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Wet Gas Metering Using Combination of Differential Pressure and SONAR Flow Meters

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1. ABSTRACT

A method to measure the gas rates and liquid rates of Type I and Type II wet gas flows is presented. The approach combines a differential pressure-based (DP) gas flow meter with a SONAR-based flow meter to provide two independent measurements of the wet gas mixtures, each with distinct and repeatable over-report characteristics due to wetness. The outputs of the two devices are then interpreted to provide gas rate and liquid rate of wet gas flows.

Experiments were conducted to validate the ability of the combination of DP and SONAR meters to measure gas and liquid rates of wet gas flows. The over-report due to wetness of a 0.6 beta ratio venturi (DP meter) and a clamp-on SONAR-based flow meter were characterized over a wide range of flow conditions broadly representative of oil and gas production and processing conditions. The experimentally determined over-report due to wetness of each was shown to be in good agreement with theoretical models predicting the over-report associated with well-mixed gas / liquid mixtures for each device.

The ability of the combination of the DP and SONAR meters to determine gas and liquid flow rates was evaluated using experimentally determined wetness sensitivity coefficients to solve for the gas and liquid rates based on the outputs of the venturi and SONAR meters installed in series on a test loop. The combination was shown to accurately measure gas flow rates to within ~+/-2% and liquid rates to within +/-10% over a wide range of wet gas flows with gas oil ratios ranging less than 4000 scft/bbl to greater than 100,000 scft/bbl.

The results of these experiments suggest that the combination of a clamp-on SONAR-based flow meter and a differential pressure-based device is a viable means to provide both liquid and gas flow rates of type I and II wet gas flows.

2. INTRODUCTION

Access to accurate and cost-effective means for measuring gas flows is important for a wide range of upstream oil and gas measurement applications. While measuring dry gas flow rate is a well-served application for a wide range of gas flow metering technologies, accurate and cost-effective measurement of wet gas flow remains a long-standing multiphase flow measurement challenge for the upstream oil and gas industry. Upstream gas measurement applications which require wet gas measurement solutions can be subdivided into two categories: 1) applications known to contain liquids, or 2) applications may contain liquids, either continuously or sporadically. The first group is the classic wet gas application such as well head production, and the second group contains flows such as separator gas outlet flows.

Currently, differential pressure-based meters are used for the overwhelming majority of gas rate measurements. For accurate measurement, it is assumed that the gas is dry, i.e. contains no entrained liquids. While this assumption may be valid for many applications, most differential pressure-based gas measurements provide no real time indication or quantification of wetness. Since the presence of even small amounts of entrained liquid can result in significant over-reporting gas rates, an unnoticed introduction of wetness to an assumed-dry gas stream can result in significant over-reporting of gas flow rates. As such, the commercial options for measuring gas continuous flows containing entrained liquids are far more limited than those available for dry gas measurement.

The effectiveness of any wet gas metering approach depends in large part on the application and the objective of the measurement. In an effort to classify wet gas applications, the literature (Mehdizadeh, 2002) has classified wet gas metering into three types of applications using the Lockhardt-Martinelli number (LM) as a measure of wetness. The Lockhardt-Martinelli number is can be viewed as square root of the ratio of the dynamic head associated with the liquid component compared to that of the gas component if the gas and liquids were flowing separately.

$$LM \equiv \sqrt{\frac{\rho_l V_{s_l}^2}{\rho_g V_{s_g}^2}} = \sqrt{\frac{\rho_l}{\rho_g}}\sqrt{\frac{A^2 V_{s_l}^2}{A^2 V_{s_g}^2}} = \sqrt{\frac{\rho_l}{\rho_g}}\frac{Q_l}{Q_g} \quad (1)$$

Where ρ is the density, V_s is the superficial velocity, A is the cross sectional area of the pipe, Q is volumetric flow rate, and the subscripts l and g denote the liquid and gas components respectively.

Type I wet gas applications are characterized by low wetness ($X < 0.02$) and typically, the primary interest in this type of wet gas measurement is an accurate measure of the gas rate. The over-report characteristics of differential pressure-based flow meters due to wetness have been well classified in the literature (Stevens, 2005). Thus, if the wetness level of a wet gas mixture is either known or can be estimated, the impact of the wetness on the gas flow measurement can be mitigated by correcting for the over-report. Thus, a common approach for Type 1 gas measurement is to use a standard differential pressure gas flow meter and correct the gas flow measurement based on some estimate of the wetness.

