WHITE PAPER

Measurement Limitations of Flow Rate Measured by Orifice Plate and How Those Limitations are Addressed

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ABSTRACT:

This technical paper describes an innovative design that addresses several limitations of flow rate measurement by orifice flowmeter. Some of those mechanical and performance limitations are; (a) maximum allowable differential pressure to limit bending of the plate; (b) requiring pseudo-fully developed velocity profile approaching the orifice plate; (c) minimum downstream straight run and distance of protruding secondary instruments downstream of the orifice plate; (d) maximum thickness of the plate bore; (e) edge sharpness of the plate bore; (f) effect of flow profile distortions on single point wall pressure taps; (g) only single phase clean fluids; (h) concentricity of the plate bore to the pipe axis; (i) circularity of the inlet-outlet flow tubes; (j) long upstream-downstream meter runs; (j) large variations in bore diameter for same meter size, and several other stringent mechanical tolerances and limits. In addition, proprietary plate seals are required for single and dual chamber orifice fittings with labor intensive maintenance of orifice meters with virtually no alarm capabilities.

This paper briefly highlights few experimental data of the author of this paper that contributed to and defined many of the above mentioned requirements and are referenced in the orifice meter standards. This paper presents experimental data that demonstrate how an innovative design is able to address those limitations and achieve reliable and repeatable flow rate measurement capability by this Differential Pressure (DP) type flowmeter. This primary element can be installed to measure gas, liquid, steam, waste-water flows, and other fluids with known or predictable fluid properties (density and viscosity). With addition of two other instruments, this device can also measure multiphase fluid flows within current field accepted limits of measurement uncertainty. By monitoring the differential pressure using remote-seal DP transducers, this flowmeter can measure flows with suspended solids, like drilling mud. Paper also describes how a custom designed primary element of this flowmeter can be installed in existing field installed dual or single chamber orifice fittings with retrofittable modification of the orifice fitting. With addition of another DP transmitter, in the event of measurement anomaly due to changes in fluid properties, failure of mechanical setup, or instrumentation, the flow computer can alarm the operator.

BACKGROUND AND PRIOR EXPERIMENTAL STUDIES:

In early 1980s several experimental studies were performed by Dr. R. Teyssandier and Dr. Z. Husain (referenced in the Orifice Meter Standards), to document and demonstrate performance of flow rate measurement by concentric thin-plate square-edged orifice meter, which was the predominantly used flowmeter in the oil and gas industry to measure fluid flows, primarily gaseous flows. The experimental setup monitoring the distribution of pressure on the pipe wall and orifice plate is shown in Figure 1. Specially machined toroidal inlet to the upstream pipe generated axisymmetric inlet flow profile in the upstream pipe and to isolate pump induced flow disturbance and mechanical vibrations, measurement section was isolated and installed on the suction side of the blower. The pressure distribution at the pipe wall and orifice plates were monitored and recorded by fast response laboratory quality precise DP transducers at two different flow rates and for three different beta ratios, covering Reynolds number range of 21,000 to 160,000.

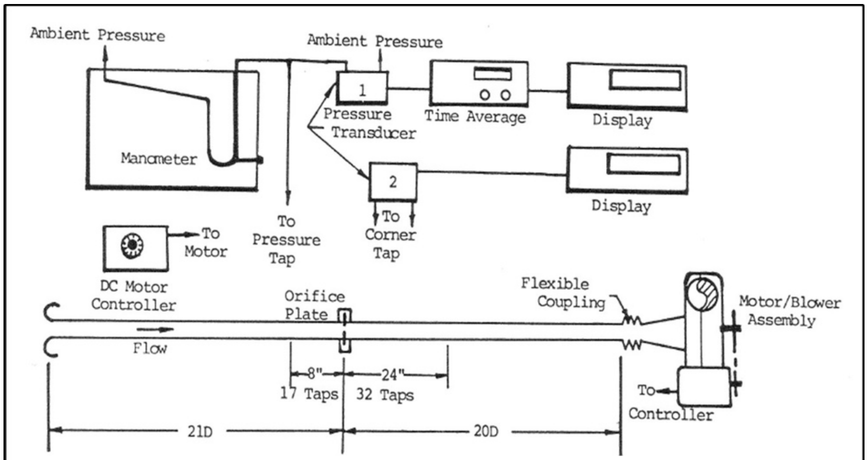

Figure 1: Experimental Setup of Pressure Gradient Measurement

The upstream-downstream pipe wall pressure ports were equidistant from each other and pressure port on both face of the orifice plate and on the land of the orifice plate bore are shown in Figure 2.

