for installation on grounds of cost, performance (turndown ratio) and previous experience with this type of meter. Steam separators were also installed to ‘knock out’ entrained water droplets.

The approximate consumption in each individual area was known, so meters were sized on the basis of information from charts supplied by the manufacturer. The manufacturer also advised on the location and installation of the meters and this advice was followed.

The meters are monitored continuously by the Trend system, data being archived to file and tape streamed. Hard copy is produced both daily and weekly for accounting purposes, for the calculation of savings, and for inputting to a fledgling M&T system.

Maintenance
Meters are recalibrated annually. The recalibration does not involve a dimensional check on the vortex shedding bar. Because of the nature of their design, vortex meters require no periodic maintenance.

Conclusions
The steam meters were installed as part of an Energy Management System and are used both for monitoring and for controlling steam usage in individual areas of the site. A lot of information is being produced on both a daily and a weekly basis but, until recently, the company did not have the management structures to take full advantage of the system. The current implementation of M&T should give more positive results in the future.

Few cross-checks are built into the system, so it is difficult for the user to assess the accuracy of individual meters. The M&T system will, however, help to highlight any inaccuracies that may exist.

Vortex meters, unlike differential pressure meters, have no means by which the transmitter can be isolated from the vortex bar. The zero point of the meter can, therefore, only be checked by isolating it from the flow. This will require a bypass arrangement if the flow is not to be interrupted.

Case History 2: Educational Establishment

System Design

Boiler fuel for the site costs approximately £300,000/year. Steam is supplied at low pressure and is used primarily for space heating in the buildings that comprise the site.

The metering system was designed to measure consumption in individual buildings, thereby providing information on which energy conservation measures might be based. Twenty-six meters have been installed, the majority supplied by Spirax-Sarco and the remainder by Gervase and Kent.

Detailed Design

Saturated steam is supplied to calorifiers located around the site, and the load variation can be significant. Variable-area meters were selected because of their high turndown ratios. In order to size the meters correctly, an energy consultant was employed: temporary meters were installed at the various relevant locations and profiles of steam demand were established. Most of the meters fitted were 50 mm.

The manufacturer provided installation instructions and the local representative suggested where the meters should be located.

Meters are read daily and on demand, since they are wired directly to a central computer. However, meter accuracy is offset by the slow sampling rate of the computer, a difficulty overcome on later meter models by the incorporation of a pulsed output.

Maintenance

The meters installed have a low maintenance requirement and during the two years since installation have neither been recalibrated nor had their primary dimensions checked. Recalibration would involve returning the meters to the manufacturer.

Conclusions

The site is difficult to monitor accurately and cheaply. The load is predominantly space heating and is spread over a large number of individual buildings. This means that significant load variations will occur and necessitates a large number of meters. The variable-area type of meter is the best choice for such an application.

The large number of buildings varying in both age and construction would have made calculation of heat losses from first principles impractical. The use of temporary metering to size the individual meters was, therefore, both sensible and practical.

Because the steam supply system is adequately steam trapped, the use of upstream separators was considered unnecessary. A few meters do have wire mesh screens installed upstream to collect solid debris.

From the start, the system was designed to be directly wired back to a central computer. The area over which the meters are spread would make manual meter reading uneconomic.

Case History 3: Paper Mill

System Design

The site spends approximately £1 million/year on coal for its boilers. Annual steam production totals 645 million lbs. Steam is generated at high pressure, expanded through turbines to generate electricity and then supplied to the paper-making machines to heat the drying rollers. There is no space heating requirement.

The metering system was designed to measure consumption in individual parts of the process as well as around the electricity generation plant. Twenty-six orifice plate meters have been installed.

Detailed Design

The steam supplied around the site is saturated, and the load to individual areas varies very little. Company policy resulted in all meters being purchased from Kent. Steam consumption was determined from the rate of paper production, the paper type and the degree of drying required. This information was passed to Kent which supplied the appropriate meters. Because of their extensive experience with this type of meter, the company engineers were able to install and commission the meters themselves.