Type II wet gas applications have wetness levels in the range of $0.02<X<0.3$. In these applications, typically both the gas rate and the liquid rate are of interest. Given the objective of measuring both the gas and the liquid rates, Type II wet gas measurements are inherently more difficult than type I. A common approach used for Type II applications is to use multiple differential pressure-based devices that have repeatable, but distinct, wetness over-report characteristics in series. The two independent measurements enable the determination of both gas and liquid flow rates. As noted in the literature (Agar, 2002 and Stewart, 2003), the challenge for these approaches is to ensure that the over-report due to wetness of each device is sufficiently repeatable and sufficiently distinct to enable adequate wet gas measurement.

Type III wet gas meters address flows with Lockhardt-Martinelli number greater than 0.3. In these applications, typically the amount of oil, water and gas are sought, and Type III wet gas applications are often viewed as a subset of the conditions typically addressed with partial separators and/or more general multiphase flow meters.

2.1 Scope

This paper describes a novel approach for Type I and Type II wet gas applications and presents flow loop data validating the concept. The approach combines SONAR-based flow measurement with differential pressure-based measurements to provide a convenient, robust solution for wet gas applications. A data set is presented that characterizes the over-report due to wetness of a SONAR meter and a venturi meter for Type I and Type II wet gas applications. A relatively straight-forward approach is presented to parameterize the wetness sensitivity of the venturi meter and the SONAR meter tested here in this work. While this characterization was used as the basis for evaluating the wet gas metering capability of the combination, it is recognized that specifics of the wet gas sensitivity parameterization is not unique. The work does, however, demonstrate the ability of the DP plus SONAR wet gas system to determine both gas and liquid flow rates of wet gas flows, without requiring any a priori knowledge of the wetness.

The experimental set-up utilized a venturi meter as the differential pressure flow measurement device. While it is recognized that the other types of DP meters have different over report characteristics, the over-report characteristic of other DP devices are sufficiently similar the device utilized in this work that conclusions should serve to validate the DP plus SONAR concept for any combination of DP meter plus SONAR meters in which the over-report characteristic of the DP device is known.

2.2 SONAR Flow Measurement

SONAR-based flow measurement leverages SONAR processing technology to determine the speed at which coherent flow patterns convect past an array of sensors. These naturally-generated, coherent flow patterns exist in virtually all types of industrial fluid flows, allowing SONAR-based flow measurement to be broadly applicable to a wide range of single and multiphase flows. The SONAR-based flow measurement technique was developed in 1998 for use in the upstream oil and gas industry and was the flow measurement principle used in the world's first downhole, fiber-optic flow meter on the Mars platform in 2000 (Kragas, 2001). Since then, SONAR-based flow measurement has evolved to include clamp-on versions and has been applied to a wide range of long-standing flow measurement challenges, with a focus on under-served multiphase applications within several industries, including Oil and Gas, Oil Sands, Mining, and Pulp and Paper (Gysling, 2003, and Gysling et al, 2005).

2.3 SONAR plus Differential Pressure Meters for Wet Gas Measurement

Unlike differential pressure devices, SONAR meters are comparatively insensitive to wetness. SONAR measurements are derived from a direct measurement of the speed at which flow moves past stationary sensors. Thus, for well mixed flows, liquid particles entrained in the flow have little influence on the measured flow rate. This insensitivity to wetness combines well with the well-documented wetness sensitivity of differential pressure-based devices to form a Type II wet gas meter. The approach is shown schematically in Figure 1. Conceptually, measuring the differential pressure across a DP device and measuring the mixture velocity with a SONAR meter provides a basis to determine flow rate and wetness of wet gas flows.

