INTRODUCTION

The V-Cone meter is a differential pressure (DP) type meter patented by McCrometer Inc., a subsidiary of Danaher Corporation. The V-Cone meter is in many respects a classical DP meter using the physical laws of the conservation of mass and energy as its principle of operation. However, there are important differences between the V-Cone meter design and other DP meter types. These differences give the V-Cone meter important performance advantages. These advantages include the ability of the V-Cone meter to operate with very short upstream and downstream straight pipe lengths, to create a low total pressure (or “head loss”), to create a very stable DP, to give a large turn down, to create relatively low signal noise and to cope well with liquid and particulates in the gas stream. The aim of this paper is to discuss the design of the V-Cone meter and explain why this design gives these advantages over traditional DP meters.

1. The V-Cone Meter is a DP Meter

The V-Cone meter like several other popular meters is a differential pressure (or “DP”) meter. These meters all work according to the same principle. That is an obstruction in the pipe (i.e., a reduction in the cross sectional area available to the flow) causes an increase in flow velocity and a corresponding reduction in pressure. Hence by measuring the upstream pressure, the temperature and the difference in the static pressure between the upstream and the minimum cross sectional areas the flow rate can be determined as long as the fluid properties are known. The flow rate determination is done by applying the laws of conservation of mass and energy.

The difference in the DP meter designs is the particular geometry of the primary element (in particular the obstruction in the pipe creating the pressure and velocity change). With the traditional DP meters the obstruction has consisted of blocking the outside of the flow area in various ways thus forcing the fluid to accelerate through a reduced opening in the centre of the pipe line. Examples of this are the Orifice Plate, Venturi and Nozzle meters as shown in Figure 1.

The Orifice Plate is a plate with a hole in the center inserted between two pipe flanges. The Nozzle is a contoured converging section (or “nozzle”) discharging uncontrolled into the full pipe area and the Venturi (sometimes called “Venturi Tube”) has a converging section (or “nozzle”), a length of straight pipe of reduced area comparative to the upstream pipe (or “throat”) and a diverging section (or “diffuser”) to allow a controlled discharge. Clearly these meters all accelerate the flow towards the center line of the pipe. The V-Cone meter does the opposite. It accelerates the flow to the outside of the pipe by having a cone positioned pointing up the center line of the on coming flow. Figure 2 shows the geometry of the V-Cone.

From Figure 2 it can be seen that the V-Cone meter upstream tapping (denoted “H” to indicate the high pressure port) is on the wall of the pipe but the downstream tapping (denoted “L” to indicate the low pressure port) is not on the wall of the pipe but on the back face of the cone on the pipe center line. This is a radical departure from the traditional DP meter designs and this design gives some significant performance improvements which will be discussed in chapter two.

The different geometry can cause some engineers to wonder if the V-Cone meter operates according to a different principle than the traditional DP meters but this is not so. The governing flow equation for the V-Cone is identical to that of all other DP meters. From the user’s point of view all secondary equipment used is exactly the same as would be chosen for any DP meter. That is the same manifolds, DP transmitters and Flow Computers are used as are used with other DP meters.
(with the flow computer requiring the V-Cone equation just as it requires the unique equation for any DP meter). Therefore use of a V-Cone meter requires no further understanding than that knowledge required to use any other DP meter. Figure 3 illustrates the typical set up of any DP meter.

**FIGURE 3. A typical DP meter set up.**

Now that it is known that the V-Cone meter is similar in set up and use to all other DP meters the differences caused by having a cone in the primary element can be discussed.

2. The Differences (and Advantages) Between V-Cone Meters and Traditional DP Meters

2.1) The Flow Equation

All DP meters work according to the principles of the conservation of mass and energy. This results in equation 1.

\[ m = EYCdAd \sqrt{2\rho \Delta P} \]  \hspace{1cm} (1)

where

- \( m \) is the mass flowrate
- \( E \) is the “Velocity of Approach Factor” \( \sqrt{ } \)
- \( Y \) is the expansibility factor.
- \( C_d \) is the discharge coefficient (i.e. the ratio of the actual to theoretically predicted flowrates).
- \( A_d \) is the minimum cross sectional area through the meter.
- \( \rho \) is the fluid density.
- \( \Delta P \) is the measured differential pressure.
- \( \beta \) is the square root of the ratio of the minimum flow cross sectional area through the meter to the inlet cross sectional area.