At present the meters are read daily, the readings being used both for energy accounting and for inputting to an M&T scheme. A recent site survey has resulted in changes being proposed, and these may involve an expansion of the metering system.

Maintenance

Meters are recalibrated during the annual shutdown and whenever problems occur. Recalibration involves only the transmitters, the view being that the orifice plate itself is unlikely to be the cause of problems. The company employs an outside contractor to service the meters, although instrument engineering capability is available on-site.

Conclusions

The limited load variation on this site during the year means that the meters installed do not require high turndown ratios. Orifice plates are best suited to this type of application. After calibration, the accuracy of the orifice plate can be ±0.75% or better, together with a repeatability of ±0.25%. The meters can be used for both energy accounting and M&T.

Case History 4: Rubber Manufacturing Company

System Design
The site has an annual energy bill of £550,000, of which £300,000 is used for purchasing coal and gas for steam production. The steam is used for both space and process heating.

The metering system was designed to monitor the steam consumption of the major production centres. Five variable-area (Gilflo) meters were installed within the production system to augment the existing steam orifice plate meter at the boilerhouse.

Detailed Design
Saturated steam is supplied to the site and, because the load to individual areas varies considerably, variable-area meters were selected for their high turndown ratio. Rotary shunt meters were also considered but were rejected on the grounds of their limited turndown capabilities.

The meters were supplied with a pulsed output and readings are relayed back to the Engineering Manager's office. The site provided the manufacturer (Gervase) with basic information on pressure, temperature, and maximum and mean consumptions. The manufacturer specified the meter sizes and supervised the installation.

The aim of the installation was to provide basic information on which energy conservation measures could be based. The system is programmed so that meters are read on a weekly basis. There are no plans to install additional meters, and current concern is focused on integrating the meter readings into the site's M&T system.

Maintenance
The Gervase meters have a low maintenance requirement and, during the three years since installation, have neither been recalibrated nor had the primary elements checked. The impulse lines to the DPCs are not readily accessible and so are not blown through at regular intervals.

Conclusions
Variable-area meters are best suited to this application where steam is required for both space and process heating and where load variations can be significant. Only the key production areas are sub-metered, the system covering 80% of site steam usage. The benefits to be obtained from any additional metering were outweighed by the cost of its installation.

The considerable amount of information produced by the system is used both for energy accounting and for consumption monitoring. Until recently, no appropriate management structure existed to allow the information to be used to target consumption or to permit action to be taken on the basis of a regular assessment of steam usage. With the current implementation of an M&T system, more positive results are expected.

Few cross-checks are built into the system. Boiler plant steam production can be checked via the feed-water flow: this has shown the boiler plant export meter to be suspect.

Case History 5: Chemical Company (Cheshire)

System Design

The site has an annual energy bill of £2.5 million of which £1.2 million is spent on coal to fire high-pressure boilers. Steam is used to generate electricity and is then sold to the various production centres as a heat supply.

The metering system was designed to measure usage in each individual area. This necessitated the installation of 20 meters on the distribution system. A further 20 meters were installed within the production areas for use as checks and to subdivide usage within those areas.

Detailed Design

The provision of superheated steam around the site avoids many of the problems common to steam metering. The load is fairly constant at 70,000 ±15,000 lb/h, so most of the meters used are orifice plates with a variety of DPCs and transmitters. The site has extensive experience of orifice plates and was able to design and specify the sizes of plate required. Steam consumption was estimated by the Technical Department and the meters were sized to give 70% of FSD at full flow. If this proves to be inadequate, the transmitters can be re-ranged.

Under current procedures, the meters are read daily and the information is used for monitoring consumption levels. Total Quality Management is being introduced and it is thought that targeting of energy use will become increasingly important.

Maintenance

Meters are recalibrated on demand rather than to any pre-set schedule. However, if a meter has not been recalibrated for two years, it is scheduled for recalibration. Primary elements are rarely checked as this involves shutting down the steam main. A glycol mixture is used to minimise the risk of impulse lines freezing.