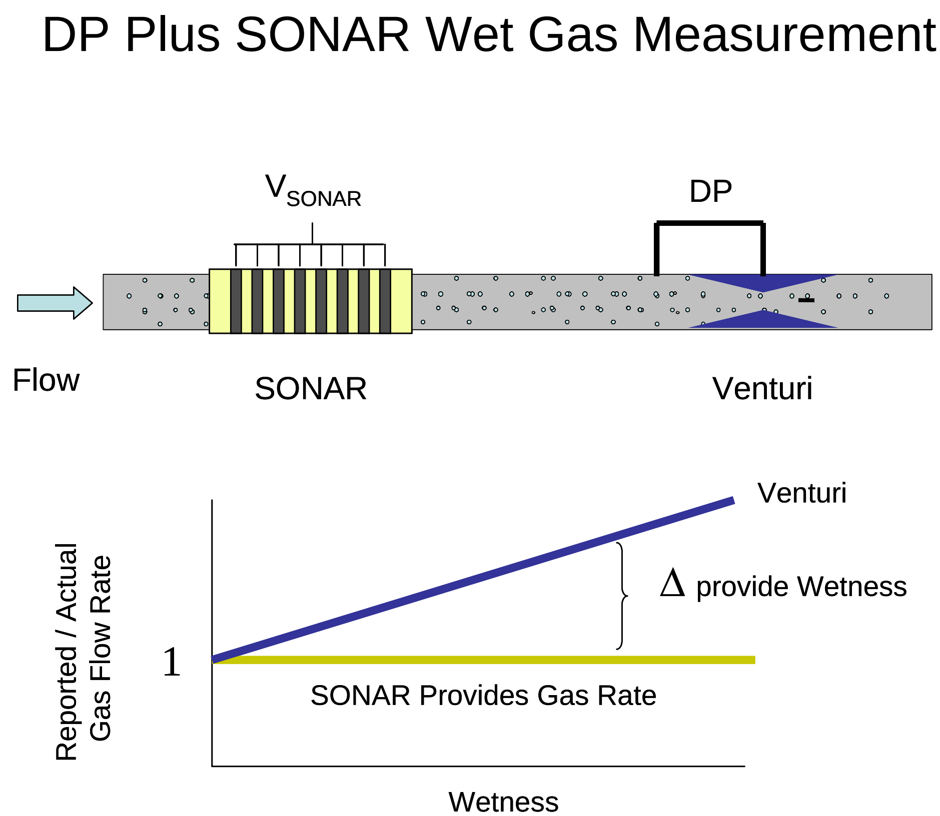

Figure 1: Schematic of Combination of DP plus SONAR Meters for Wet Gas Measurement

Since SONAR meters are available as clamp-on meters, the combination of SONAR and DP meters becomes an attractive clamp-on retrofit to convert existing DP meters operating in wet gas applications to provide accurate Type I and Type II wet gas meters.

3. DISCUSSION

3.1 Differential Pressure-Based Flow Meters Over-Report Measuring Wet Gas

For well mixed flows, it is well known that differential pressure-based flow meters characteristically over-report gas flow rates in the presence of wetness. Differential pressure devices measure the pressure change associated with a known change in flow path geometry. To accurately determine flow rate, the density of the fluid is required. For well mixed wet gases, the effective density of the gas / liquid mixture is strongly influenced by wetness, causing significant increase in differential pressure associated with a given flow path geometry with increasing wetness at constant gas flow. Within the wet gas community, this over-reporting due to wetness is expressed as the ratio between the flow rates reported with liquid present to the flow rate reported without the liquid present.

Assuming well mixed flows of low axial Mach numbers with no phase change between the gas and liquid, the over-report *(OR)* of the DP device can be expressed theoretically as:

$$OR = \sqrt{\frac{\Delta P_{TP}}{\Delta P_g}} = \sqrt{\frac{C_{D_{TP}}\,(\frac{1}{\beta^4}-1)\,{}^1\!/\!_2\,\rho_{TP}V_{TP}^2}{C_{D_g}\,(\frac{1}{\beta^4}-1)\,{}^1\!/\!_2\,\rho_g V_{s_g}^2}} \qquad (2)$$

Where V_{TP} is the mixture velocity for the two phase (TP) flow and is V_{sg} the superficial gas velocity for the gas only flow. C_D is the discharge coefficient and β is the square root of the throat diameter to the upstream diameter of the DP device.