Depending on specific DP meter geometries some of the above parameters are calculated in different ways. For the V-Cone the following should be noted.

a) Due to the different geometry the V-Cone meter beta ratio is not calculated by the standard equation 2 but by equation 3.

\[ \beta_{Traditional} = \sqrt{\frac{A_d}{A}} = \frac{d}{D} \]  \hspace{1cm} (2)

\[ \beta_{V-Cone} = \sqrt{\frac{A_d}{A}} = \sqrt{1 - \left(\frac{d_c}{D}\right)^2} \]  \hspace{1cm} (3)

where \( A \) is the upstream pipe cross sectional area, \( d \) is the traditional throat diameter, \( D \) is the upstream pipe diameter and \( d_c \) is the cone diameter. Figure 4 illustrates the origins of these equations.

**FIGURE 4. The Difference in beta calculations between the V-Cone and traditional DP meters.**

b) Clearly the calculation of the minimum cross sectional area for the V-Cone meter will be different to the traditional DP meters. The comparisons are shown in equations 4 & 5.

\[ A_{dTraditional} = \frac{\pi}{4} d^2 \]  \hspace{1cm} (4)

\[ A_{dV-Cone} = \frac{\pi}{4} (D^2 - d_c^2) \]  \hspace{1cm} (5)

**b) The Expansibility (Y) Equation**

For all DP meters including the V-Cone meter if the fluid flowing is liquid the expansibility factor is effectively unity as the expansion factor corrects for changes in density through the DP meter and liquids are effectively incompressible. If the fluid is a gas however the flow is compressible and the correction factor is required. The
Orifice Plate meter has an experimental expansibility equation as shown in equation 6. The V-Cone meter has had its expansibility equation found by experiments at NEL in the UK [1]. The V-Cone meter expansibility equation is shown in equation 7.

Orifice Plate Meter: \( Y = 1 - (0.41+0.35\beta^4) \frac{\Delta P}{kP_1} \) (6)

V-Cone Meter: \( Y = 1 - (0.649+0.696\beta^4) \frac{\Delta P}{kP_1} \) (7)

\( \kappa \) is the isentropic exponent and \( P_1 \) is the upstream pressure. Again it is clear that the V-Cone meter behaves similarly to other DP meter devices.

d) The Discharge Coefficient, \( C_d \) and Meter Calibration

For all DP meters the discharge coefficient is defined as shown in equation 8.

\[
C_d = \frac{m_{\text{actual}}}{m_{\text{theoretical}}} = \frac{m_{\text{actual}}}{EY_A \sqrt{2 \rho \Delta P}}
\] (8)

Where \( m_{\text{actual}} \) is the actual flowrate and is the theoretical flowrate calculated by consideration of the mass continuity equation and Bernoulli (energy) equation.

V-Cone meters need to be “calibrated” to find the value of the discharge coefficient. Calibration for all DP meters consists of using a reference meter of extremely low uncertainty (which gives a flowrate value as close to the actual flowrate as can practically be managed) upstream of the DP meter in question and fitting the results to equation 8. Over a large turn down (a wide range of flowrates) V-Cone meters are found to have a discharge coefficient which is a function of the upstream pipe flow Reynolds number. For small turndowns an averaged discharge coefficient is often sufficiently accurate for many applications. Figure 5 shows a typical V-Cone meter calibration.

Note that in Figure 5 the discharge coefficient line fit is quoted to have an uncertainty of 0.5%. This is the quoted uncertainty for all V-Cone meters. To achieve this McCometeter calibrates all meters over the operational range of the flow.

