TWO PHASE FLOW METER UTILIZING A SLOTTED PLATE

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INTRODUCTION

The purpose of a two phase flow meter is to provide the user values of the gas and liquid flow rates passing through a pipe. The classical technique to determine these flow rates is separation of the two phases and the individual measurement of the gas and liquid flow rates. This is accomplished using settling tanks, centrifugal separators, and other such devices. Three major problems associated with these devices are size, cost, and incomplete separation. Given enough space, time, and money, one can achieve complete separation. However, the resulting systems are frequently large, making their use a problem on off shore facilities and remote locations. A current development are the two phase flow meters which do not separate the gas and liquid but measure the flow rate of both as they flow together through the flow meter. Some use radiation devices to measure the density of the mixture while others have large positive displacement meters.

Murdock[1] discussed the use of a standard orifice flow meter for measurement of a two phase flow. The principle of a differential pressure (DP) flow meter states that the pressure drop increases linearly with the fluid density and as the square of the fluid velocity. Hence, the meter is sensitive to both density and flow rate. It turns out that the response of the orifice is not repeatable enough for use in two phase flows. As the line pressure varies, the meter response changes from decreasing to increasing at low liquid loadings. There is also a problem with the daming effect of the orifice plate.

The meter of choice became the venturi meter since it minimizes the daming effect. Several studies were made using the venturi meter and it was found it responds best with accompianied by a mixing plate upstream. That is, a homogenous mixture produces the best response. Since a single venturi meter is sensitive to two variables, density and velocity, another device must be used to provide the second measurement. This is where the radiation based density measurement device comes into play. There are commercial meters available which consist of a mixing plate, venturi meter, and radiation device. The presence of the radiation device is problematic in that safety requirements make its use more restrictive.

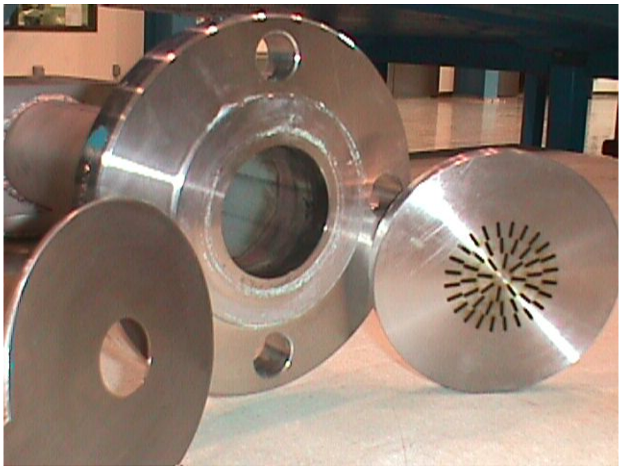

Figure 1. Beta = 0.50 Slotted and Standard Plates

The slotted DP meter was developed at Texas A&M in response to the need to have a single phase flow meter that is insensitive to upstream flow conditioning. Figure 1 shows an example of the slotted plate. The slots have a radial orientation and extend very close to the pipe wall. In this manner, the flow does not have to accelerate to the pipe centerline to pass through the meter. It has been shown that these slotted plates are insensitive to upstream velocity profiles and are only half as sensitive to swirl as a standard orifice plate. Morrison, et al.[2] illustrated the slotted plate varied $\pm$0.25% under flow conditions where a standard orifice plate varied over 6%. Both plates had beta ratios of 0.50 as shown in Figure 1.

As part of a contract with the Gas Research Institute, the response of the slotted plate to wet gas was investigated. It was found that the pressure drop across the plate increases monotonically with increased gas wetness and that no upstream mixing plate is required. In fact, upstream mixing plates have no effect upon the response of the meter compared to the naturally occurring flow in the pipe. This encouraged the investigators to determine if the slotted plate could be used as a two phase flow meter.

Flow visualizations of the slotted plate operating in two phase flows show that the turbulence generated by the plate result in the gas and liquid becoming very well mixed downstream for the plate. This presented several options on the design of a two phase meter since as the venturi and orifice, it is sensitive to both density and velocity. Due to the relatively homogenous flow downstream of the slotted plate, it can be used as both a flow meter and a mixing device with the placement of a venturi or densitometer device downstream of the slotted plate. In fact, given the volumetric flow rate the slotted DP meter will determine the flow's density or given the flow density, it will measure the flow rate.