For mixtures with small liquid phase fractions, the mixture velocity with the liquid present is not significantly different from that of the dry gas velocity (V_{TP}/V_g ~1)). Mixture density can be expressed as a volumetrically weighted average of the component densities:

$$\rho_{TP} \equiv \phi_{gas}\rho_{gas} + \phi_{liq}\rho_{liq} \qquad (3)$$

Applying these assumptions to equation (2), over-report for well mixed wet gas flows through differential pressure devices can be expressed as a simple function of the liquid to gas mass ratio (LGMR):

$$OR = \sqrt{\frac{\Delta P_{wet}}{\Delta P_{dry}}} = \sqrt{1+\frac{\dot{m}_{liq}}{\dot{m}_{gas}}} = \sqrt{1+LGMR} \qquad (4)$$

This theoretical formulation of the over-report, applicable well mixed flows with low liquid void fractions, serves as a simple, but useful, first principles estimate of the impact of entrained liquids on the over-report function of DP meters.

The well mixed formulation derived above differs from the classic idealized analysis of Murdock aimed at flows through orifice plates (Murdock, 1962). Although the physics is similar, in Murdock's idealized formulation it is assumed that the gas and the liquid phases remain separate and do not transfer momentum between each other as they flow through the orifice plate. Applying a constant pressure boundary condition upstream and downstream of the orifice to both the gas and the liquid streams results in the liquid phase flowing significantly slower than the gas phase as the two streams pass through the orifice. In this idealized formulation, the liquid displaces the flow area through the orifice remaining for the gas and resulting in an increase in the differential pressure across the orifice due to the liquid. This stratified flow model results in a theoretical over-report due to wetness being directly proportional to the Lockhardt-Martinelli parameter (LM).

$$OR_{DP} = \sqrt{\frac{\Delta P_{TP}}{\Delta P_{dry}}} = 1 + LM \qquad (5)$$

$$\text{Where } LM \equiv \sqrt{\frac{\dot{m}_{liq}Q_{liq}}{\dot{m}_{gas}Q_{gas}}} = \sqrt{\frac{\rho_{gas}}{\rho_{liq}}}LGMR$$

3.2 SONAR Meter Over-Report Measuring Wet Gas

For well mixed flows, the theoretical over-report of SONAR meters due to wetness can be calculated by assuming that the SONAR meter continues to accurately measure the mixture volumetric flow rate. Thus, the well-mixed theoretical over-report for the SONAR meter is given by:

$$OR_{SONAR} = \frac{Q_{liq} + Q_{gas}}{Q_{gas}} = 1 + \frac{Q_{liq}}{Q_{gas}} = 1 + \frac{\rho_{gas}}{\rho_{liq}} LGMR = 1 + \sqrt{\frac{\rho_{gas}}{\rho_{liq}}} LM \quad (6)$$

3.3 Experimental Set-up

Experiments were conducted on the 4 inch multiphase flow loop at the Colorado Engineering Experimental Station, Inc.(CEESI) facility in Nunn, Colorado to evaluate the performance of a DP plus SONAR wet gas meter. A picture of the SONAR meter and venturi meter installed in the loop is shown in Figure 2. The flow facility generated fully-developed wet gas flows of known input liquid rate and input gas rate. The flow was first passed through a SONAR meter, clamped on to a standard 4inch, schedule 80 pipe, and then through a 0.6 beta ratio standard venturi meter. Stoddard Oil and Natural Gas were used as the working fluids.

Figure 2: Picture of DP plus SONAR Configuration installed on 4 inch Multiphase Loop at CEESI (Flow is from right to left)

3.4 Test Matrix

The performance of the combination was characterized at pressures of 200 psi and 1000 psi (gas-to-liquid density ratios of 0.013 and 0.08, respectively), over flow velocities ranging from 20 ft/sec to 80 ft/sec, and for wetness ranging from 0.0 to 0.2 Lockhardt-Martinelli numbers. The densimetric Froude number, defined below, ranged from 1.5 to 7.0. The data is presented in Table 1 for the 200 psi set points and in Table 2 for the 1000 psi set points. For each pressure and nominal flow rate, the first set-point was a dry gas calibration point. For each subsequent wet gas test point, the input liquid rate was adjusted as the gas flow rate was maintained to achieve the desired wetness.

