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# An Introduction to Flow Metering Systems

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## Chapter 1 Introduction

#### 1.1 The Course

Books and courses about flow meters are fairly common. In practice, though, flow meters seldom work in isolation – especially in applications where large amounts of valuable product change hands. This course therefore addresses the wider topic of flow metering systems.

A flow metering system includes at least one flow sensing element, probably more than one. Depending on the application, there may be an array of supporting equipment such as analysers, densitometers, a meter prover and sampling. The resulting signals need one or more flow computers to bring them together and perhaps a station computer to combine stream values and print reports.

The reasons for needing a flow metering system instead of a standalone meter vary from one application to another, and will be discussed in detail as the course progresses. Briefly, the main ones are:

- Measuring over a wider flow range than a single meter can handle
- Determining flow in a form that the meter does not directly measure
- Providing redundancy
- Providing quality, as well as quantity, measurement

Flow metering systems are most commonly applied to oil, natural gas, and basic refined products such as diesel and gasoline. The common factor between all these fluids is that they are mixtures with no well-defined composition and therefore unpredictable properties. Properties of pure products are predictable, so some simplifications are possible where they are measured – but that is not the main topic here.

Clearly, the flow sensing element is a critical part of a flow measurement system. This course covers the main flow meter types used for high-value transactions in some detail. Additional material is provided on a few less common meter types and those likely to be encountered in secondary functions.

Despite their importance, the flow sensing elements themselves are often among the less complex components in a flow metering system. A large part of this course is therefore devoted to topics such as proving, sampling, and secondary equipment.

Flow measurement involves at least its fair share of physics, mathematics and statistics. The course therefore includes a number of brief Guides to background material, especially scientific basics. The objective is not to make the delegates feel that they are back at school and so (as their name suggests) these parts of the course are overviews, with an emphasis on giving a "feel" for the material

The goal of this course is to provide a high-level overview of flow measurement systems, and to introduce the overall context in which they operate. Over the years it has proved to be of interest to a wide range of delegates. The course is sufficient in its own right to give management with some technical background an overview of this complex discipline. Engineers starting out in the industry will have a sound basis from which to move on to more detailed study in their area(s) of special interest. Specialist engineers who have worked in a particular area of flow measurement such as software will benefit from understanding how their discipline fits into a wider context.

#### 2.6.2 An Introduction to Liquid Systems

The picture below shows a good-sized liquid metering system, using a very conventional design. More modern designs are covered later. The picture was taken in the factory during wet testing, which can be seen by the black temporary piping connected to the inlet and the outlet. The following paragraphs briefly summarise the main elements of the system. Please do not be concerned if the functions of these parts are not clear at this stage – the details are covered later in the course.



The main system elements are identified by numbers.

- 1. A single inlet flange is provided, enabling the entire package to be dropped into place quickly on site. The inlet flange is installed directly onto the end of an inlet header, which divides the flow between three metering streams. Each of the streams is rated for 50% of the design flow of the system. In principle, the third stream is therefore for redundancy though in many cases it will be used full-time if capacity needs to be increased later, so it can also be seen as contingency.
- 2. A hand operated inlet isolation valve and inline strainer are installed upstream of each meter. Less obviously, a flow conditioning element is installed in each upstream meter tube to optimise the performance of the flow meter. The inlet valves are used only to isolate each stream for maintenance and are therefore commonly left open. As stream duty selection is performed using the outlet valves, the inlet valves are not always fitted with actuators.
- 3. The meters themselves are 12" turbines, visible just to the left of the walkway. The size and weight of the meters is negligible in comparison with the system as a whole.
- 4. One high-integrity valve per stream leads to the prover header. Any one of these valves may be opened, while at the same time closing the corresponding valve to the export header, to connect one meter at a time in series with the meter prover for on-line checking (meter proving). These valves are operated frequently as part of the automatic meter proving sequence, so they are actuated for operational convenience and to allow the computer system to control them.