The response of a DP meter varies with the amount of obstruction produced by the meter. This is typically represented by the ratio which is the square root of the ratio of the open area of the device to the cross sectional area of the pipe. The response of the meter to two phase flow also varies with b ratio. Two different two phase flow meters have been developed at Texas A&M University. One uses a slotted plate upstream of a venturi and the other uses two slotted plates of differing beta ratios. Since the slotted plates are not sensitive to upstream flow conditioning, both meters are actually evaluated simultaneously with a = 0.43 slotted plate five pipe diameters upstream of a = 0.467 slotted plate which is followed by a =0.527 venturi two pipe diameters downstream. The two slotted plates have been reversed in order and it has been shown that the mixing provided by the upstream plate does not alter the response of the downstream plate from what is was when it was upstream. Typically, the flow in the Texas A&M facility is stratified as it approaches the meter. Some additional studies were performed with a = 0.501 orifice plate used in place of the venturi. The standard orifice plate results are not presented since the uncertainties for it are substantially larger than for either the slotted plate or venturi meters.

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The flow loop used in this study uses air supplied by screw compressors at 7 atmospheres gage. A dual rotor turbine flow meter calibrated using sonic nozzles measures the air flow rate. The sonic nozzles were calibrated by CEESI. This provides an uncertainty in the the air flow of approximately 0.5% of measured value. The liquid is water supplied by a pump and metered by one of two coriolis flow meters. The coriolis meters are used since they provide a measurement of the water density and flow rate. Uncertainties of around 0.2% are obtained from the water flow meters. Pressures and temperatures of the air and water are recorded before the two are mixed upstream of the two phase flow meter. An electropneumatic valve is located downstream of the meter run. This valve is used to maintain the desired pressure in the meter run. Upstream valves on the air and water lines are used to set the flow rates.

RESULTS

Figures 2-3 show how the discharge coefficient of each meter varies as the quality (X) and the differential pressure divided by the upstream line pressure (dP/P). Quality is equal to the mass flow rate of the gas divided by the total mass flow rate (gas and liquid). This is different that the void fraction or gas volume fraction but is directly related to each. It was selected since it does not vary with line pressure, only the individual component mass flow rates. The value dP/P is used to calculate the expansion factor for standard orifice flow meters. It was found to be an important parameter for two phase flows.

The common method used to determine the individual component flow rates is to follow the lead of Murdock[1] and calculate the ratio of the gas volumetric flow rate as indicated if only gas is flowing through the pipe (Qi) and divide that by the actual gas volumetric flow rate (Qac). This ratio as measured in a calibration facility is then expressed as a function of some other parameters. Murdock's relationship required information about discharge coefficients for liquid only and gas only flow rates and is rather cumbersome to use. Most recent results are presented in terms of the Lockhart-Martinelli number. This is equal to: $LM = \frac{1-X}{X}\sqrt{\frac{\rho_{gas}}{\rho_{liquid}}}$. Depending upon the parameter used, the accuracy of the function relating the measured pressure drop and fluid density will be affected. This is illustrated in the remaining figures shown. The ratio, Qi/Qac, is presented as a function of quality (X), the Lockhart-Marinelli number (LM) and the nondimensionalized density, * where $\rho^* = \frac{\rho_{mixture} - \rho_{gas}}{\rho_{liquid} - \rho_{gas}}$. It was found that the parameter that produced the best accuracy varied with each flow meter.

The first step in analyzing the measurements is to determine equations for the gas only discharge coefficient. These are obtained from the following equation:

$$C_d = \frac{\dot{m}\sqrt{1-\beta^4}}{A\beta^2\sqrt{2\rho\Delta P}}$$

where $\dot{m}$ is the mass flow rate and A is the pipe cross-sectional area. The standard deviations of the gas only discharge coefficient curve fits were 0.24, 0.32, and 0.70% for the = 0.43 slotted plate, 0.467 slotted plate, and 0.527 venturi respectively.

Given the gas only discharge coefficients, the indicated gas only flow rates (Qi) were calculated for the two phase flows using the gas density, gas only discharge coefficients, and measured pressure differential. These were divided by the actual gas flow rate and the ratios plotted. These results were plotted with dP/P as a parameter. It was determined that this parameter was an important secondary effect. The b = 0.43 slotted plate results (Figures 6-8) show some interesting trends in that Qi/Qac increased as the quality decreased but showed a marked decrease below qualities of 0.5. The same trend is apparent when plotted as a function of the Lockhart-Martinelli number but without quite the same prominence. However, when using r* as the independent variable, this decrease is not apparent. Evidently, the manner in which density is compensated for is of great importance. When determining a flow equation using the three independent parameters, X, LM, and r*, along with dP/P, standard deviations of 1.4%, 0.92% and 0.99% were achieved. This indicates that it is possible to compute the gas flow rate to within 2% accuracy for a 95% confidence interval.

