EFFECTS OF ENTRAINED LIQUID ON ORIFICE MEASUREMENTS

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INTRODUCTION

Natural gas often has some liquid content. The liquid may be water, hydrocarbons, or compressor oil. As this gas flows through an orifice meter is the gas being measured correctly? The measurement methods and calculations described in ANSI/API 2530 are for dry gas.

Many researchers have studied the effect of entrained liquids on orifice measurement. The existing literature can provide much information about orifice flowmeter errors. This information can be used to determine the course of future orifice plate research efforts.

This paper will discuss four test programs that were conducted to examine the effects of entrained liquids on orifice meter performance. The results of these programs will be discussed as well as some simple flow models. The flow models will be used to explain why research into this area has been so difficult. The flow models are not intended as a guide for measurement correction.

WET GAS

The liquid in natural gas may be in the form of very small droplets or there may be enough liquid to completely fill the pipe at times. The behavior of the gas passes through phases as the liquid content and flowing velocities change. These phases are referred to as flow regimes. Three simple flow regimes will be introduced.

Flow Regime 1

The first regime has the least amount of liquid in the flow. When the amount of liquid in the flow is low, the liquid is in the form of drops being carried in the flow stream. The drops are continually colliding with the pipe wall while new drops are formed when the gas flow scours the liquid from the pipe surface. As the liquid content increases in the flow, more and bigger drops hit the wall resulting in a film of liquid coating the entire pipe surface. As the film thickens, the roughness of the pipe wall begins to change due to the liquid filling in low spots on the pipe surface. The pipe seems to become very smooth. The film moves down the surface of the pipe and is pushed onto the orifice plate by the flowing gas. As the liquid streams across the plate, the plate surface conditions also begin to change. Streaks on orifice plates suggest that the liquid is drawn across the surface as lines of fluid stretching from the outer edge of the plate into the bore. Streaks make the orifice plate surface rough. The liquid also makes other changes to the meter geometry. Liquid near the edge of the bore makes the sharp edge seem less sharp to the approaching flow and liquid coating the inside surface of the bore make the bore diameter effectively smaller.

Flow Regime 2

Let the amount of liquid in the pipe increase so that there is more than enough liquid to completely coat the pipe. If the gas velocity is low enough, a thicker layer of liquid may form on the bottom of the pipe. The thick layer of fluid may acquire a rough surface if the liquid surface becomes rippled or wavy or the surface may be smooth. The thick layer of fluid is flattened against the pipe bottom by the flow. If the gas velocity increases, the thick layer of fluid can be flattened so much that it becomes a uniform coating on the inside surface of the pipe. As the flow approaches the orifice plate a puddle of liquid may form just in front of the plate. Large drops can be carried from this puddle through the orifice bore. As the large drops pass through the orifice plate bore the area of the plate effectively decreases, restricting the much faster gas flow. Liquid still moves across the plate surface in streaks and collects near the bore and on the inside surface of the bore. The liquid behavior can change quite a bit in this flow regime with small changes in gas velocity and liquid load.

Flow Regime 3

If the liquid in the flow continues to increase, a permanent thick layer of liquid forms at the bottom of the pipe. The liquid surface does not change as the amount of liquid increases and the layer begins to fill the pipe. Liquid is dammed up in front of the orifice plate and is being drawn through the orifice bore at a constant rate by the gas flow. Much of the flow area of the orifice bore is now occupied by liquid which is moving at a much slower rate down the pipe than the gas.

TEST METHODS AND TERMINOLOGY

Two-phase or multi-phase flow are terms that may be used to describe wet gas flow. Wet gas is two-phase flow because there is a gas phase and a liquid phase present in the pipe. Wet gas researchers can measure the gas flow and liquid flows separately before combining them in the test section. The liquid and gas flowrates can be changed allowing researchers to use a wide range of liquid loads. A common way of describing the amount of liquid in the flow is to use a mass ratio. A common expression for mass ratio is:

$$\text{Mass Ratio} = \frac{\text{Mass flowrate of liquid}}{\text{Mass flowrate of gas}} \quad (1)$$

The mass ratio may also be called liquid load and is often expressed as a percent.