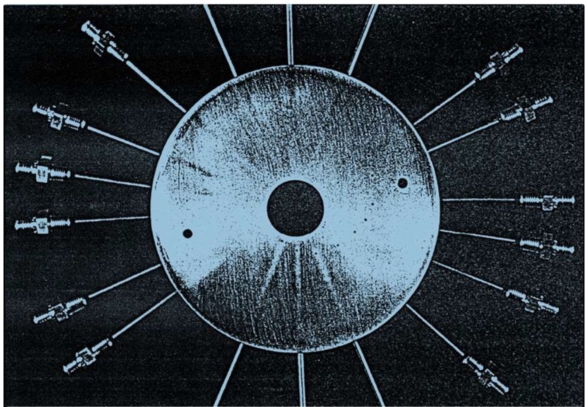

Figure 2: Orifice Plate Pressure Tap Holes

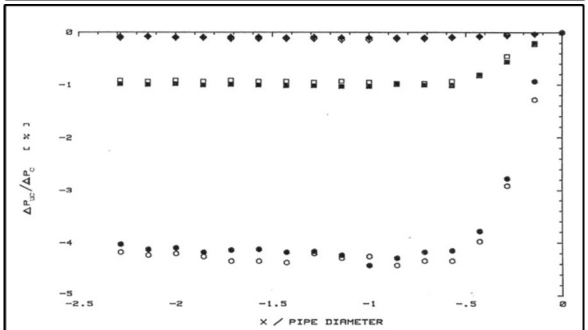

Figure 3: Nondimensionalized Pressure distribution on Upstream Pipe Wall

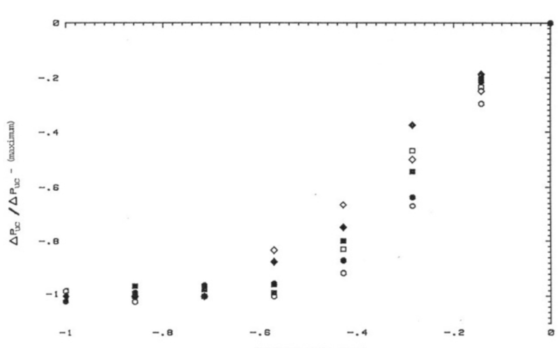

Figure 4: Upstream Pipe Pressure Distribution Normalized by Maximum DP of Corner and Bore Taps.

Experimental data indicated that the differential pressure between the pressures at the corner of the pipe and upstream face of the orifice plate and the pressure at the land of the orifice bore generated the most stable and precise differential pressure for all beta ratios and flow rates. It was also observed that when the differential pressures at any point on the pipe and orifice plate were referenced to the corner tap and normalized by the corner and bore differential pressure, the normalized differential pressures were independent of the flow rate (Figure 3). It was further noted that the differential pressures of any beta ratio when normalized by the maximum pressure for that flow rate, the pressure distribution was independent of both flow rates and beta ratio (Figure 4).

Figure 5 is the downstream pressure distribution normalized by the maximum pressure. The plot demonstrates dependence of the pressure distribution on the beta ratio. Data also show that for the flow to reattach on the pipe wall, a minimum distance of about 3.5D to 4D downstream from the orifice plate is necessary. Other factor that affects the flow reattachment point on the wall is the flow exiting the orifice bore. Through another experimental investigation performed by the author to determine the influence of the plate thickness (E) and thickness of the orifice bore land (e), it was demonstrated that if the flow exiting from the bore is allowed to reattach on the land of the bore, the reattachment point on the wall is altered, affecting pressure at the downstream pressure tap. Hence, when an orifice plate thickness (E) is more than the thickness at which flow may reattached on the flat section of the bore, plate must be beveled on the downstream to eliminate possible reattachment of the flow on the land of the bore. Figure 6 is the plot of the downstream distance normalized by the dam height of the orifice plate, which shows that the reattachment point on the pipe is a function of the dam height.

There were several other detailed experimental studies by the author on performance of orifice meters and influence of different mechanical tolerances of orifice meters. Many of those test results were published in the public domain, while several are not. Based on the observations and knowledge with applicable laws of flow physics, design improvements were implemented in developing

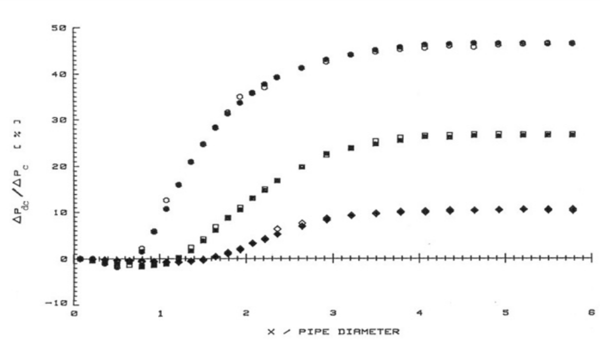

Figure 5: Downstream Pipe Pressure Distribution Normalized by Maximum DP of Corner and Bore Taps.