4. RESULTS

The results of the test are tabulated in Tables 1 and 2 for the 200 psi and 1000 psi pressures, respectively. The results can be considered in two parts. The first part evaluates the response of each of the meters to wetness independently. As described above, wet gas measurement systems based on dissimilar wetness sensitivities require each device to have a repeatable and distinct response to wetness. As described above, the response of venturi meters, orifice plates, and V-cones is well-documented in the literature, and therefore, the novelty of this aspect of the data is focused on the over-report characteristics of the SONAR meter.

The second part examines the performance of the combination of the SONAR meter and the venturi meter as a wet gas metering system. For this section, a methodology to parameterize the wetness sensitivity of the two devices was developed. The detailed overall system accuracy will depend, to some extent, on the details regarding the characterization of the wetness sensitivity. Testing two devices in series on the same line simultaneously ensures that both devices are presented practically identical conditions, an important aspect in assessing the performance of the combination of the two devices as a Type II wet gas metering system.

Table 1: Test Matrix Reference Conditions and Over Reports at 200 psi

	Set Point Targets		*Input Reference Flow Rates*				*Flow Parameters*						
Point No.	*VSgas (ft/s)*	*Loop Pressure (psig)*	*Gas density (lb/ft3)*	*Qgas (acfh)*	*Liquid Density @ Meter P and T (lb/ft3)*	*Qliq @ Meter (ft3/hr)*	*LM*	*Liquid to gas Mass Ratio*	*Gas Volume Fraction*	*Gas Oil Ratio (scft/b)*	*Densimetric Froude Number*	*Venturi over-report*	*SONAR OverReport*
1	80	200	0.595	22741	45.98	0.0	0.000	0.000	100.0%		2.91	0.00%	0.00%
2	80	200	0.621	22268	46.09	492.8	0.191	1.586	97.8%	3352	2.95	62.83%	-0.88%
3	80	200	0.614	22542	46.01	398.8	0.153	1.283	98.3%	4185	2.96	53.73%	0.68%
4	80	200	0.609	22694	45.96	328.4	0.126	1.059	98.6%	5103	2.97	46.13%	1.59%
5	80	200	0.606	22724	45.95	266.3	0.102	0.864	98.8%	6290	2.96	40.91%	0.99%
6	80	200	0.602	22894	45.94	194.9	0.074	0.633	99.2%	8635	2.97	33.81%	-0.07%
7	80	200	0.598	22981	45.93	138.6	0.053	0.452	99.4%	12155	2.97	27.12%	0.77%
8	80	200	0.592	22951	45.91	67.5	0.026	0.224	99.7%	24822	2.95	15.49%	1.77%
9	80	200	0.588	23067	45.93	27.6	0.011	0.092	99.9%	60830	2.94	7.15%	2.45%
10	80	200	0.585	22918	45.95	13.4	0.005	0.045	99.9%	124091	2.91	3.97%	2.52%
11	80	200	0.580	22719	45.98	0.0	0.000	0.000	100.0%		2.87	-1.07%	0.20%
12	60	200	0.629	17607	46.00	0.0	0.000	0.000	100.0%		2.31	0.00%	0.00%
13	60	200	0.644	17710	46.07	373.6	0.178	1.475	97.9%	3472	2.37	57.43%	3.61%
14	60	200	0.640	17555	46.08	309.0	0.149	1.242	98.3%	4152	2.34	48.53%	3.72%
15	60	200	0.637	17643	46.09	259.6	0.125	1.045	98.6%	4959	2.34	42.52%	4.17%
16	60	200	0.634	17447	46.11	205.4	0.100	0.842	98.8%	6187	2.31	35.54%	4.78%
17	60	200	0.631	17542	46.12	156.9	0.076	0.643	99.1%	8137	2.32	29.21%	4.19%
18	60	200	0.628	17631	46.12	103.5	0.050	0.425	99.4%	12369	2.32	22.74%	3.58%
19	60	200	0.624	17432	46.12	52.0	0.026	0.218	99.7%	24315	2.28	13.43%	2.67%
20	60	200	0.620	17583	46.12	20.5	0.010	0.086	99.9%	61854	2.29	6.29%	2.65%
21	60	200	0.618	17676	46.11	10.2	0.005	0.043	99.9%	124830	2.30	3.52%	2.39%
22	40	200	0.608	11631	46.08	0.0	0.000	0.000	100.0%		1.50	0.00%	0.00%
23	40	200	0.618	11762	46.19	249.3	0.183	1.570	97.9%	3413	1.53	49.75%	10.68%
24	40	200	0.614	11859	46.15	205.4	0.150	1.291	98.3%	4173	1.54	44.31%	9.23%
25	40	200	0.611	11891	46.13	174.1	0.127	1.096	98.6%	4930	1.54	39.96%	8.43%
26	40	200	0.609	11758	46.11	137.8	0.102	0.880	98.8%	6159	1.52	33.71%	6.76%
27	40	200	0.606	11812	46.09	103.7	0.077	0.663	99.1%	8212	1.52	28.33%	5.70%
28	40	200	0.604	11791	46.07	68.7	0.051	0.442	99.4%	12357	1.52	21.40%	3.05%
29	40	200	0.601	11724	46.05	34.6	0.026	0.225	99.7%	24365	1.50	13.91%	1.19%
30	40	200	0.598	11814	46.03	13.3	0.010	0.087	99.9%	63583	1.51	7.21%	-0.35%
31	40	200	0.596	11884	46.02	6.7	0.005	0.043	99.9%	128160	1.52	4.22%	-0.64%