- 5. A further high-integrity valve per stream leads to the outlet header. These valves perform two duties. First, they are operated as part of the meter proving sequence. Second, they are used to optimise the number of flowing streams, depending on the current system throughput. Again, these valves are operated frequently under automatic control of the computer system so they need to be actuated.
- 6. The meter prover in this case is a bidirectional type. It consists of a large loop of pipe containing a spherical pig (sphere), which is commonly wrapped around the edge of the system. The vertical end chambers used to catch the sphere at each end of its travel are clearly visible to the right, and between them it is just possible to make out the four-way valve, which is used to shuttle the sphere back and forth by reversing the flow direction in the loop. The left-hand end of the prover is turned upwards, a sign that this system has been designed to fit within a space constraint. If space is very tight, the prover might even double back on itself in a "scorpion" design.
- 7. The outlets of the three streams plus the meter prover are brought together at the downstream header, and leave through a single flange in the same way as the inlet.
- 8. A platform and hoist are provided at one end of the meter prover to allow the sphere to be withdrawn from the prover for inspection and maintenance. A sampling and analysis cabinet sits beneath the platform, out of shot.

### Introduction to Flow Metering Systems

construction can be used instead of the metal construction shown, which can reduce cost as well as enhancing temperature stability.

The photographs below show the inside of two different analyser shelters.



- 10. Dual gas chromatographs continuously measure the composition of the process gas. This information is used by the flow computer system to calculate its density and the energy content. The measurement is critical to the correct operation of the system, so it is duplicated to improve availability.
- 11. The gas sample feed to the chromatographs is fed via quite a complicated conditioning system, in this case fitted inside the house. Shell Design and Engineering Practices, for example, do not allow this as it contains several potential leakage points. In this case, it would be installed somewhere outside the house.
- 12. It is common to fit extra analysers not directly associated with flow metering in the analyser shelter to take advantage of the available sample conditioning. An H<sub>2</sub>S analyser is visible in this picture. Out of shot, there is also a hydrocarbon dew point analyser. A wide range of other instruments may be encountered such as water dew point analysers, total sulphur analysers, and occasionally dedicated analysers for components of particular concern such as CO<sub>2</sub> analysers. This potentially creates a problem if the local regulator deems that everything in the house is part of the metering system, and therefore is subject to its approval.
- 13. It is common to fit DP and Pressure transducers in the analyser shelter. They are affected by ambient temperature, so it enhances their performance if they are installed in an air conditioned environment.
- 14. It is quite common for a deadweight tester to be permanently installed in the analyser shelter, and connected to the DP and Pressure transmitters by valve manifolds or flexible tubes with quick-connects. This enables routine calibration to be performed conveniently and with minimum disturbance. In this case, extra care is needed when designing the analyser house support structure to avoid movement.

It may be worth noting at this point that air conditioning is not the only way to keep sensors at constant temperature. A much simpler technique is to install them in thermostatically heated enclosures.

#### 3.6 Standard volume

The golden rule of flow measurement is: if possible, work with mass. Mass is reliable. When a certain mass flows into a pipe, then in steady conditions the same mass will flow out again. Add together the mass totals of each component in a gas, and the result is the total mass. Mass is straightforward, most people have a feeling for what it is, and as we have seen it can be directly measured.



The concept of standard volume is that we take the actual flow in the pipe and measure it. Then we pass it through an "Imaginary Process" that regulates the temperature and pressure to a well-defined set of conditions, and measure the flow again with an imaginary flow meter. The imaginary flow indicated by the imaginary meter is standard volume.

Depending on local preference, the conditions at the outlet of the Imaginary Process may be:

- 1.01325 bar a and 15°C
- 14.696 psi a and 60°F
- Various other options, for example 20°C in Australia, 30°C in Thailand

It is impractical to build the Imaginary Process, so we have to invent some mathematical way to decide what the imaginary meter will read. Because the mass that enters the process must balance with the mass that leaves (Section 3.3.1) it is possible to write a very simple equation:

 $q_m = q_v \times \rho = q_s \times \rho_s$ 

In words, the mass flow is equal to the real volume flow multiplied by the real density, and it is also equal to the standard volume flow multiplied by the density at standard conditions. Rearranging the equation in terms of standard volume:

$$q_s = \frac{q_m}{\rho_s} = q_v \times \frac{\rho}{\rho_s}$$

Calculating the standard volume therefore comes down to developing a model of the effect on the product density of regulating the temperature and pressure to standard conditions. Many standards and calculation methods exist for different products and situations. The popular API equations for Crude Oil introduce some additional terms that simplify the calculations, but at the cost of obscuring the principles -

#### 4.10 Summary of Liquid Flow Meters

The black-and white selection chart below is from the API Manual of Petroleum measurement standards chapter 5.1, which was last revised in 2005. It does not cover ultrasonic or Coriolis meters. The API chart reflects the point that larger turbine meters are more tolerant of high viscosity. Notice also that small PD meters are considered acceptable for very low viscosity service, which is borne out by their widespread use in gasoline stations.



