# Still Going Strong – Why Venturi Tubes Continue to Enjoy Enduring Popularity in the Oil and Gas Industry

**Harry Lawrence, DP Flow Product Manager, ABB Limited,** Oldends Lane, Stonehouse, Gloucestershire, GL10 3TA. Tel: +44 (0)1453 826661; Fax: +44 (0)1453 827856. Email: harry.lawrence@gb.abb.com, Web: www.abb.com/instrumentation

*Despite being based on technology which is over 100 years old, Venturi Tubes continue to be a widely applied form of flow measurement in the Oil and Gas Industry. In this article, Harry Lawrence, Flow Product Manager for ABB Limited, explains the basic principles involved in the measurement of flow using differential pressure (DP) producers and the reasons for the enduring popularity of the technology for Oil and Gas applications.*

The origins of differential pressure measurement can be traced back to 1738, when Italian mathematician Daniel Bernoulli determined that the total energy (kinetic + pressure + potential) within a flowing fluid is constant. Some 60 years later, another Italian - Giovanni Battista Venturi - determined that a fluid flowing into a restriction gains kinetic energy (velocity) at the expense of pressure and that some of the pressure is recovered when the fluid leaves the restriction.

Almost 100 years after this, in 1887, an American named Clemens Herschel applied the earlier findings of Bernoulli and Venturi into the design of a flow meter which he very generously named the Herschel Venturi Tube in acknowledgement of the pioneering work of the Italian. Today they are commonly referred to simply as Venturi Tubes.

## Design

The general design of a Venturi Tube is simple, as can be seen from Fig 1.

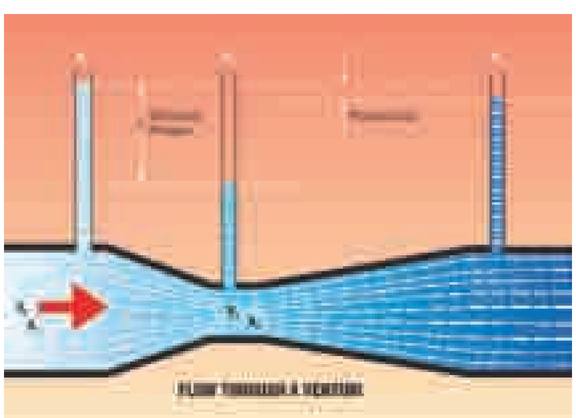

*Figure 1*

It consists of a parallel inlet section of the same diameter as the pipe, followed by a coned reduction (typically 21° included angle) and a parallel throat section. The outlet is also conical, but with a shallower angle (typically 15°) than the inlet. The outlet cone either finishes at the same diameter as the pipe (referred to as Classical Venturi – the most common design) or at a diameter smaller than that of the pipe (a Truncated or Short Venturi). The high (i.e. upstream) pressure tapping is located just before the inlet cone and the low (downstream) pressure tapping is at the centre of the throat section.

When the measured fluid – which can be a liquid or a gas or even a mixture of the two – flowing at a velocity v1 through a pipe of cross-sectional area A1 passes through the restriction, the area of the fluid path is reduced (A2) and consequently the fluid has to move at a higher velocity (v2) to maintain the same flowrate. This is a consequence of the continuity equation, which also includes the fluid density (ρ):

$$\textit{Mass Flowrate } Q = \rho.A1.v1 = \rho.A2.\ v2$$

For the common requirement for Volumetric measurement at constant fluid density, this simplifies to:-

$$\textit{Volume Flowrate } Q = A1.v1 = A2.\ v2$$

As the velocity increases, the Kinetic Energy (which equals ½ * mass * velocity2) also increases. As the Law of Conservation of Energy states that energy cannot be created or destroyed, this increase in kinetic energy must be at the expense of some other form of energy. In this case it is the Pressure energy that is reduced, leading to a lower pressure in the Venturi throat P2 compared to that upstream of the throat P1. This differential pressure or DP has a value of (P1 - P2).

In the pipework downstream of the device, the pressure recovers partially to P3, such that the device causes a loss of some of the line pressure (P1 – P3) but a smaller loss than the generated differential pressure. The relationship between velocity and differential pressure provides the basis on which all differential pressure devices operate.

Each DP device deviates to some extent from the calculated (i.e. theoretical) relationship, which is based on the ratio of restriction diameter to pipe diameter. One reason for this is that when the fluid passes through the restriction, it continues to 'converge' for a short distance after the restriction throat. This means that the minimum diameter of the fluid "jet" (called the Vena Contracta) can be smaller than the throat of the restriction and the velocity in it is therefore higher, as shown in Fig 2.