Table 2: Test Matrix Reference Conditions and Over Reports at 1000 psi

	Set Point Targets		*Input Reference Flow Rates*				*Flow Parameters*					*Over Report due to Wetness*	
Point No.	*VSgas (ft/s)*	*Loop Pressure (psig)*	*Gas density (lb/ft3)*	*Qgas (acfh)*	*Liquid Density @ Meter P and T (lb/ft3)*	*Qliq @ Meter (ft3/hr)*	*LM*	*Liquid to gas Mass Ratio*	*Gas Volume Fraction*	*Gas Oil Ratio (scft/b)*	*Densimetric Froude Number*	*venturi over-report*	*SONAR OverReport*
32	60	1000	3.544	17312	44.34	0.0	0.000	0.000	100.0%		5.50	0.00%	0.00%
33	60	1000	3.567	17238	44.39	366.4	0.075	0.262	97.9%	16058	5.49	16.73%	1.92%
34	60	1000	3.558	17335	44.37	295.1	0.060	0.211	98.3%	20037	5.52	13.84%	1.65%
35	60	1000	3.552	17199	44.36	215.7	0.044	0.156	98.8%	27185	5.47	10.53%	1.73%
36	60	1000	3.550	17235	44.35	180.8	0.037	0.130	99.0%	32489	5.48	9.05%	1.59%
37	60	1000	3.546	17266	44.34	138.7	0.028	0.100	99.2%	42428	5.49	7.21%	1.62%
38	60	1000	3.544	17298	44.34	91.4	0.019	0.066	99.5%	64478	5.49	5.03%	1.40%
39	60	1000	3.539	17339	44.34	46.6	0.010	0.033	99.7%	126722	5.50	3.05%	1.27%
40	60	1000	3.537	17316	44.34	22.9	0.005	0.017	99.9%	257065	5.49	2.10%	1.17%
41	60	1000	3.533	17374	44.34	11.2	0.002	0.008	99.9%	528745	5.51	1.38%	0.86%
42	40	1000	3.537	11605	44.56	0.0	0.000	0.000	100.0%		3.67	0.00%	0.00%
43	40	1000	3.544	11486	44.60	244.0	0.075	0.266	97.9%	16019	3.64	16.44%	1.51%
44	40	1000	3.540	11582	44.60	383.7	0.118	0.415	96.8%	10276	3.67	23.95%	0.74%
45	40	1000	3.533	11446	44.61	195.7	0.061	0.215	98.3%	19897	3.62	13.77%	1.54%
46	40	1000	3.527	11514	44.62	148.4	0.046	0.162	98.7%	26401	3.63	10.98%	1.57%
47	40	1000	3.523	11558	44.63	122.8	0.038	0.134	98.9%	32015	3.65	9.41%	1.41%
48	40	1000	3.515	11421	44.62	90.4	0.028	0.100	99.2%	42961	3.60	7.19%	1.60%
49	40	1000	3.513	11448	44.63	61.0	0.019	0.067	99.5%	63754	3.60	5.24%	1.55%
50	40	1000	3.507	11452	44.63	30.0	0.009	0.033	99.7%	129727	3.60	3.41%	1.79%
51	40	1000	3.503	11508	44.63	14.9	0.005	0.016	99.9%	262034	3.62	2.02%	1.28%
52	40	1000	3.500	11526	44.63	7.7	0.002	0.008	99.9%	511285	3.62	1.46%	1.12%
53	80	1000	3.462	21544	44.37	0.0	0.000	0.000	100.0%		6.77	0.00%	0.00%
54	80	1000	3.490	21764	44.36	473.9	0.078	0.274	97.9%	15723	6.87	18.10%	0.99%
55	80	1000	3.480	21566	44.32	367.4	0.061	0.215	98.3%	20072	6.80	14.21%	0.76%
