Effects of Abnormal Conditions on Accuracy of Orifice Measurement

GM 1100

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Introduction

The effects of abnormal conditions on orifice plate based flow measurement is a broad topic. The research on abnormal effects has typically focused on issues such as the effects of bent plates, plate eccentricity, dulled orifice bore leading edge, the presence of water and liquified hydrocarbons, and many other conditions found in pipeline orifice meters. Abnormal conditions may also describe conditions that are considered acceptable as they are within the guidelines specified by standards like ANSI/API 2530.

ANSI/API 2530 is the standard that covers orifice plate based flow measurement of natural gas. It contains equations for calculating flow, specifications for the installation of orifice flow meters, and methods for gas sampling.

This paper will discuss potential problems in four areas of orifice based flow measurement: calculation of discharge coefficients, calculation of expansion factors, flow conditioning, and gas sampling. Each of these topics is covered by the standard but a great deal of detail is left out of the standard. In many cases only a detailed knowledge of the history behind the standard allows flow measurement personnel to recognize when potential problems are arising.

Calculation of Flow

The equation for calculation of flow is as follows:

$$q_m = C_d E_v Y \left(\frac{\pi}{4}\right) d^2 \sqrt{2\, g_c \rho_{t,p} \Delta P}$$

where :

C_d = orifice plate discharge coefficient

d = orifice plate bore diameter

ΔP = orifice differential pressure

E_v = velocity of approach factor

g_c = dimensional conversion constant

q_m = mass flow rate

$\rho_{t,p}$ = density of fluid at flowing conditions

Y = expansion factor

The calculation of the discharge coefficient and expansion factor are performed using equations that were produced using experimental data. The experimental data was obtained by flowing gases and liquids through different line sizes with a range of orifice plate bore sizes. When producing equations from experimental data some compromises are always required. A discussion of the compromises and limitations of the equations will follow.

The calculation of gas density is performed using an analysis of the gas composition. The gas composition is often determined using a gas sample that has been taken in the field. The accuracy of the resulting gas composition is affected by the gas sampling method.

Flow conditioning is covered in the standards under installation requirements. The effects of improper orifice meter installation is often discussed in terms of the effect on the discharge coefficient. The effect on the discharge coefficient results in over-measurement or under-measurement of flow. Flow conditioning has been the subject of much research since the early 1980's. A brief discussion of some of the results may give the reader an understanding of future changes in ANSI/API 2530.

Discharge Coefficient

In the 1980's, testing was performed at several different facilities to produce a database of discharge coefficient data for the calculation of natural gas discharge coefficients. The National Bureau of Standards (NBS) collected the data and monitored the testing. The resulting data was used to produce one equation that is used for all lines sizes from 2 inch up and all beta ratios covered by the standards.

Two problems exist with the equation that was produced for the calculation of discharge coefficients. The first is that the data do not fit the equation very well in some situations. The second is that high flow/high Reynolds number data were either not used or not available to produce the discharge coefficient equation.

Two plots are shown below. Figure 1 shows the experimental data and ANSI/API 2530 equation for a two inch orifice meter with a 0.24 beta. Figure 2 shows the results from testing a 24 inch orifice meter with a 0.75 beta. The horizontal axis shows the bore Reynolds number and the vertical axis shows the discharge coefficient. The circles in each plot show the data points that were taken to produce the discharge coefficient equation and the black line shows the discharge coefficients calculated using the equation from ANSI/API 2530.

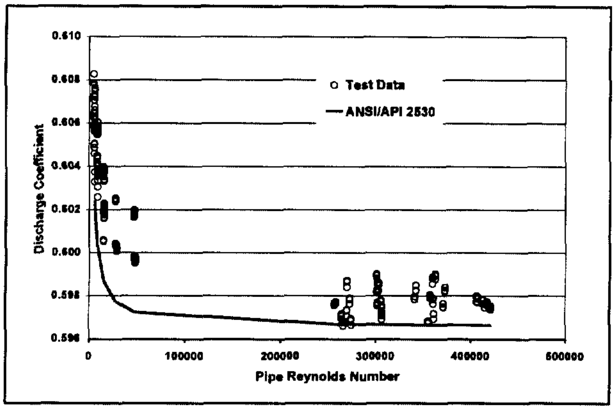

Figure 1. Orifice test data and ANSI/API 2530 discharge coefficients for 2" pipe Beta= 0.2413