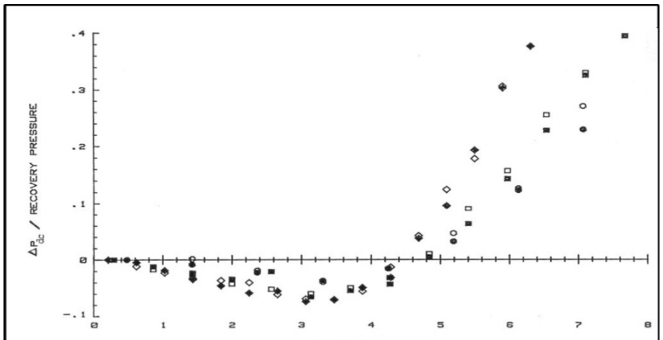

Figure 6: Downstream Pressure Distribution with Distance from the Orifice Plate Normalized by the Dam Height.

this new DP type flowmeter with a central bore for better performance and to address several of the stringent mechanical tolerances and requirements of flow rate measurement by orifice meters.

Another experimental investigation by the author on effect of orifice plate eccentricity is briefly discussed here to emphasize the influence of physically averaged multiple pressure taps on precision of flow rate measurement and how that reduces the bias error. Figure 7 shows the test setup for determining the effect of plate eccentricity on flow rate measurement.

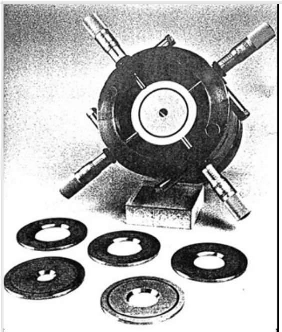

Figure 7: Orifice Plate Eccentricity Test Setup.

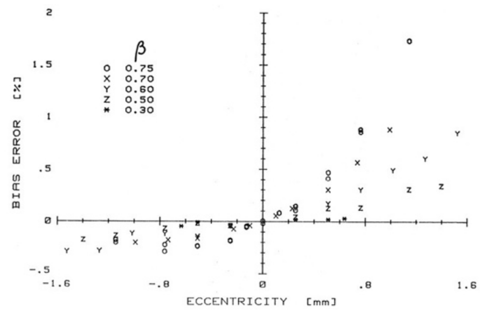

Figure 8: Bias Error of Different Beta Plate for Eccentricity of the Orifice Plate.

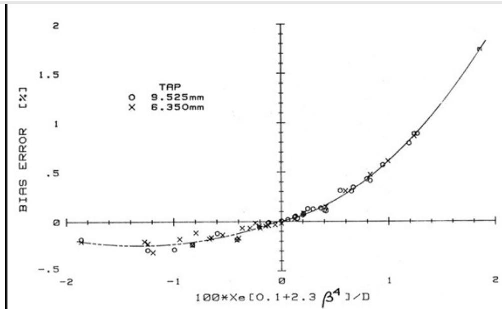

Figure 9: Normalized Eccentricity for Different Beta Ratio Plates and Different Tap Sizes.

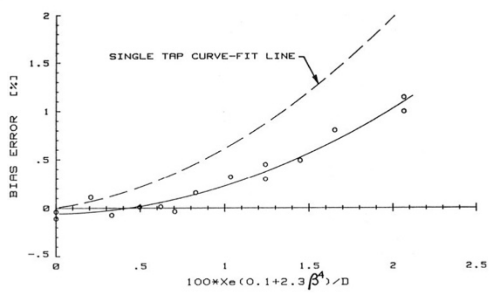

Figure 10: Error of Plate Eccentricity when Two Opposite Pressure Taps are Averaged

When axis of the orifice bore is not concentric with the pipe axis, there is a bias error in flow rate measurement. Figures 8 shows the bias as function of eccentricity and Figure 9 displays how that bias can be predicted by nondimensionalizing eccentricity as a function of the pipe diameter and beta ratio. Figure 10 shows that the bias error can be significantly reduced by mechanically averaging diametrically opposite pressure taps. Study also demonstrated that the bore diameter of the pressure tap has minimal influence on the monitored differential pressure.