Wet gas studies are performed using systems similar to the one shown in Figure 1. Dry gas enters the system on the left side. An orifice plate or some other flowmeter is used to accurately measure the flow of dry gas into the test section. Liquid flow enters the test system from the bottom of the figure. The flowrate of liquid is accurately measured prior to being injected into the test system. The liquid is injected downstream of the flowmeter used to measure the dry gas flow and upstream of the orifice flowmeter being tested. The total flowrate passing through the meter being tested is the sum of the dry air and the injected liquid. As flow passes through the orifice flowmeter being tested the differential pressure, static line pressure, and temperature are measured. These values allow a calculation of flow which can be compared to the known flowrate of the combined gas and liquid.

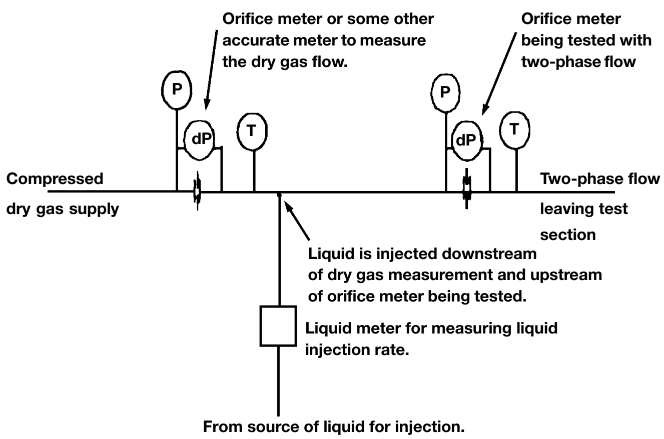

FIGURE 1. Typical Two-Phase Test Setup

PREVIOUS RESEARCH

There has been a considerable amount of research on the effect of entrained liquids on the performance of orifice plates. A few of the papers will be discussed in terms of the flow regimes described above.

Flow Regime 3

Murdock performed a number of tests using orifice meters in two-phase flow. The testing was performed using steam/water, air/water, natural gas/water, natural gas/distillate, and natural gas/salt water combinations. Testing was conducted at pressures ranging from near atmospheric to over 900 psia. Testing was performed using 2-1/2″, 3″, and 4″ piping and beta ratios of 0.25 to 0.5. The mass ratio varied from about 0.02 to over 8. A plot of some of Murdock's data is shown in Figure 2.

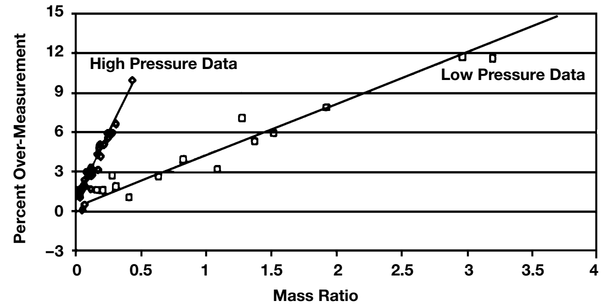

FIGURE 2. Some of Murdock's experimental data

Note that as the mass ratio increases the percent of over-measurement increases. Also note that the errors increase more rapidly when the system pressure is higher. The data shown is grouped along the two straight lines shown on the plot. The trend of increasing flow measurement error as pressure increases appears to be clear. The clear trend suggests flowing conditions are stable. The flow in Regime 3 is stable. The large increase in differential pressure due to the load of the liquid passing through the orifice bore dominates any other effects and clearly correlates with pressure.

Flow Regime 2

McConaghy *et. al.* performed tests to determine the effects of liquid and solid contaminants on orifice plate performance. The testing was performed using high pressure natural gas and a system composed of 10″ piping with beta ratios of 0.2 and 0.6. The mass ratios were varied from 0.004 to 0.0004.

Orifice plate surface conditions were varied by machining grooves into the plate surface and by putting grease on the orifice plate surface. Two different groove depths and many different grease applications were examined. Test results showed that plate roughness caused under-measurement of flow but only when the height of the roughness became large enough to disturb the flow across the plate.

Two-phase flow testing was performed by injecting glycol or oil into the natural gas flow stream upstream of the orifice plate. After each of the test runs the orifice plate was removed for inspection. Residue on the plates indicated that some puddling of liquids was taking place just in front of the orifice plate and radial streaks indicated that the liquids were moving across the plate surface. From these descriptions it appears that these tests were performed in the second flow regime discussed above. The liquid behavior in this flow regime can vary considerably.