The latest version of ISO 5167 [2] recommends that Venturi meters should be calibrated for flows where the Reynolds number is greater than one million. Thus, the Venturi and V-Cone meters have similar calibration requirements. Orifice Plate meters (and Venturi meters at Reynolds numbers lower than one million) do not need to be calibrated as long as the upstream and downstream flow conditions are met as then the discharge coefficient can be read off a table [2]. However, these upstream and downstream straight lengths are considerable and as the V-Cone meter does not need these extra pipe lengths (see section 2.2) the weight and space saved by a V-Cone meter can match the extra cost of the pipe work or flow conditioner required making the V-Cone meter extremely competitive.

For any given V-Cone meter (or any other DP meter) if a constant discharge coefficient is used then with a read upstream pressure and differential pressure and with the fluid properties known equation 1 can be directly applied. If any given V-Cone meter (or any other DP meter) has a line fit describing the discharge coefficient to the Reynolds number relationship found by calibration then an iterative solution is required. The Reynolds number is calculated by equation 9. The iteration for a V-Cone meter (or any other DP meter) is given by equation 10. A starting flowrate for the iteration is recommended to be that found by initially considering the discharge coefficient to be unity. This ensures a quick convergence of the iteration.

\[
Re = \frac{4m}{\pi \mu D}
\] (9)

where

- \( Re \) is the flows upstream Reynolds number
- \( m \) is the mass flowrate
- \( D \) is the upstream pipe diameter
- \( \mu \) is the fluid viscosity

\[
m = \left( EYA_d f \left( \frac{4 m}{\pi \mu D} \right) \sqrt{2 \rho \Delta P} \right) = 0
\] (10)
4m

\[ C_d = f(Re) = f \left( \frac{4m}{\pi \mu D} \right) \]

2.2) Flow Conditioning

An advantage the V-Cone meter has over other meters is that it is a flow conditioner as well as a flow meter. This results in the meter having the ability to operate in installations where other meters in the market (DP and non-DP meters) cannot. With space and weight in many industrial applications being important the savings in space, weight and cost of avoiding the requirement for large straight lengths of pipe upstream and downstream of the metering station by using a V-cone meter can be considerable.

The V-Cone meter will continue to operate as the upstream length is reduced to less than the minimum allowed by other meter designs. In fact V-Cone meters have been installed successfully directly onto the downstream flange of various pipe disturbances (e.g. 90° bends, out of plane double bends, valves etc) and continued to give reliable readings. Figures 6 and 7 show the difference in using an Orifice Plate meter and a V-Cone meter in a confined space. The test graphs are courteously of NIST.

2.3 A Stable Differential Pressure

With the V-Cone meters unique positioning of the downstream pressure port on the back face of the cone the differential pressure is very stable. In fact, with the downstream port not in direct contact with the flow past the minimum cross sectional area, what is in reality being read is the pressure created by the vortices generated behind the cone. The strength of these vortices (and hence the magnitude of the DP read) is dictated by the shear force of the jet coming off the end of the cone. Hence, the vortices strength is a direct indication of the flowrate.

Figure 8 shows a sample result of experiments conducted to show the relative fluctuation in the DP readings of a \( \frac{1}{2} \)" Orifice meter and a \( \frac{1}{2} \)" V-Cone meter. The parameter \( \delta \) is the standard deviation of the DP around its mean.

Clearly the V-Cone has less pressure fluctuations than the Orifice Plate meter. Figure 8 is from an internal McCrometer report [5].

2.4) The V-Cone Meter Turn Down

The V-Cone meters turndown (i.e., the ratio of highest to lowest readable flow with in the quoted 0.5% uncertainty) is 10:1 for a single DP transmitter. This is considerably higher than other DP meters (e.g., an Orifice Plate turndown for a single DP transmitter is typically 3:1). This performance is due to the positioning of the downstream pressure port on the back end of the cone and the stability of the DP signal produced.
2.5) The Total Pressure (or “Head”) Loss

The total head loss of the V-Cone meter is relatively low compared to other DP meters and many other type of flow meters. In fact the V-Cone meter head loss is comparable to the Venturi meter (i.e., the DP meter traditionally designed to be low head loss meter). Note that both the V-Cone meter and the Orifice Plate meter do not measure the pressure at a point in contact with the streamlines of the main flow but rather at a point in contact with the vortices. (see Figure 10a and Figure 10b).