It is to be noted that a unique and complex discharge coefficient equation for orifice meter, developed for the orifice meter standards, includes different terms relating to the beta ratio, distance of upstream-downstream pressure taps from the orifice plate, and the Reynolds number, which is function of density and viscosity of the fluid at flowing conditions. Since, one inch upstream and one inch downstream pressure taps are not hydrodynamically similar for different line sizes, the discharge coefficient of orifice plate remains a function of the tap location and line size. As a thin square edge orifice plate cannot be subjected to high differential pressures due to possible bending of the plate, historically significant variations in bore diameter are in use to optimize the limited range of DP transmitters or chart recorders. Even today, when technologically advanced smart DP transmitters are available with remotely resettable wide range of span and precise pressure monitoring capability, the oil and gas industry still install orifice plates with infinite variations in beta ratio.

AVERAGING CENTER-TAP AND FLUID PROPERTY EFFECT

Prior experimental results indicated that the flow through the bore being the highest velocity for the meter, that generates the most dominant, repeatable, and stable differential pressure between the pressure at the upstream corner tap and pressure at the land of the bore. In addition, by averaging the pressure through multiple pressure taps, effect of flow profile distortions is reduced. Hence, an investigative experimental study was performed with a modified design of the commercially available differential pressure type meter, especially because that design offered the capability to withstand very high differential pressure across the primary element without bending. Figure 11 is the averaging Center Tap TorusWedge design.

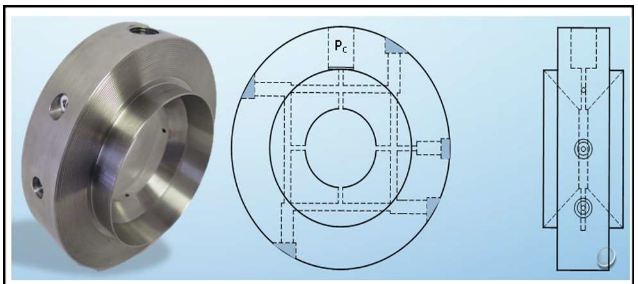

Figure 11: Averaging Center Tap TorusWedge

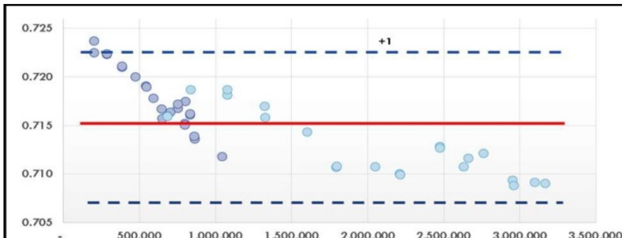

Figure 12: Discharge Coefficient vs Reynolds number of Different Line Size, Beta Ratio, and Calibration Fluid.

It is important to note that for orifice meters, a unique discharge coefficient equation was developed when different line sizes, beta ratios, and fluid properties are expressed as non-dimensional parameters. Hence, modified design of Center Tap Torus (CTT) meters of two different sizes with different beta ratios were flow calibrated with air and water as the calibration fluids and the differential pressure between the upstream pressure tap and averaged center tap was used to calculate the discharge coefficient by applying Bernoulli's equation. Figure 4 displays that although an orifice plate is an abrupt change in cross-sectional area for the flow, yet flow starts to adjust for the bore in the upstream section of the pipe before physically reaching the bore. This was the other consideration for selecting the TORUS whose ramp aided the flow to adjust for the bore of the primary element. So, the discharge coefficient (Cd) of the modified TORUS was expected to be higher than that of orifice meter with same beta ratio. Figure 12 is the plot of the discharge coefficients as a function of Reynolds number of two different sizes of TORUS CENTER-TAP (TCT) meters with different beta ratios. Dark blue data sets are plot of 6-inch TCT meter with 0.54 beta ratio, calibrated with water. The light blue data sets are that of a 4-inch TCT meter with 0.3 beta ratio bore and calibration fluid was high pressure air. Meters were calibrated at two independent NIST traceable calibration facility. For these tests, measurement uncertainty of the water calibration facility was of the order of +/-0.15% and the air calibration facility was about +/-0.30%. Plotting the discharge coefficient, Cd, as a function of the pipe Reynolds number captures the effect of the fluid properties on the Cd values. Within the uncertainty of calibration systems, data demonstrates that when the discharge coefficient of the TCT meter is plotted as a function of Reynolds number, the variability of the meter performance is minimized like the discharge coefficient equation of orifice meters.