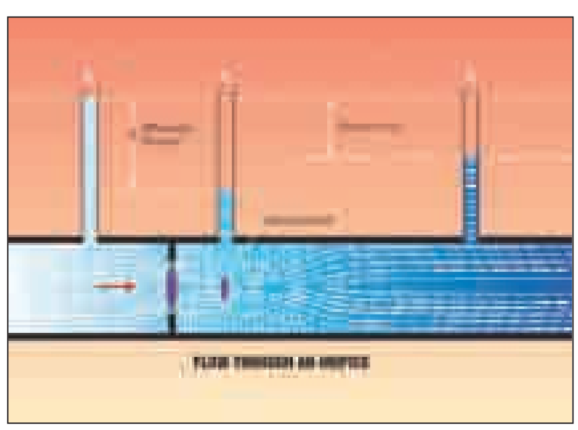

*Figure 2*

Consequently the actual pressure reduction is greater than that calculated from the restriction diameter. To correct for this (and for other non-ideal effects), a Coefficient of Discharge (usually referred to as C) is applied. The ideal value of this coefficient would be 1.0 but the actual value varies from one class of DP device to another. It also varies within a given class of device, depending on the β-ratio (the ratio of the restriction diameter to the pipe bore diameter).

In the case of the Venturi, the flow path through the device is smooth and controlled, leading to only a minimal correction being required. The value of C for a Venturi tube is typically in the region of 0.98 – 0.995, compared to typically 0.6 – 0.65 for an orifice plate. Comparing Fig 1 (for a Venturi with no obvious vena contracta) and Fig 2 (for an orifice plate with a noticeable vena contracta), the reason for the difference in the value of the coefficient becomes more apparent.

The relationship (much-simplified!) between flowrate Q, coefficient C and differential pressure h is :-

$$Q = k1.C.\sqrt{h}$$

$$\text{or } h = k2.Q2\ /\ C2$$

The "constants" k1 and k2 depend upon the fluid properties, the working conditions and the pipe size, but if those are fixed then the values of (k1.C) and (k2.C) are also constant.

This leads to an even simpler basic relationship of:

$$Q \propto \sqrt{h}$$
$$\text{or } h \propto Q2.$$

This latter expression makes clear why a doubling of the flowrate through a differential producer causes the generated DP to increase by a factor of 4 (i.e. 22); if the flow is halved, the DP is reduced by a factor of 4. This is referred to as a square law relationship.

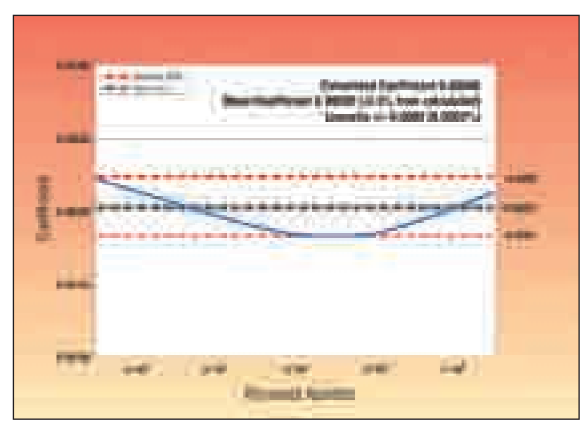

*Figure 3*

In using the meter to measure the flowrate, it is necessary to know the differential pressure generated and this is usually achieved using a differential pressure transmitter. Modern DP transmitters can easily correct for the square law in the measurement, making the output linear to flow.

Furthermore, multi-variable DP transmitters are available which enable mass flowrates of gases to be measured. They measure both DP and static pressure and accept a temperature input, with onboard computation of mass flowrate.

A theoretical value of the coefficient C is derived from empirical data contained within international standards, the most commonly used of which is ISO 5167: 2003. The uncertainty of this coefficient varies with the device and the flowing conditions but is typically 0.6

– 1 %. To achieve better overall performance, the actual coefficient for the unit “as manufactured” is needed and for this it is necessary to flow calibrate the unit at flowrates as near as possible to the flow range of the specific application. The calibration of the Venturi should preferably be performed together with its DP transmitter and is achieved by passing known volumes of water through the unit in various measured time intervals. The results of a calibration are usually plotted in terms of actual coefficient (calculated from the properties of the fluid used in the calibration, the flowrates and the differential pressures that those flowrates generated) against Reynolds Number and the linearity of the device over the desired flow range is then determined from that data see example in Fig 3.