The test results showed considerable variations. Testing conducted using a low beta plate and high injection rates produced a smaller effect on flow measurement than testing with a high beta orifice plate and lower injection rates. The authors suggest that there were many potential mechanisms which could affect flow measurement. Some of the mechanisms produce under-measurement of flow and some of the effects produce over-measurement of flow. Over-measurement of flow was caused by the effective decrease in orifice bore area as large droplets passed through the hole. Over-measurement was also caused by the roughness of the orifice inlet piping changing as the liquid layer made the surface smooth. There were several potential mechanisms that could cause under-measurement of flow. Increasing orifice plate surface roughness, puddling of liquid in front of the plate, liquid on the plate surface close to the orifice bore, and increasing pipe roughness as the surface of the liquid film becomes rippled or wavy all cause undermeasurement of flow. The authors felt that many of these mechanisms were present at the orifice plate all of the time. Other mechanisms, such as the puddling, large droplets passing through the orifice bore, or varying roughness of the film surface may appear and disappear with small variations in flow. Depending on how these mechanisms interact it was found that the flow measurement errors could be very small or the mechanisms could produce significant under-measurement errors.

Flow Regime 1

Ting and Corpron performed testing using compressed air and water. The pipe size used was 8 inch and the beta ratios were 0.5 and 0.7. The injected water produced mass ratios of 0.02 down to 0.0002. The test results showed a negligible shift with the 0.5 beta plate but showed large shifts with the 0.7 beta plate. Under-measurement of flow by as much as 1.7% with a 0.7 beta plate occurred at high Reynolds numbers.

Clear trends of increasing under-measurement as mass ratio increased and as Reynolds number increased showed that the testing was performed in the first flow regime described. An even coating of liquid covers all of the pipe internal surfaces. The injection rates were high enough to maintain some level of coating but it is not clear whether or not there was damming of liquids in front of the plate or large droplets of liquid passing through the orifice bore. In fact, this is one of the problems with testing conducted by injecting liquids into a gas stream. It is never clear whether or not damming of liquids in front of the plate occurred. With these test results it was not clear whether or not the under-measurement was caused by the film of liquid alone or if some other mechanism such as puddling contributed to the measurement error.

Work by the present author attempted to answer the question about the effects of thin films of liquids in orifice flowmeters. Testing was performed for the Gas Research Institute using compressor oil in systems flowing dry compressed air. Testing was performed in 2 inch, 6 inch, and 10 inch pipe. Beta ratios tested were 0.25, 0.5, and 0.7.

This testing was unique as it did not use liquid injection. The orifice plates and piping immediately upstream of the orifice meter were coated with oil. After allowing the excess oil to drain away the piping system was assembled and testing was started. Figures 3 and 4 show some of the test results. The plots show the percent change in discharge coefficient. A positive shift in discharge coefficient corresponds to under-measurement by the same percentage. Each test was started by taking data at low flowrates and then proceeding to higher flowrates. Once the maximum flowrate had been achieved data was taken as the flowrate decreased back to the original flowrate. The magnitude of the shifts tended to decrease as the test proceeded. This change corresponded to the diminishing oil film as the air swept the oil out of the system. After each test the piping was taken apart and the plate and piping were inspected. These inspections revealed that nearly all of the oil had been scoured from the pipe wall by the flowing air during each test. The data in Figure 1 show that when the test ended there was still a large under-measurement of flow. A very small amount of oil could therefore produce under-measurement of flow. Consistent under-measurement errors occurred when both the orifice plate and upstream piping were coated with a thin film of oil.