STREAMLINE THE METER DESGIN

Since, experimental study established the basic performance characteristics of TORUS CENTER-TAP (TCT) meters, additional modifications to the primary element were implemented to simplify and streamline the design to minimize manufacturing cost and offer ease of installation in the field. The modified design was flow tested to ensure that the performance and precision of measurement were not compromised. As the primary element of the TCT meter is resistant to bending under high differential pressure across the meter, it was not necessary to offer TCT meters with large variations in bore sizes. Based on calculated sizing of TCT meter for typical operating flow rate range of different line sizes, it was observed that almost all flow rate applications could possibly be measured by TCT meters with beta ratios of either 0.5 or 0.7. The differential pressure at maximum flow rates of natural gas at typical operating pressures and for different line sizes could be maintained to around 100 kPa (400 inches of water column) with selection of 0.5 or 0.7 beta ratio. To date, there was only one application for which a 0.3 beta ratio TCT meter was installed, because the user replaced an existing orifice meter and wanted to use the same DP transmitter that was there for the client's orifice meter beta ratio plate.

When the operating flow rate is expected to change and the installed smart DP transmitter's span can be remotely re-ranged to the expected range of DP for the TCT meter, then a meter with fixed beta ratio can be installed to cover the entire operating flow rate range of that line. Note that flow rate rangeability can also be extended with stacked DP transmitters.

Original design of the Torus meter had ramps on both sides of the bore and the meter could be instrumented to measure flows in both directions. As most applications monitor flows in one direction only, standard design of the TCT meter was modified and truncated to a flat on the downstream side of the meter. Design details of the modified TCT meter is shown in Figure 13. For uni-directional flows, pressures at the upstream corner of the pipe and primary element is monitored by the pressure tap that is connected to the groove in the TCT plate and the pressure at the bore (center tap) is monitored by the pressure tap, which connects to the groove in the bore of the TCT meter. For bi-directional-flow applications, the TCT meter have symmetric ramp on either side of the bore and identical corner grooves on both sides of the plate. When the flow direction change, the downstream groove becomes the upstream high-pressure port for the flow. The center tap is the common low-pressure port for both directions of flow. A TCT meter installed to measure bi-directional flows, is installed

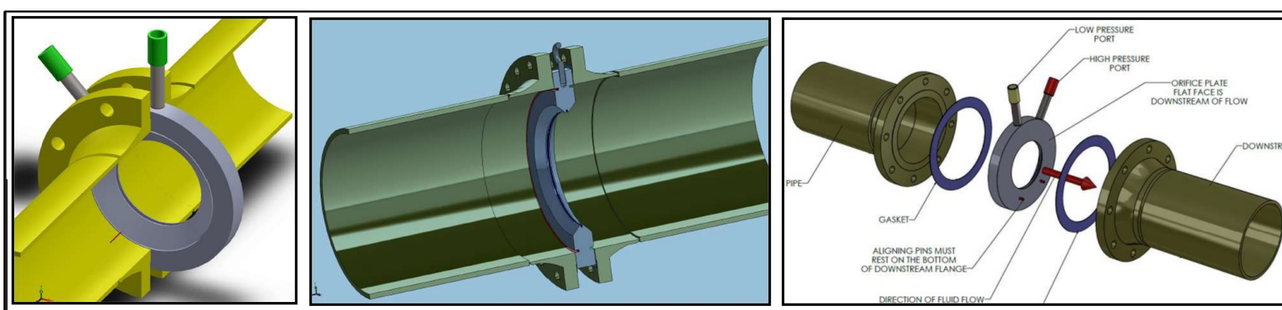

Figure 13: Design of the CTT meter for uni- and bi-directional flows

with two DP transmitters and the DP transmitter displaying higher DP value between the two transmitters would be the indicator of the flow direction. The flow computer can be programmed to detect the direction of the flow. For same line size, a TCT meter designed to measure bi-directional flows is thicker than the flow element measuring uni-directional flows. In Figure 13 two alignment pins are shown, that are installed on the downstream side of the TCT meter. The location of the alignment pins are matched to the inside dimension of the downstream pipe ID, so that when the TCT meter is installed between the upstream-downstream flanges, the meter is concentric with axis of the pipe.

To date, several dimensionally identical TCT meters of different line sizes were machined and flow calibrated. The discharge efficient as a function of pipe Reynolds number for multiple dimensionally identical TCT meters (within machining tolerance) display repeatable trend of data and are typically within the measurement uncertainty of the calibration facility. Figure 14 is calibration data of seven 150 mm (6 inch) CTT meters of same beta ratio, within machining tolerance of +/- 0.125 mm (+/- 5 thousandth of an inch), which resulted in less than +/-0.2% variations in beta ratio. These seven meters were installed to measure flare gas. Meters were calibrated at a calibration facility that is set up to calibrate meters for drilling mud flows, using Coriolis meter as the reference master meter. For these calibrations, Coriolis meter was operated over the low mass flow rate range of that master meter and the system uncertainty was +/- 2.0%.