The same procedures were used for the b=0.467 slotted DP meter and the b=0.527 venturi meter. These results are shown in Figures 9-14. For the b=0.467 slotted plate, the Lockhart Martinelli number produces the best results with a standard deviation of 0.99%, very similar to the b=0.43 slotted plate. However, the venturi is best represented by the quality showing very little effect of dP/P. The standard deviation is 1.7% for this case compared to 2.3% for the Lockhart-Martinelli representation and 3.5% for r*. The uncertainty for the two slotted plates are comparable at 95% confidence intervals of 1.8% and 2.0% for the b=0.43 and 0.467 slotted plates compared to 3.4% for the venturi. Even though the venture was placed behind two slotted plates, which should thoroughly mix the gas and liquid, the uncertainty was almost twice as large.

CONCLUSIONS

The absolute accuracy of DP meters used in two phase flow meters is of great importance since the normal technique is to use two meters and solve simultaneously for the actual gas flow rate. It can be quite difficult to obtain accurate results given that the response of the different meters are very similar and the solution will vary wildly with small inaccuracies in the measured differential pressure, gas density, or liquid density. Errors of less than 0.5% in measured values can cause very large errors in the calculated gas flow rate. Therefore, it is of the utmost importance to use meter elements and instrumentation that are as accurate as possible. This problem is emphasized by the desire to have the same dynamic range for the gas flow only while having significant variance in liquid present. This produces a much larger range of differential pressures resulting in either much higher pressures differentials than in single phase orifice runs or the need for highly accurate low differential pressure measurements. The higher differential pressures are possible with the slotted plate since the mechanical design allows for larger pressure forces without plate deflection. Even though the slotted plate generates permanent head losses less than a comparable orifice plate, the increased pressure differentials result in larger permanent head losses. The current work has shown that the venturi/b=0.43 slotted plate combination is less sensitive to differential pressure measurement errors than the b=0.43-0.467 combination. However, the two slotted plate combination is close to having the same sensitivity. This shows how even though the response characteristics are more similar, the higher accuracy of two slotted plates almost offset the more distinct response curves due to the higher uncertainty in the venturi.

[1]Murdock, J.W., “Two-Phase Flow Measurements with Orifices,” J. Basic Engr. Vol. 84, pp 419-422, Dec. 1962.

[2]Morrison, G.L., Hall, K.R., Holste, J.C., Macek, M.L., Ihfe, L.M., DeOtte, R.E., Jr., and Terracina, D.P.,"Comparison of Orifice and Slotted Plate Flowmeters," Flow Meas. Inst., Vol. 5, No. 2, 1994, pp. 71-77.

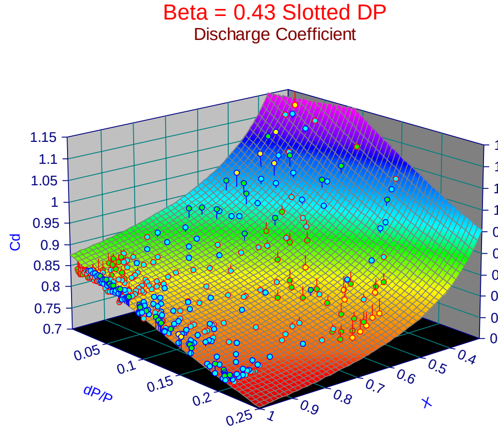

Figure 2. Beta=0.43 Slotted DP Meter Cd(X,dP/P).

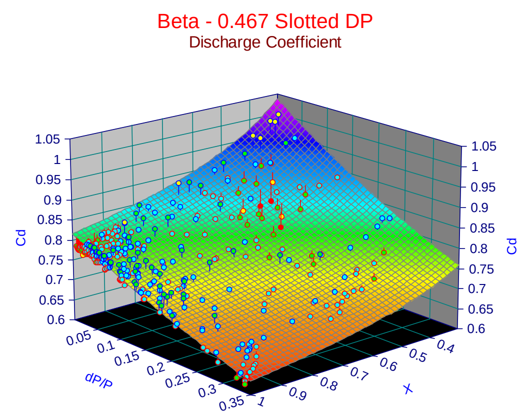

Figure 3. Beta = 0.467 Slotted DP Meter, Cd(X,dP/P)