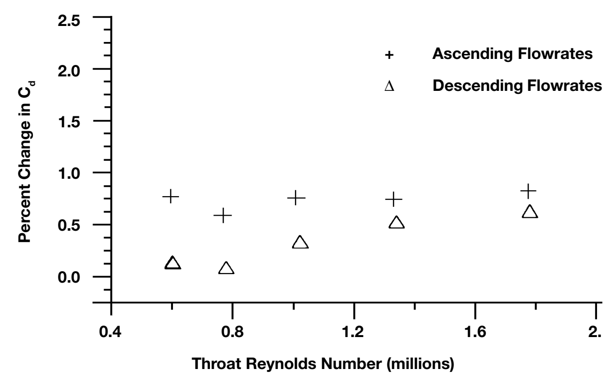

FIGURE 3. 6″ Pipe, ß= 0.67 Thin Oil Film on Orifice Plate and Pipe

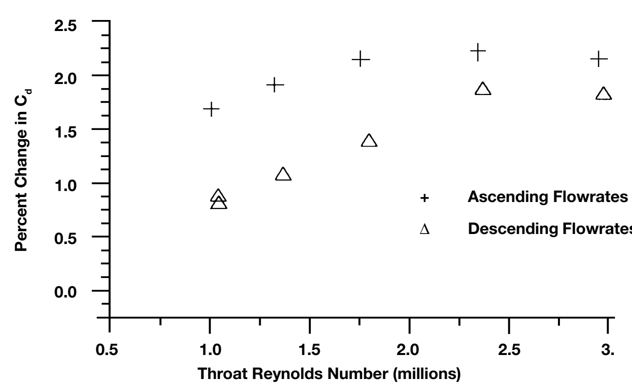

FIGURE 4. 10″ Pipe ß= 0.66 Thin Oil Film on Orifice Plate and Pipe

CONCLUSIONS

Three two-phase flow regimes were described. The first flow regime had very low liquid content. The liquid content was just enough to produce a thin coating of liquid on all of the orifice meter internal surfaces. Research performed with low injection rates has shown that flow is under-measured. The undermeasurement is consistent and in some cases can be over 1%. The second flow regime had a higher liquid content than the first regime. The liquid content was high enough that a thicker layer of fluid could form at the bottom of the pipe. This thicker layer of fluid could become redistributed around the pipe surface if fluid velocities increase. Puddling of liquid in front of the orifice plate could also occur. In this flow regime there is a lot of variability in the behavior of the liquid and as a result the flow measurement may not be affected or there may be substantial under-measurement of flow. The third flow regime has enough liquid in the pipe so that there is a permanent thick layer of fluid on the bottom of the pipe. The surface of the liquid has a fairly constant roughness. The liquid is dammed up in front of the orifice plate and is drawn through the orifice bore at a steady rate. Orifice plates used with liquid loads this high consistently over-measure flow. The amount of over-measurement is affected by the flowing gas pressure.

FUTURE RESEARCH

Figure 5 shows the general trends in flow measurement error from the papers discussed. The plot shows the percent error in flow measurement as the liquid to air mass ratio increases. The values shown are included only to provide some idea of the magnitude of the measurement errors. This plot and the previous discussion can provide some insight into the course of future research.

In flow regime 3 the orifice meter clearly over-measures flow. Future testing must be performed with natural gas and liquids that are representative of liquids found in pipelines. Murdock's work clearly showed that the flow measurement errors changed as line pressure changed. Those changes must be examined in detail. Any other effects such as how beta ratio and Reynolds number change the over-measurement need to be identified and studied.

In flow regime 2 the performance of the orifice plate experiences a great deal of variability. The research results of McConaghy *et. al.* illustrate the potential variability in flow measurement. If future research also shows variability then the research results may be used to establish some boundaries of the possible errors in flow measurement. These boundaries could extend from 0.0% or slightly positive flow measurement error to as much as 1% under-measurement. Test results should also define the upper and lower mass ratio boundaries of this region.

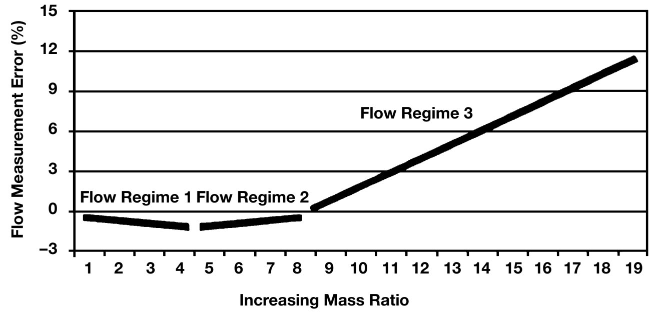

FIGURE 5. General Trends in Flow Measurement Error

The performance of the orifice plate in flow regime 1 is not as variable as in flow regime 2. The data suggest that the orifice meter under-measures flow when thin films of liquid coat the internal surfaces of the pipe. Although it appears that Reynolds number does not strongly affect measurement errors future research needs to verify this as well as the effect of beta ratio, line size, and pressure.

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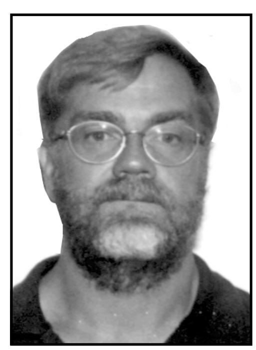

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