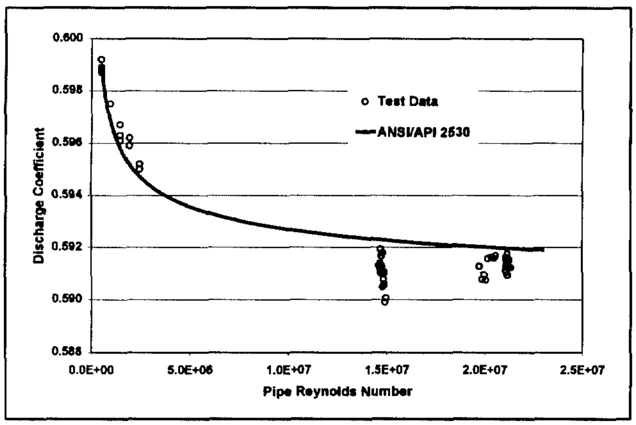

Figure 2. Orifice test data and ANSI/API 2530 discharge coefficient for 24" pipe Beta=0.7504

In the first plot there is a difference in excess of 0.5 percent at the low flowrates. Many production and gathering systems use 2 inch orifice meters. If they are running low betas and low differential pressures then they may be incurring significant flow measurement errors.

The second plot shows a potential error of 0.3% at the highest Reynolds number. These are the highest Reynolds numbers used in the development of the discharge coefficient equation and yet they only go up to a differential pressure of 42 inches of water at a line pressure of 950 psia. These are relatively low flows for many natural gas pipelines. The assumption has been made that as the flow or Reynolds number increases that the discharge coefficient stops changing.

In both of the situations just discussed the flow measurement would be conducted in compliance with standards. Most gas contracts require buyers and sellers flow measurement to agree within some tolerance. If systems are being operated in a manner similar to what is shown in the two plots then it may be difficult to balance out flow measurement.

What are the solutions to these problems? Perhaps we can have more than one equation for the calculation of orifice meter discharge coefficient. Computers are in common use in flow measurement today. Multiple equations for orifice meter discharge coefficient should not present major difficulties. Maybe a little more testing should be done at high flowrates/Reynolds numbers to see what the differences are between the predicted discharge coefficient and the actual discharge coefficients.

Expansion Factor

The flow equation is used to calculate the flow of gas through the bore in an orifice plate, however, with the exception of the bore diameter there are no measured parameters at the bore. The flow equation uses upstream or downstream pressure to calculate density and the differential pressure across the orifice plate to calculate flow through the bore. A gas expands as the pressure of the gas decreases. The expansion factor is used to describe the expansion of a gas as it passes through the hole in an orifice plate.

The expansion factor formula used today was developed by Dr. Edgar Buckingham (1932). The equation he developed is for a straight line. Later work by Murdock and Foltz (1953) suggested that the actual equation should be curved but the limited amount of data produced by their research didn't support a new equation and instead they stated that the linear equation produced by Dr. Buckingham seemed to be correct. A theoretical derivation of the expansion factor also suggests that the equation should be a curve instead of a straight line. Additional work was performed by Kinghorn (1986) and by Seidl (1996). The results of these two experimental efforts suggest that the expansion factor used today is incorrect. There is not enough experimental work available today to produce a new expansion factor formula so we will continue to use the equation in ANSI/API 2530. It may be that the difficulties in fitting a single equation to the discharge equation data discussed above could be simplified with a better expansion factor formula.