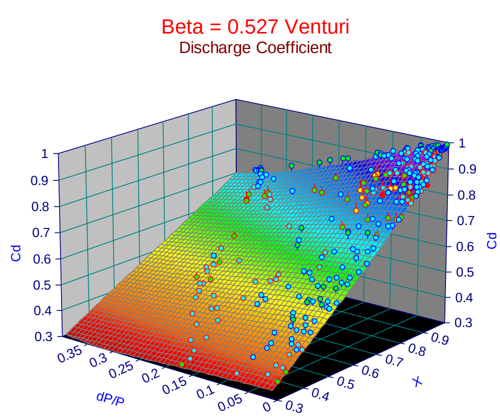

Figure 4. Beta = 0.527 Venturi, Cd(X,dP/P

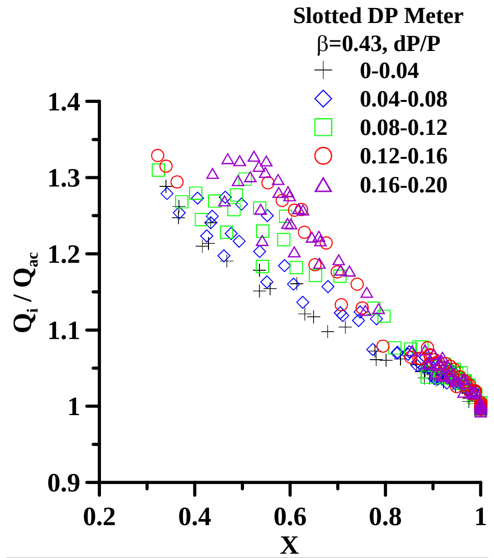

Figure 6. Qi/Qac variance with quality, X, β=0.43 Slotted Plate

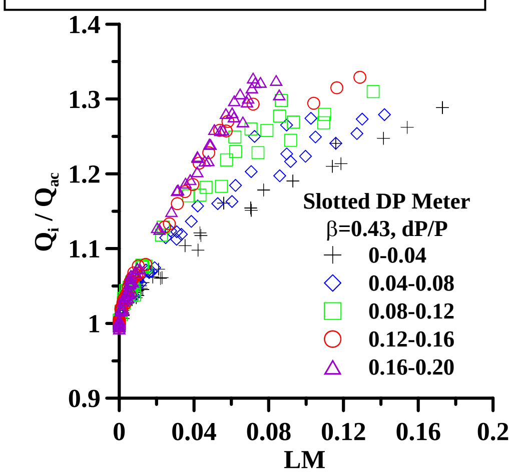

Figure 7. Qi/Qac variance with Lockhart Martinelli number, β=0.43 Slotted Plate

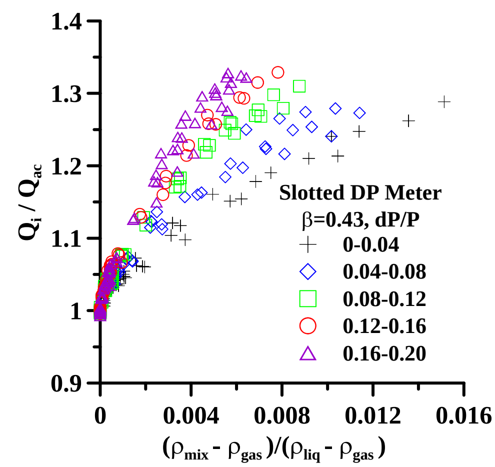

Figure 8. Qi/Qac variance with ρ*, β=0.43 Slotted Plate

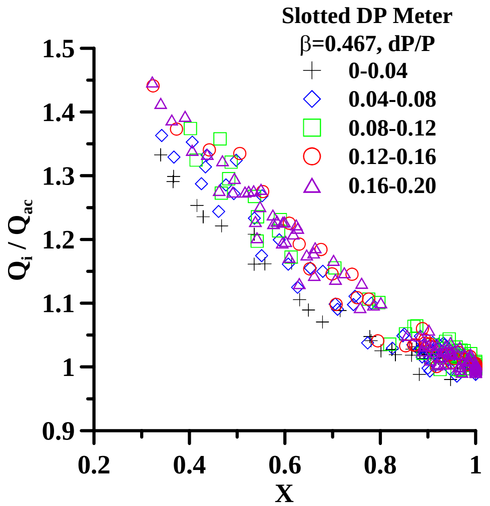

Figure 9. Qi/Qac Variance with Quality, β=0.467 Slotted Plate.