Superimposed on the main chart is the region where an ultrasonic meter might be considered. It is placed as it is because of the potential problems with small ultrasonic meters and high viscosity. Some manufacturers may be able to supply meters that operate outside this area.

Coriolis meters are not shown, because they are available in all but the largest sizes and tolerate almost any viscosity. The Coriolis region would therefore cover almost the entire chart. However, the decision to use a Coriolis meter is affected by whether mass flow is the desired measurement – deriving standard volume from mass involves an additional term compared to volume meters, and therefore increases its uncertainty. It is also more difficult to prove Coriolis meters.

The table below gives a very rough personal set of rankings for different types of meter, with 1 as the best. Rating generic meter types is subjective as so many variants are available, so others are free to differ.

Туре	Proving	Size Range	Contamination	Size & Weight
Turbine	1=	1=	3	1
PD	1=	1=	4	4
Ultrasonic	3	4	1	2
Coriolis	4	3	2	3

#### 5.5 Uncertainty Calculations

When a user buys an expensive metering system, the single most important objective is to achieve a given measurement uncertainty – and to do so demonstrably. The uncertainty calculations are therefore as much a key part of a metering system as its physical components, and no discussion of high-accuracy metering would be complete without a reference to them.

This is a brief introduction designed to give a general idea of what is involved. It departs from the style of the rest of the course by interspersing the course material with a detailed, though admittedly highly artificial, exercise. A full course in uncertainty is available for those who wish to pursue it further. For obvious reasons the solution is only given in the course slides.

Achieving and maintaining a required uncertainty affects metering systems in many ways, for example:

- It determines the choice of instruments
- It determines the number of streams
- It has operational consequences such as frequency of meter proving
- It has maintenance consequences such as choice of test equipment

The principles of uncertainty calculations are not hard to follow if you do not mind some statistics, but the practicalities justify their reputation for being difficult. The main steps in performing an uncertainty analysis are:

- Identify the uncertainty to be calculated
- Gather all uncertainties
- Convert them to a common basis
- Combine them
- Report the result in the required manner

#### 5.5.1 How long is a Piece of String?



A piece of string about 250mm long is measured using a metal ruler with 1mm increments. Working in groups:

1) Brainstorm the potential sources of measurement uncertainty (if you have experience of HAZOP analysis you could apply similar techniques).

2) Categorise the sources of uncertainty according to whether you would expect them to:

- a) Be the same for every measurement over a reasonably extended period
- b) Change between measurements made in quick succession
- c) Change between measurements made on different days

3) Identify errors that you consider may change when the measurement is made by different observers, and mark them with (d).

#### 8.1.1 The Backflush Column

The components that enter the GC are not controlled, and if some very heavy component were to arrive it could take a long time to exit. If a single column were used it would be necessary to allow enough time to allow the heaviest possible component to make its way through the column. That could be quite a while, and the exact length of time is not known in advance. This problem is solved using a backflush column.



In the diagrams above, the backflush column is on the left and the main column (there may be more than one in practice) is on the right. At the beginning of an analysis run flow is forward, and the two columns are connected together. After a predictable amount of time, all of the components of interest will pass through the backflush column and start to be separated in the more sensitive main column. Heavier components that will not be analysed in detail remain in the backflush column.

The backflush column is now connected to the detector, and flow is reversed. This ejects all the heavy components. By symmetry, any separation that took place during forward flow is now reversed, so all the heavy components leave together and can be detected as a single "virtual" component.

Analysis in the main column can now continue. Because the range of components that entered the main column is controlled, the analysis time can be fixed.