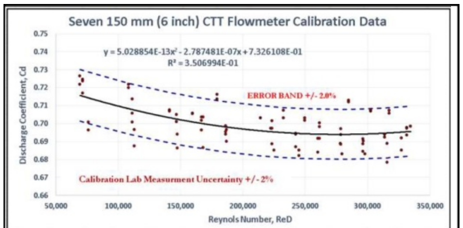

Figure 14: Calibration Data of Seven CTT Meters of Same Beta Ratio

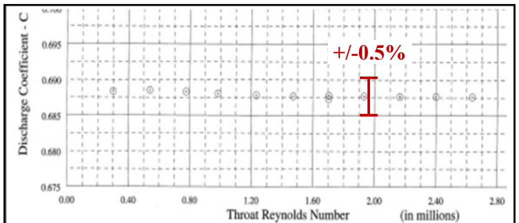

Figure 15: Calibration Data of one of the 7 CTT Meters

Figure 15 is the calibration data of one of the 7 TCT meters that was calibrated at more precise calibration facility, over significantly higher Reynolds number range. The measurement uncertainty of that facility was better than +/-0.15%.

API MPMS Chapter 22.2 requires that for fiscal applications, flow rates measured by any differential pressure type flowmeter for which there is no industry standard, individual flowmeter shall be flow calibrated to establish the discharge coefficient values for that meter and preferably calibrated over the operating Reynolds number range or calibration should demonstrate that the discharge coefficient curve is approaching an asymptotic value. Since bending of the TCT meter is not of concern, data of Figure 15 are for the TCT meter that was calibrated with water and at maximum Reynolds number, the differential pressure was about 480 kPa (about 2,000 inches of water column, which is 72 psid).

INFLUENCE OF DOWNSTREAM DISTURBANCE ON FLOW RATE MEASUREMENT

The low-pressure port of the TCT meter being at the bore of the meter, the pressure reading is dominated by the kinetic energy at the bore of the meter. So, downstream disturbances is expected to have negligible influence on the kinetic energy due to the physical restriction of the bore. Unlike orifice meter, where downstream disturbance can influence the pressure at the downstream tap, the pressure at the bore is not expected to be influenced by close proximity of protruded sampling probe or thermowells, provided that probe or thermowell is more than 5 times the probe diameter (blockage width) downstream of the pressure tap. This observation was reported by the author in his doctoral dissertation, which was an experimental investigation of the near and far fields of jets, wakes, and shear layers. That experimental study indicated that no noticeable upstream influence of a protruding object in the flow was observed beyond five times of the width of the blockage in the flow. Figure 16 is plot of calibration data of a 250 mm (10 inch) TCT meter, installed with a 13 mm (0.5 inch) probe, protruding to the center of the pipe at 0.5D downstream of a unidirectional TCT meter. Two sets of calibration data in Figure 16 are with and without the probe in the downstream pipe the calibration fluid for this test was water and at lowest flow rate the differential pressure was close to 2.5 kPa (10 inches of water column). Data demonstrates that a sampling probe installed in close proximity downstream of the TCT meter, it would not affect the measurement of flow rate. It is to be noted that in production field of rich gas, flow rate is often measured by orifice flowmeters. The closest allowable downstream distance of the sampling probe is 4.5D from the orifice plate, to eliminate possible disturbance to

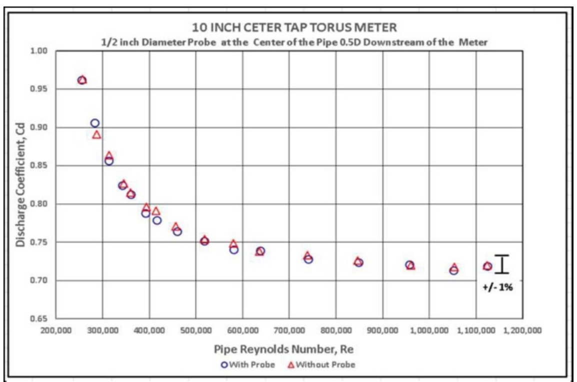

Figure 16: Effect of Proximity of Downstream Probe

the pressure measured at the downstream pressure tap. Temperature of rich production gas, flowing at high line pressures, is often close to the hydrocarbon dew point of the gas. So, quite often a sampling probe installed 4.5D downstream of the orifice plate fail to collect representative sample of the flowing gas, as some of the heavier hydrocarbons condense and flow near the bottom half of the pipe at 4.5D downstream of the orifice plate. A TCT meter installed with a sampling probe close to the primary element should gather better representative sample of rich gas flows than a sample probe installed 4.5D downstream of an orifice plate.