The uncertainty or accuracy of the expansion factor can be approximated by the following equation:

$$\text{Uncertainty } (\%) = \pm 4\left(\frac{\Delta P}{P}\right)$$

where :

ΔP = differential pressure (psid)

P = line pressure (psia)

This equation and the chart in ANSI/API 2530 show that if gas is flowing with a static pressure of 50 psia and a differential pressure of 300 inches of water then the uncertainty is about 0.87 percent. If the static pressure decreases to 20 psia and the differential pressure drops to 120 inches of water the uncertainty is still 0.87 percent. This example shows that as the static line pressure drops then the differential pressure will need to be decreased if flow is going to be measured accurately. This is a problem for many producers. As gas is produced from wells the pressure in the wells will steadily decrease. Eventually, all producers will be faced with flow measurement problems due to the uncertainty or accuracy of the expansion factor. The reason the uncertainty in the calculated expansion factor grows so large is because there is limited experimental data at low pressures and high differential pressures.

What are the solutions to the expansion factor problems discussed above? One sure solution is to conduct research which will produce expansion factor data. A large set of expansion factor data would allow a final determination as to whether the present expansion factor formula is valid. Data at low line pressures and high differential pressures would allow the uncertainty of the calculated values to be lowered allowing producers to calculate flow more accurately.

Flow Conditioning

In the early 1980's data became available that suggested that the minimum length requirements of ANSI/API 2530 were not adequate when flow conditioning was used. Subsequent testing showed that flow conditioners do not "fix" the problems created by upstream elbows, valves, and other system components as well as had been assumed. In fact, it was found that the effect of flow conditioners on flow requires more straight upstream pipe to than the standards require.

Testing was performed at several facilities in the following manner. An orifice flow measurement system was set up with a flow conditioner upstream. The flow conditioner could be positioned at several different distances upstream of the orifice meter so that the effect of flow conditioner location could be tested. Another flow measurement system was placed in the same system either well upstream or well downstream of the orifice meter/flow conditioner being tested. The second flow measurement system was set up to measure flow very accurately. With two flow measurement systems in the same line it was possible to determine the errors in flow measurement caused by the flow conditioner by comparing the measured flowrates of the two systems. Figure 3 shows the effect of a 19 tube bundle upstream of an orifice flow meter as reported by Morrow and Park (1992). The horizontal axis shows how far upstream of the orifice meter the tube bundle was positioned and the vertical axis shows the percent error in flow measurement. The results shown in Figure 3 are specific to the upstream piping configuration and cannot be applied to other system configurations. In this instance, the flow conditioner caused a negative shift in discharge coefficient until the flow conditioner was approximately 7 to 10 diameters upstream of the orifice meter. A negative shift in discharge coefficient will cause over-measurement of flow. As the distance between the flow conditioner and the orifice meter was increased, the discharge coefficient was shifted in the positive direction. A positive shift in discharge coefficient will cause under measurement of flow. Eventually, as the distance between the flow conditioner and the orifice meter was increased the percent under-measurement gradually approached zero until at approximately 40 pipe diameters the orifice flow meter was measuring flow correctly again. Many different flow conditioners were tested in this manner and, in general, it was found that at seven pipe diameters upstream of the orifice flow meter there were significant flow measurement errors, both over and under-measurement depending on the type of flow conditioner. As the distance between the flow conditioner and the orifice flow meter increased the errors tended to decrease or to cross zero as in Figure 3 and then decrease.

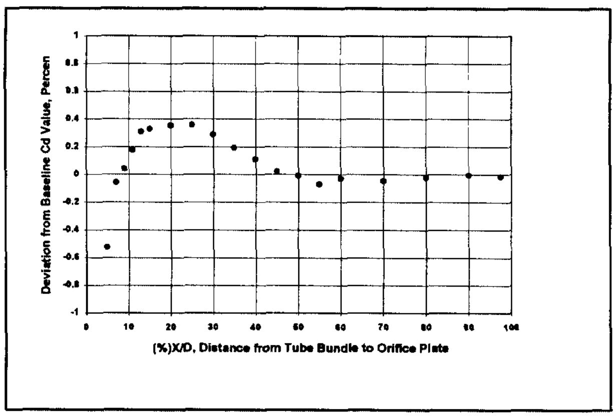

Figure 3. Deviation from baseline Cd value

Figure 3 shows deviation from baseline Cd value for a meter tube length of 100D downstream of a 90 degree elbow with a 19 tube straightening vane located at various distances, X/D, upstream of the orifice plate.