#### 8.1.2 Calibration and Carrier Gas

A gas chromatograph is not a particularly stable device. It therefore needs a bottle of reference gas with a known composition, which it uses to adjust itself periodically. This is most often done every 24 hours, and at this rate a bottle of calibration gas lasts for about six months. Other frequencies are possible.

There are various ways of blending calibration gas, the most common being gravimetric. Each bottle is supplied with its own calibration certificate, from which the composition must be entered in the GC (or its controller if it is separate). The smaller the percentage of a component, the more difficult is it to control it accurately. There is a school of thought that believes that it is therefore a good plan to "enhance" the heavy components in calibration gas to improve the blend accuracy. There is a flaw in this thinking ...

At best, using an unrepresentative calibration gas increases the uncertainty by a known amount. At worst, it increases it by an amount that cannot be calculated. The increase is because a GC has a linearity. The reason why the increase may be impossible to calculate is that it is expensive to do a linearity check on a GC, so an accurate linearity figure is often unavailable. Sometimes a generic specification figure is not available either.

#### 9.4 Energy and Reactions

It was mentioned briefly in the introduction that atoms trade electrons with other atoms when it is energetically favourable to do so. Atoms do not mate for life, however. If an opportunity arises for the atoms in a system to rearrange themselves in a way that is even more energetically favourable than they have already found, they are quite willing to do so. One form of this process is known as "burning", and another is known as "exploding".

Those of you who have open fires at home will have noticed that they do not light themselves. The diagram on the right is a slightly tongue-incheek representation of what is going on at a chemical level. State 2 (burnt) has a lower energy level than State 1 (not burnt), which means that it is more stable and so energetically favourable. However,



there is an energy "hump" that has to be overcome in order to get from one state to the other – and that is where a match comes in. Once the match has provided enough energy to enable the first few molecules to react, the energy they release enables their neighbours to react, and so on. In other words, burning – like most chemical processes – is a chain reaction.

The size of the energy hump – more formally known as the ignition energy – varies from one hydrocarbon to another. The rather vague statement that unsaturated hydrocarbons are not as stable as saturated hydrocarbons could therefore be made to sound more scientific by saying that their ignition energy is lower. The wording of the previous sentence is carefully chosen: the measurement of ignition energy is actually a bit of an art, and the results should be treated with caution. One procedure gives the following ignition energy values in mJ:

Methane (CH <sub>4</sub> )	0.28
Ethane (C <sub>2</sub> H <sub>6</sub> )	0.24
Ethylene (C <sub>2</sub> H <sub>4</sub> )	0.07
Acetylene (C <sub>2</sub> H <sub>2</sub> )	0.017

When we come to look at hazardous areas, we will see that Ethylene demands extra care when protecting against explosion hazards. This is simply because it can be ignited by a smaller spark.

#### **Burning Hydrocarbons**

The process of burning hydrocarbons can be formally described by chemical equations such as:

 $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ 

In words, one molecule of Methane combines with two molecules of Oxygen to produce one molecule of Carbon Dioxide and two molecules of Water. This reaction releases about 50.029 MJ per kg of Methane burnt – assuming that the water leaves as vapour. If the water is condensed, it releases heat as it turns to liquid and adds about 10% to the total energy output, increasing it to 55.516 MJ per kg of Methane burnt. This is the principle that condensing boilers use to boost their energy output. You may remember from an earlier session that these figures are called the "Inferior" and "Superior" calorific values.



Each set of water draw runs consists of at least three measurements of the volume of the prover. For a bidirectional prover, the prover volume consists of a complete round trip of the sphere. For a compact prover, five measurements should be considered. If a set of runs is consistent within  $\pm 0.02\%$ , it is accepted and the average taken.

Because the tank is vented to atmosphere the pressure in the prover while water is collected will be consistent at constant flow. Repeatable results may therefore be obtained even if a small leak is present (including leakage past the sphere). A second set of runs is therefore performed at a significantly different rate of flow from the first. Any shift between the two sets indicates leakage, which must be investigated.

Finally, a third set of runs is performed at the original rate of flow. The result of the calibration is the average of the three sets of runs.

Most large-volume provers have four detectors for redundancy, so four volumes need to be calibrated and then entered in the flow computer system. If the spacing between the detector pairs at each end of the prover is the same, two of the prover volumes will be very similar. In this case particular care is needed to ensure that the new volumes are entered in the correct order.