LARGE BIDRECTIONAL TCT METER

Figure 17 is the calibration data of a 500 mm (20 inch) bidirectional TCT meter. Within the uncertainty of the manufacturing tolerance and precision of the calibration facility, the data in both directions are primarily the same. The actual operating Reynolds number for this application was over the range of 11 million to 21 million. Reported feedback from the user confirmed that the product balance achieved with the TCT meter in both direction of flow is better than 0.5%.

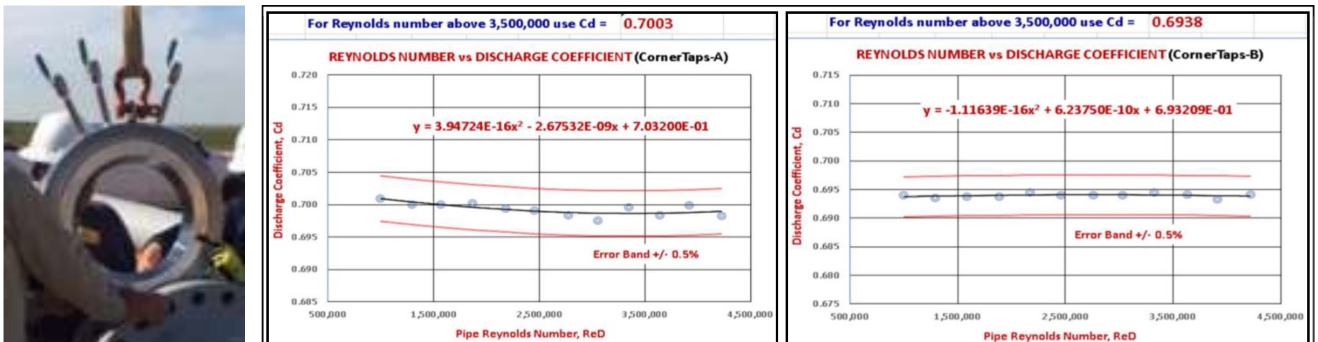

Figure 17: Calibration Data of Bi-directional TORUS CENTER-TAP Meter

MINIMUM UPSTREAM / DOWNSTREAM LENGTH

The pressure tap of an orifice meter is at one location on the pipe wall. That is the reason for the requirement of the pseudo-fully developed flow profile to achieve precise and repeatable DP measurement, as the azimuthal orientation of the pressure tap with respect to a non-symmetric velocity profile cannot be predicted. In the prior versions of the orifice meter standard, it was stated that for fiscal measurement, the upstream downstream pressure taps of orifice meter should be aligned at the same axial plane. Since flow profile for orifice meters are pseudo-fully developed, that requirement was later removed from the standards. For the TCT meters, the high-and-low pressure taps are monitoring the pressure of two grooved chambers, providing certain level of pressure averaging capability. This pressure averaging capability of grooved corner tap was demonstrated by the experimental study of small-bore orifice meters, also known as Honed Flow Section. Those data and design of orifice meters smaller than 50 mm (2 inch) nominal pipe diameter, were published in the 6th edition of ASME Fluid Meters (1971). Test report indicated that pressure measured in a grooved channel have averaging capability and achieves relatively stable pressure reading by minimizing effects of flow induced-pressure fluctuations. The orifice meter standard, ISO 5167, allows use of upstream-downstream corner-tap orifice meter design.

Figure 18: High and Low Pressure Taps to the Grooved Ports.