If it is also noted that the typical discharge coefficient of the Orifice Plate meter is 0.6 [2] and the typical discharge coefficient of the V-Cone meter is 0.8 then for a given flow rate and equivalent meter geometries Equation 1 shows that the differential pressure of the V-Cone meter is less than for the Orifice meter. As the upstream pressure is the pipe pressure before it is influenced by the meter in question then the higher differential pressure produced by the Orifice Plate indicates a lower downstream pressure which indicates stronger vortices. This therefore is the reason why the V-Cone meter has a lower total head loss than the Orifice Plate meter as stronger vortices means greater energy losses.

Miller [6] gives the head loss calculations for different meters. Figure 11 shows a comparison of many meters that have had their total head loss predicted according to the equations given by Miller. Water in a 3” pipe line was used with a flow rate of 1145 liters per minute flow rate. Clearly the V-Cone meter is similar to the Venturi meters and better than the other meters in this comparison.

2.6 Contaminated Flows

The V-Cone meter is sturdy and copes with particulates in the flowing fluid well. The cone is protected by the boundary layer that exists around it so most small solid
particles tend not to strike the cones edge and therefore the cone survives in abrasive flows longer than many other meters. It does not wear quickly unlike an Orifice Plates sharp edge. When damage does occur tests have shown that even moderate damage to the cones edge around the minimum cross sectional flow area has had only a small effect on the meters performance. Due to the geometry of the V-Cone meter there is no place for contaminates to collect and therefore the meter tends to be self cleaning.

2.7 Wet Gas Flow Metering

Wet gas metering is becoming increasingly essential in many different industries. DP meters are considered to be one of the better single phase meters for use in wet gas flows (i.e., gas flows with a relatively small quantity of liquid present). All DP meters tend to give a positive error (called an “over-reading”) when liquid is present in a gas flow. The V-Cone meter allows most of the liquid phase in a wet gas to pass by undisturbed along the pipe wall meaning it tends to have a relatively small positive error compared to other DP meters.

Figure 12 shows a comparative plot of the effect of liquid in a gas flow on a geometrically equivalent (0.55 beta ratio) V-Cone meter and Venturi meter. The quantity of liquid is shown in terms of a parameter called the Lockhart-Martinelli parameter denoted by “X.” Equation 11 defines X.

\[ X = \frac{m_l}{m_g} \left( \frac{\rho_g}{\rho_l} \right) \]  

where \( m_g \) and \( m_l \) are the gas and liquid mass flowrates respectively.
\( \rho_g \) and \( \rho_l \) are the gas and liquid densities respectively.

Thus in Figure 11 with a constant pressure of 60 Bar (i.e., set fluid densities) the parameter X is indicating the ratio of liquid to gas mass flowrates in the wet gas. The V-Cone meter has a slightly smaller liquid induced error than the Venturi meter. The spread visible for both meter types at the higher relative liquid to gas ratios is partially due to a relationship between over-reading and pressure among other effects but this is beyond the scope of this paper. What is clear however, is that the V-Cone meter continues to operate when liquid is present in the gas flows and for a given liquid to gas ratio it reads with a repeatable and therefore predictable error.

FIGURE 12. A plot showing the comparative performance of a V-Cone meter and a Venturi meter used with wet gas flow.

STANDARDS

The V-Cone meter is covered by the API 5.7 document for differential pressure meters [7]. It also has custody transfer approval in Canada.

CONCLUSIONS

The V-Cone meter is a relatively new meter on the market that operates according to the same principles as other traditional DP meters but with significant advantages. These are the elimination of large pipe runs, a stable differential pressure is produced, a high turndown is obtained using a single DP transmitter, a low head loss is produced, the meter is more resistant to wear than many other designs and handles wet gas flows better than any other DP meter. These advantages are slowly becoming known throughout the many industries and the V-Cone meters market share is continuing to increase throughout the world.

REFERENCES


5. Ifft S. McCrometer Internal Report “Signal Noise Ratio Comparison with V-Cone and Orifice Plate.”