56	80	1000	3.473	21565	44.29	287.6	0.048	0.168	98.7%	25630	6.80	11.26%	0.54%
57	80	1000	3.470	21570	44.27	230.1	0.038	0.135	98.9%	32029	6.79	9.28%	0.57%
58	80	1000	3.466	21521	44.25	173.0	0.029	0.102	99.2%	42492	6.78	7.09%	0.44%
59	80	1000	3.464	21485	44.24	125.5	0.021	0.074	99.4%	58449	6.76	5.56%	0.64%
60	80	1000	3.462	21537	44.22	104.3	0.017	0.061	99.5%	70506	6.78	4.66%	0.47%
61	80	1000	3.460	21541	44.22	87.1	0.014	0.051	99.6%	84430	6.78	4.06%	0.49%
62	80	1000	3.460	21553	44.20	80.2	0.013	0.047	99.6%	91806	6.78	3.84%	0.52%
63	80	1000	3.460	21590	44.19	69.1	0.011	0.041	99.7%	106617	6.79	3.29%	0.41%
64	80	1000	3.458	21571	44.18	58.7	0.010	0.034	99.7%	125410	6.79	3.04%	0.46%
65	80	1000	3.455	21592	44.17	45.8	0.008	0.027	99.8%	160838	6.79	2.55%	0.45%
66	80	1000	3.453	21616	44.16	34.3	0.006	0.020	99.8%	214994	6.80	2.04%	0.34%
67	80	1000	3.452	21618	44.15	23.2	0.004	0.014	99.9%	317900	6.80	1.65%	0.32%
68	80	1000	3.449	21620	44.15	11.5	0.002	0.007	99.9%	643925	6.80	1.28%	0.34%
69	20	1000	3.491	5764	44.57	0.0	0.000	0.000	100.0%		1.81	0.00%	0.00%
70	20	1000	3.450	5766	44.53	474.9	0.296	1.059	92.4%	4125	1.80	45.58%	-19.92%
71	20	1000	3.449	5789	44.54	308.8	0.192	0.687	94.9%	6366	1.81	31.69%	-29.93%
72	20	1000	3.443	5860	44.55	154.3	0.095	0.340	97.4%	12896	1.83	17.58%	6.39%
73	20	1000	3.439	5710	44.56	78.0	0.049	0.176	98.7%	24854	1.78	9.92%	4.47%
74	20	1000	3.436	5725	44.57	38.4	0.024	0.087	99.3%	50601	1.78	5.34%	2.17%
75	20	1000	3.433	5751	44.58	16.4	0.010	0.037	99.7%	119175	1.79	2.07%	0.37%
76	20	1000	3.429	5760	44.59	7.7	0.005	0.017	99.9%	255078	1.79	0.86%	0.09%

4.1 Over Report Due to Wetness

The over-report as defined in Equation 2 is plotted versus Lockhardt-Martinelli number for the venturi meter and the SONAR meter in Figure 3. A dry gas set point was recorded for each pressure and gas rate tested. The output of the SONAR flow meter and the venturi meter was calibrated to the reference meter, and thus the offset for each dry gas point was, by definition, zero; and the over-report is due solely to the wetness. Data points 70 and 71 at the lower limit of Froude numbers and higher limits of wetness were clearly out-of-family and were excluded from the graphical presentation of the results.