Although it has been determined that the straight upstream pipe length requirements in the 1990 edition of ANSI/API 2530 are not long enough, it is obviously not practical to modify all existing orifice meter installations. It is also not practical to build new orifice meter installations with 40 pipe diameters of straight pipe between a tube bundle and the orifice meter. Any solution the flow committee working on the revision to ANSI/API 2530 comes up with will be a compromise.

Possible solutions to this problem include additional testing to determine the effect of flow conditioner position on a wider range of pipe size/orifice size combinations than were tested initially. Another possible solution is to place another flow meter in the line temporarily with the orifice flowmeter. This second flow meter could be one that is unaffected by the flow conditions. The orifice flow meter could then be calibrated in place and the effect of elbows, valves, and flow conditioners could be taken into account.

Natural Gas Sampling

A sample of the natural gas flowing through an orifice meter is used to find the density of the gas. The density of the gas is used in the flow measurement equation. The sampling of natural gas flowing in a pipe has the greatest potential for creating flow measurement errors. The large number of sampling methods, the variety of materials used in sampling, and the different places sampling points are located are factors that can be controlled fairly easily. Factors that are less easily controlled are the cleanliness of sampling equipment, how well personnel follow procedures, and the weather.

Natural gas is composed of many constituent gases with different molecular weights. The heavy constituents, often referred to as C6+, have the greatest impact on the calculated density of the gas. These heavy constituents can be inadvertently removed from or concentrated in the gas being sampled in a variety of ways.

The heavy constituents are more likely to be attracted to and remain on surfaces in sampling tubes and sample bottles. This is referred to as adsorption. Behring and Foh (1998) found that all materials which come into contact with the gas being sampled adsorb some of the gas. This phenomena can be reduced somewhat by reducing surface roughness and by thoroughly testing and controlling the materials used in sampling.

The heavy constituents condense from a vapor phase to a liquid phase at a higher temperature than the other gas constituents. When the temperature of natural gas is slowly lowered, condensation of heavy gas constituents will begin to occur. The condensed liquid will have a composition dominated by C6+ components leaving the remaining gas with a lower density than it would have if the heavy components had remained in a vapor phase. The temperature of the gas being sampled can be reduced below the heavy component condensation temperature in a number of ways. If the sampling equipment is cold prior to sampling the heavy components may condense as the gas passes through the sample lines and sample bottle. This can raise or lower the gas sample density depending on where the condensation occurs. If there is a pressure drop as the gas passes through the sampling system Joule-Thompson cooling may lower the temperature adequately for condensation of heavy components to occur. This has been found to raise the sample density in some cases when the pressure drop occurs at the sample bottle inlet. If the temperature of the sample bottle is allowed to fall once the sample has been taken condensation of heavy components may occur. This may not affect gas sample density if the bottle is rewarmed in a proper manner prior to testing.

The heavy constituents are more likely to be absorbed by greases and residues in sampling equipment than lighter constituents. Many sampling components have a light coating of oil when purchased. These oils adsorb heavy gas components leaving a gas sample with a low density. Some sampling equipment is difficult to clean and can have grease and dirt residues which preferentially adsorb heavy gas components.

Sampling research is currently being conducted to determine the best ways to sample. Evaluating the errors due to sampling problems is difficult due to the large number of ways in which errors can be introduced.

Conclusion

Four areas of potential orifice measurement error have been discussed. The four areas were the calculation of discharge coefficient, the calculation of expansion factor, the effect of flow conditioning on measurement accurracy, and the effect of gas sampling on flow measurement accuracy. Additional testing can be performed to reduce potential errors in the case of discharge coefficient and expansion factor. Increasing the number of equations to calculate discharge coefficient using the present database of discharge coefficient information is a potential solution for some discharge coefficient errors. The flow conditioner problem can be solved by calibrating orifice meters in place but will probably be resolved by a compromise between flow measurement accuracy and piping modification costs. The gas sampling problem which has the greatest potential for causing orifice flow measurement errors can be eliminated to a large degree but the method of solution will only be known after more research is conducted.

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