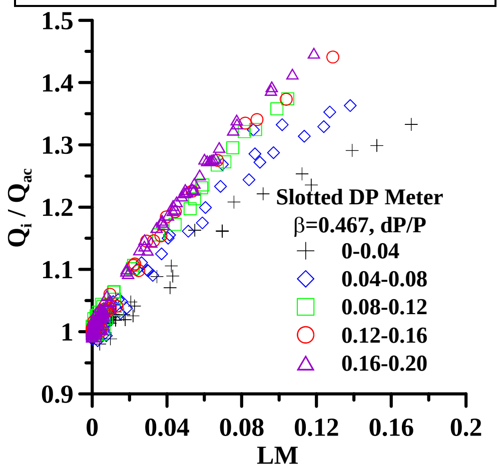

Figure 10. Qi/Qac Variance with Lockhart Martinelli Number, β=0.467

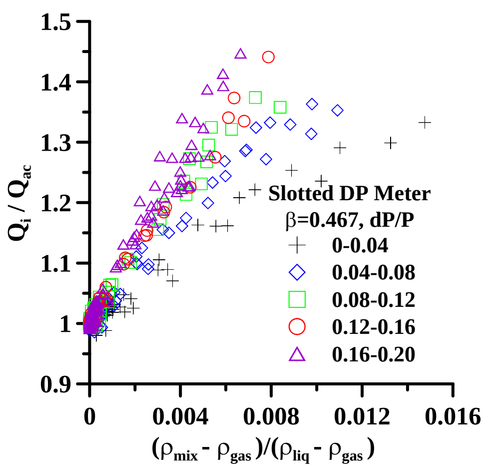

Figure 11. Qi/Qac Variance with ρ*, β=0.467 Slotted Plate

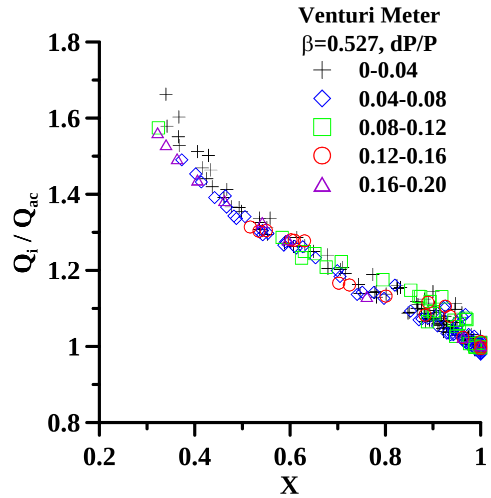

Figure 12. Qi/Qac Variance with Quality, β=0.527 Venturi.

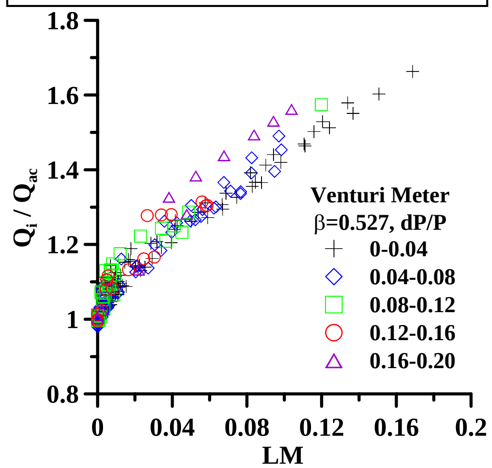

Figure 13. Qi/Qac Variance with Lockhart Martinelli Number, Venturi

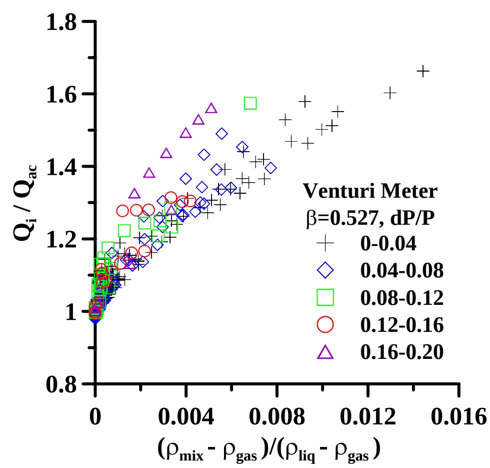

Figure 14. Qi/Qac Variance with ρ*, β=0.527 Venturi