Conclusions

By deliberately oversizing the meters, their effective turndown ratio is reduced. A good orifice plate can have a turndown ratio of 5:1 after calibration, but this can be reduced to 3.5:1 by oversizing. In this particular application, such a reduction is not important as the range of steam flows expected does not exceed 2:1.

The use of glycol in the impulse lines deserves further comment. Depending on the strength of the mixture, glycol can provide protection down to –10°C, which should be more than adequate for most locations in the UK. Two problems can, however, arise:

- if the steam is to come into direct contact with foodstuffs, the use of glycol will be prohibited;
- care will be needed when blowing through the impulse lines in order to ensure that the mixture strength is equalised on both sides of the DPC.

12. LIST OF SUPPLIERS

Listing of a supplier does not constitute an endorsement of its competence and neither does non-listing of a supplier discriminate against its competence. The list will be updated at each reprint.

Company	**Telephone No**	**Type of Meter Offered**
ABB Instrumentation Ltd	01480 475321	N, O, P, Rs, Tu, W
Able Instruments	01189 311188	P
Alison Engineering	01268 526161	Th
Chell Instruments	01692 402 488	Th
Crane Perflow	020 8451 4577	O, N, P
Deltafluid Products Ltd	01744 453688	Vt
Endress & Hauser	0161 998 0321	O, P, Vt
Fisher Rosemount Ltd	0161 430 7100	O, Va, Vt
Flomar Ltd	01162 403430	O, P, Vt, Va
Flowline Manufacturing Ltd	020 8207 6565	Tu, Vt, Va
Foxboro GB Ltd	01293 526000	O, N, Vt, Tu
Industrial Flow Control	01268 540429	“V Cone”, Vt, Tu
IPL	01305 263673	Vt
KDG Instruments	01293 525151	Va, P
Liftreel	01932 247822	P
Siemens	0161 446 5270	O
Spirax-Sarco Ltd	01242 521361	O, Va, Vt
USF Wallace & Tierman	01732 771777	Va

Code

O – Orifice plate
P – Pitot tube
Vt – Vortex shedding
N – Nozzle
Va – Variable-area
Tu – Turbine
Th – Thermal
W – Wedge
Rs – Rotary shunt

13. <u>BIBLIOGRAPHY</u>

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Fuel Efficiency Booklet 2, *Steam*.

Harris, P.S. *Energy Monitoring and Target Setting Using CUSUM*. Cheriton Technology Publications, 1989.

APPENDIX 1

GLOSSARY OF TERMS

Accuracy	–	a measure of a meter’s performance in indicating a correct flow rate value against a ‘true’ value obtained by extensive calibration.
Adiabatic Expansion	–	expansion of a fluid without heat entering or leaving the system.
Bernoulli’s Theorem	–	at any point in a tube through which a fluid is flowing, the sum of the potential energy and the kinetic energy is constant.
Blowdown	–	the control of the level of concentration of dissolved and suspended solids in boiler water.
Coriolis Effect	–	the effect of rotation on a particle which is on the surface of a rotating body.
Degree Day	–	the measure of the variation of outside temperature used to determine how energy consumption is related to the weather.
Enthalpy	–	the heat content of a system given by $H = U + PV$ where U is the internal energy, P is the pressure and V is the volume of the system.
Monitoring and Targeting	–	a management technique used to maximise the potential for saving energy at a site.
Pipe Length	–	usually described in terms of the pipe diameter: thus in a 150 mm diameter pipe, ten pipe lengths would be 1.5 metres.
Repeatability	–	the ability of a meter to indicate the same value for an identical flow rate.
Reynolds Number	–	a dimensionless quantity applied to a fluid to describe the state of flow: at low flow rates (low Reynolds Numbers) flow is laminar while over a certain critical value, flow becomes turbulent.
Sensible Heat	–	the rise in temperature of a fluid as a result of the addition of heat.
Tundish	–	a piece of equipment used as a link between the ladle and the continuous caster in the steel-making process.
Turndown Ratio	–	the range of flow rates over which a meter will work within the accuracy and repeatability tolerances given: it is expressed as the ratio between the maximum and minimum flow rates. Also called the Range, Rangeability or Effective Range.