Reynolds Numbers are a means of comparing the dynamics of two or more flow systems which are geometrically similar but dimensionally different. For example, it would be valid in the comparison of these two situations:-

1. Water flowing in a full, circular pipe of 24” (600 mm) diameter.
2. Oil flowing in a full, circular pipe of 6” (150 mm) diameter.

The geometric similarity must be maintained and consequently the same direct comparison could not be made if one was, for example, in a pipe of rectangular cross-section and the other in a pipe of circular cross-section.

The Reynolds Number is given by:-

$$Re = \frac{v.d.\rho}{\mu}$$

***where:*** ***v = average fluid velocity in m/s ( ft.s-1 in US units)***
***d = local diameter of pipe in m ( ft in US units)***
***ρ = density in kg/m3 (lb.ft-3 in US units)***
***μ = dynamic viscosity in kg.m-1.s-1 ( lb.ft-1.s-1 in US units)***

The Reynolds Number is dimensionless (i.e. has no units) and is a particularly useful means of comparing or predicting the performance of flowmeters under different conditions (of density, viscosity, flowrate, etc.). Venturi tubes vary greatly in size and flow capacity, making the prediction of their performance over a wide range of fluids and pipe sizes difficult. This prediction can, however, be achieved by expressing the coefficient in terms of the application Reynolds Number (which involves pipe diameter, velocity and fluid properties).

In addition it permits a common fluid such as water to be used as the calibration medium, even for a device that will ultimately be used on a totally different liquid (e.g. oil, HC liquid, etc). It even enables a water calibration to be sensibly performed for a device that will be used on gas. Gases, however, have very low viscosities and tend to be transferred at high pipeline velocities. As can be quickly deduced from the Reynolds Number formula, this leads to very high Reynolds Numbers being generated – values much higher than those normally achievable using water as the calibrating medium.


However, the requirement often arises for the calibration medium to be in the same “phase” as the application so as to better establish the coefficient and its stability. These factors together lead to some devices being calibrated using gas – a complex and costly operation often requiring the use of specialist third party gas calibration centres.

If a water calibration is acceptable, some manufacturers have suitable water calibration rigs in-house, enabling them to offer economic flow calibrations. The alternative for those who do not have such in-house facilities is to use third party water calibration centres, but this usually involves additional expense and delay.

In recent years the use of Venturi meters has been extended into the field of sub-sea measurement and processing, where their attributes make them particularly suitable for the hostile environments found in such applications. For example they are suitable for fabrication in specialist corrosion-resistant materials such as Super Duplex, Monel™, Inconel™, etc. They can also be designed for the high process and ambient pressures routinely found in sub-sea applications and are suitable for the multi-phase fluids found in production (oil + gas + water + sand). It is also relatively easy to integrate specialist sub-sea DP transmitters, cabling systems and manifolds with the Venturi assemblies.

## Conclusion

The basic technology of the sensor may be mature, but it still has a large role to play in the Oil & Gas Industry. Why ? Because it is a simple, well understood technology yet is accurate (even more accurate when calibrated), economical (even in large sizes and in special materials), can be used at high pressures and/or temperatures and is suitable for almost all of the liquids and gases that the Oil & Gas Industry needs to measure. Add to all this the availability of sub-sea and multiphase versions and the case for Venturi Meters is overwhelming.

Is Venturi technology mature? Definitely! Is it outdated? Absolutely not!

### Advantages of DP devices

Some of the advantages users gain by using DP flowmeters are :-

- Mature established technology
- Available in a wide size range
  - 2 inch to 48 inch, and larger !
- No moving parts
- Performance of device can be calculated from measurement of key dimensions
- Basic uncertainty can be calculated without calibration
  - calibration can further reduce the uncertainty
- Applicable to a wide range of liquids and gases
- Available in a wide range of materials to suit process fluid/conditions
- Designs available for high temperatures and/or pressures

The Venturi Tube offers further advantages over other DP devices :-

- Significantly lower pressure losses
  - leading to reduced pumping/compression costs
- Good performance even at high ß-ratios (i.e. large ratio of bore diameter to pipe diameter)
- Less affected by upstream disturbances
- Profile resists the effects of wear
  - offers a particularly stable calibration
- Tolerant to presence of some solids in the fluid
- Suitable for passage of multiphase flows and wet gas
  - requires application of special algorithms to process.

In the Oil and Gas Industry, Venturi Tubes are found in many applications, such as : -

- Sub-sea metering
  - MEG injection
  - Water injection
  - Oil/gas/water production
- Topside and on-shore metering
  - oil
  - dry gas
  - wet gas
  - produced water