Limited tests are performed to determine the minimum upstream-downstream straight run required for typically encountered piping configurations. Effect of more commonly encountered upstream-downstream piping configurations measurement by CTT meters were experimentally investigated. Those piping configurations include elbows, tees, concentric and eccentric reducers and expanders, and full-open gate valves upstream of the meter. Tests do not include partially open upstream valve, but partially open downstream valve controlling the flow rate was tested for several line sizes. Two identical TCT meters installed in series and separated by 5 pipe diameters were flow calibrated over a flow rate range of 5:1. Then the locations of the meters were swapped. The discharge coefficients of both meters repeated within the measurement uncertainty (+/-0.25%) of the calibration facility, over the entire flow rate range of the test. Limited test results of upstream-downstream piping configurations indicate that 3D of minimum straight run is required downstream of unidirectional TCT flow meter and at least 5D upstream straight run is required between the upstream piping configurations and the TCT meters. If space is available, 10D upstream straight run is recommended. Since individual meter is flow calibrated, if for installed meter available space for straight run of pipe is limited, the TCT meter can be flow calibrated by duplicating the actual upstream-downstream piping configuration to capture their effect on the discharge coefficient of the meter. Until adequate database is compiled, each TCT meter should be flow calibrated prior to its installation in the line. Also, when possible and achievable, TCT meters will be flow calibrated over the operating Reynolds number or in the Reynolds number range where asymptotic value of the Cd value is achieved.

RETROFITTABLE SOLID TCT PLATE FOR SINGLE AND DUAL CHANBER ORIFICE FITTINGS

The TCT meter design is further modified to retrofit and replace the carrier plate of existing dual and single chamber orifice fitting. Basic design details are shown in Figure 20. The CTT meter is machined as an integral part of the carrier plate, thereby retaining the capacity to withstand high differential pressure across the plate. Depending on the size and pressure rating of the Orifice fitting, the isolating seals would either be a single or double commercially available O-ring seals on either side of the plate, to isolate the inner chamber of the fitting from the line pressure. The O-ring seals are held in place by specially designed dove-tail groove to ensure that the O-rings do not roll out of the groove while moving the Solid Plate TCT meter in and out of the fitting. The inner-chamber pressure is equalized to the Center Tap pressure by the two side holes drilled to connect to the Center Tap groove to the inner chamber. That pressure is monitored by a proprietary designed pressure fitting installed through one of the two drain holes at the bottom of the fitting. The existing upstream pressure tap will be the high-pressure port for the installed Solid Plate CTT meter.

Figure 19: Solid TCT Plate to Retrofit and Replace Carrier Plate of Installed Single or Dual Chamber Orifice Fitting.

The sealing material for the solid plate TCT meter for dual and single chamber orifice fitting is commercially available standard O-ring and not cost prohibitive proprietary seals that are often damaged and replaced after each orifice plate change or inspection. Having a contoured or sloped inlet and pressure averaging port, axisymmetric of flow profile at the pressure ports or surface roughness of sloped inlet section of the TCT meter is not as critical as that of an orifice flowmeter.

Note that another DP transmitter can be installed to monitor the differential pressure between upstream-downstream pressure tap of the orifice fitting. Since Bernoulli's Equation is valid for both differential pressures between the upstream and center taps and the upstream and downstream taps, at any flow rate the ratio of the two monitored differential pressures are repeatable. Hence by comparing differential pressure ratio of the two DP transmitters an alarm logic can be developed for the orifice fitting installed with the solid plate TCT meter. Therefore, if at any flow rate the pressure ratio does not match the historical pressure ratio data for that flow rate, that would indicate either leakage through the seals or failure of one or both DP transmitters.

Since no permanent alteration to the original dual or single chamber fitting has to be performed to retrofit the Solid Plate TCT meter, if for any reason the user wants to return to prior method of measuring the flow rate by orifice plate, the changes to the fitting can easily be reverse. If the representative sample of rich gas is desired, the sampling probe through the downstream pressure tap of the orifice fitting could be inserted to the depth of the dam height of the TCT meter. That location would be a well-mixed flow regime and provide relatively better representative sample of the rich gas than samples collected at 4.5D downstream of an orifice plate.

CONCLUSION

This paper documents chronological development of an innovative DP type flowmeter that through experimental investigation and field installed meters demonstrates the following:

- This meter can address several performance limitations and does not require many stringent mechanical tolerances of orifice meters.
- A simple and modified design of the primary element can replace the carrier plate of single and dual chamber orifice fitting.
- By flow calibrating individual meter this TCT meter can be installed for fiscal measurement (API Chapter 22.2).
- Meter requires relatively shorter upstream-downstream straight runs compared to that required for orifice meters.
- Precise flow rate measurement is achieved with significantly higher rangeability with the same primary element.
- For sloped inlet and grooved pressure ports, less frequent plate inspection is required.
- By installing second DP transmitter, this TCT meter offers diagnostic capability in the event of changes in fluid properties, mechanical malfunction, seal leakage, or failure of secondary instrument.
- Meter can measure flow rates of liquid, stream, liquid with suspended solids, and/or multiphase flows.
- Meter can collect better representative samples, especially when flow is rich gas.
- For Solid Plate design, the seals are standard O-rings and not high-priced proprietary seals.

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