APPENDIX 2

EVALUATION OF BOILER EFFICIENCY

Once boilers have been built and installed, it is important to keep a frequent check on their efficiency. This can be achieved by periodic tests and by monitoring performance. In the UK, the relevant testing code is described by BS 2885 but this is complex and requires a quantification of all boiler losses. There are alternatives for more routine determination of boiler efficiency.

The first step is to draw a schematic diagram of the boiler installation to establish an appreciation of the various contributions to the boiler heat balance, Fig A1.

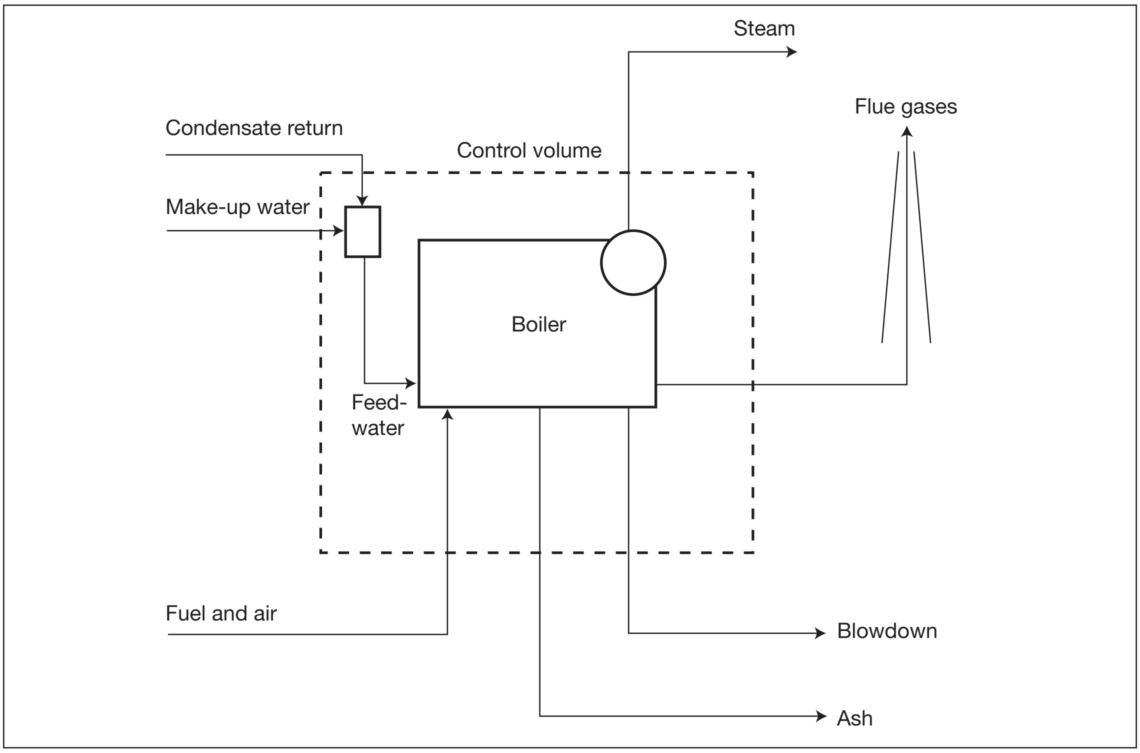

Fig A1 Streams used in calculating boiler efficiency

The efficiency of steam generation is then defined as the proportion of the calorific value in the fuel that is converted to steam output. Decide which elements of the heat balance would be expected to appear in the slope of the graph of steam output and which in the intercept and decide, using Steam Tables, what the heat content of the steam would be.