#### 13.2.2.2 Use of Water

The top of the tank must be open to atmosphere for it to operate properly, so hydrocarbons cannot be used for safety reasons. Water has several advantages as a calibration medium, and a few disadvantages:

- It is non-hazardous
- It is cheap and readily available
- When the tank is drained, water runs off the walls of quickly (but see below)
- It is comparatively non-volatile, and therefore does not lead to evaporation errors as long as the run time is reasonably short.
- It has a low thermal expansion coefficient compared to hydrocarbons, so temperature differences between the prover and the tank do not make a large contribution to the uncertainty. The density vs. temperature relationship of <u>pure</u> water is well-known (though non-linear) so the necessary small

#### 14.3 Standards

This section lists a selection of the wide range of available standards relating directly to flow measurement that are most frequently mentioned in specifications in the author's experience. A great many other standards are also indirectly relevant, for example the ASME standards on pressure containment, but they would make the list far too long (and hard to maintain).

A few niche standards are mentioned that might otherwise not be noticed, along with some particularly relevant general standards. A few words of explanation are sometimes added in *italics*. For a more wide-ranging discussion of standards, you may wish to consider the separate Flow Calculations course.

Although flow measurement is a conservative industry, there have been a comparatively large number of updates in the last few years. Years of standards below are updated on a "best endeavours" basis and may be incorrect even at the time of going to press. It is advisable to check the relevant web sites to see if standards have been updated before quoting them.

#### 14.3.1 AGA Standards

#### AGA 3 - Part 1: 2012

Orifice Metering of Natural Gas Part 1: General Equations & Uncertainty Guidelines

#### AGA 3 - Part 2: 2000

Orifice Metering of Natural Gas Part 2: Specification and Installation Requirements

#### AGA 3 - Part 3: 2013

Orifice Metering of Natural Gas Part 3: Natural Gas Applications

#### AGA 3 - Part 4: 1992

Orifice Metering of Natural Gas, Part 4: Background, Development Implementation Procedure

#### AGA 5: 2009

Fuel gas energy metering.

#### AGA 8: 1994

Compressibility Factor of Natural Gas and Related Hydrocarbon Gases.

#### AGA 9: 2007

Measurement of Gas by Multipath Ultrasonic Meters.

#### AGA 10: 2003

Speed of Sound in Natural Gas and Other Related Hydrocarbon Gases

#### AGA 11: 2013

Measurement of Natural Gas by Coriolis Meter.

#### 14.3.2 GPA Standards

#### GPA TP-15: 2007

Simplified Vapor Pressure Correlation for Commercial NGL's (dual-numbered API MPMS 11.2.5)

#### GPA TP-25: 1999

Temperature Correction for the Volume of Light Hydrocarbons Tables 24E and 23E.

Now superseded by TP-27, but with only minor changes.

#### GPA TP-27: 2007

Temperature correction for the volume of NGL and LPG (dual-numbered API MPMS 11.2.4)

#### GPA 2145: 2009

Table of Physical Constants for Hydrocarbons and other compounds of interest to the Natural Gas Industry

#### GPA 2172: 2009

Calculation of Gross Heating Value, Relative Density and Compressibility Factor for Natural Gas Mixtures from Compositional Analysis.

This standard is used in conjunction with GPA 2145 for calorific value at 60°F reference conditions and combustion temperature.

#### 14.3.3 ISO Standards

#### ISO 2186: 2007

Fluid flow in closed conduits -- Connections for pressure signal transmissions between primary and secondary elements

#### ISO 2715: 1981

Liquid hydrocarbons -- Volumetric measurement by turbine meter systems

#### ISO 3170: 2004

Petroleum liquids -- Manual sampling

#### ISO 3171: 1988

Petroleum liquids -- Automatic pipeline sampling

#### ISO/TR 3313: 1998 (withdrawn)

Measurement of fluid flow in closed conduits -- Guidelines on the effects of flow pulsations on flowmeasurement instruments. *Now withdrawn, but still the most definitive source on the subject.* 

#### ISO 5024: 1999

Petroleum liquids and liquefied petroleum gases -- Measurement -- Standard reference conditions

#### ISO 5167-1:2003

Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -- Part 1: General principles and requirements