The measurement of the flue gas composition and temperature (see Fuel Efficiency Booklet No.2 *Steam*) enables a measurement of the losses of heat in the flue.

Fig A2 shows the graph of steam vs fuel input for the boiler in the textile works. The line of best fit has the formula

$$\text{Steam} = 0.337 + 0.000513 \times \text{fuel (GJ)}$$

where the slope has units of million lb per GJ. 1 lb is 0.4356 kg. The slope is therefore 0.0002235 x 0.4356 million kg/GJ or 1/0.0002235 = 4,474 kJ/kg.

This boiler produces saturated steam at 120 psig, or 726 kPa absolute pressure. The heat content of saturated steam at this pressure (obtained from Steam Tables) is 2,763 kJ/kg. The site achieves a 70% condensate return which provides a boiler feed-water temperature (measured) of 68°C, which (also from Steam Tables) has a heat content of 286 kJ/kg. The net heat added to the steam is therefore 2,763 – 286 = 2,477 kJ/kg.

The efficiency, η, is therefore

$$\eta = \frac{\text{heat in steam}}{\text{heat added as fuel}} = \frac{2{,}477}{4{,}474} = 0.554 \text{ or } 55.4\%$$

which leaves a lot of scope for improvement. Good performance would be in the range 75% to 80%. See Energy Consumption Guide 66 *Steam generation costs*.

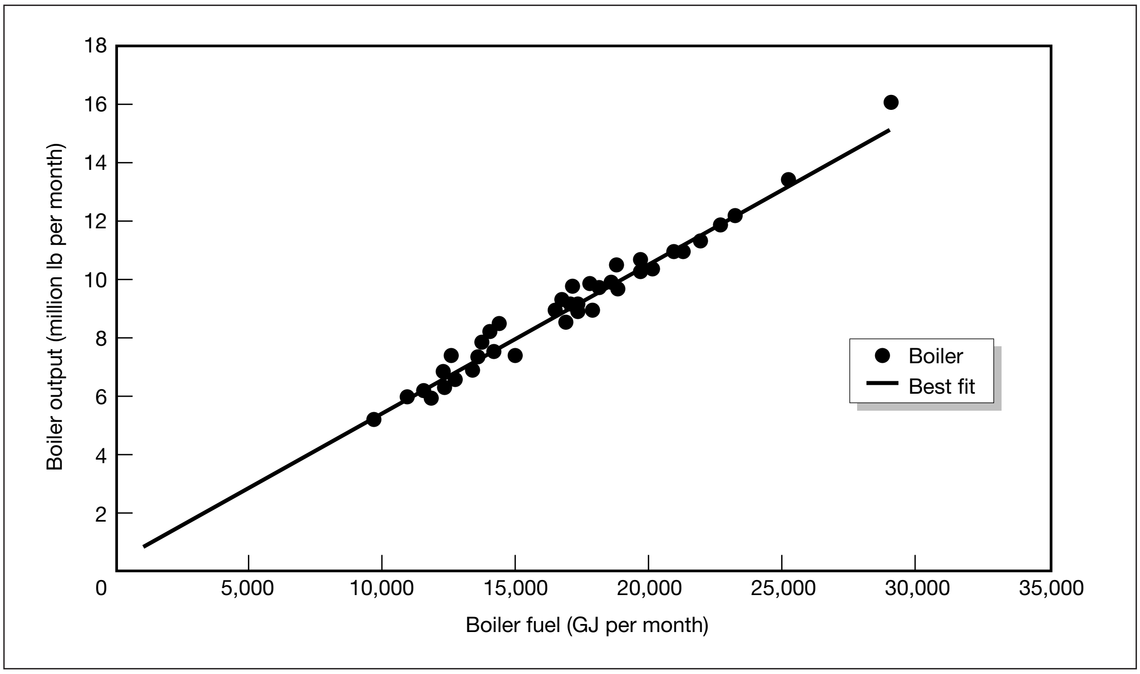

Fig A2 Boiler steam vs fuel input