As shown in Figure 3, the over-report of the venturi meter exhibits sensitivity to pressure, with the higher pressure and lower pressure data exhibiting different characteristics. For each pressure, the over-report of the venturi meter was fairly linear with Lockhardt-Martinelli number. However, noting that the idealized Murdock formulation predicts a wetness over-report equal to the Lockhardt-Martinelli number, quantitatively, the wetness sensitivity of the venturi meter tested herein was significantly greater than that anticipated by the idealized Murdock formulation.

The SONAR meter exhibited a repeatable response the wetness which was significantly reduced (~10X less) compared to that of the venturi meter. The SONAR meter exhibited quantitatively similar over-report as a function of liquid to gas mass ratio for the two pressures.

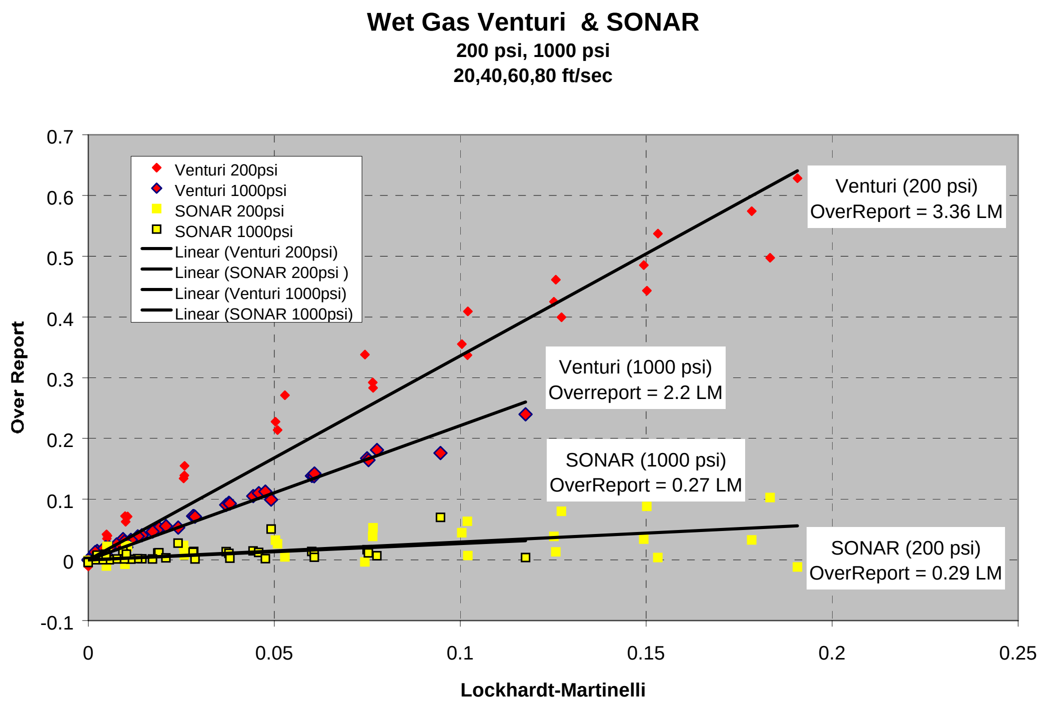

Figure 3: Over Reading of SONAR and Venturi Meters as a Function of Lockhardt-Martinelli Number

The over-report characteristic of the SONAR meter did, however, exhibit sensitivity to densimetric Froude number. The densimetric Froude Number is a non-dimensional measure of the mixedness of a gas / liquid mixture and is defined as the square root of the ratio between the dynamic pressure of the flowing gas phase to the gravimetric pressure head (ρgD where g is the acceleration due to gravity) generated by a column of liquid with a height of the diameter *(D)* of the pipe immersed in the gas phase:

$$Fr = \sqrt{\frac{\rho_{gas} V_{mix}^2}{(\rho_{liq} - \rho_{gas}) g D}} \qquad (7)$$

In flows with high densimetric Froude numbers, the gas and liquid phases tend to be well mixed. In flows with low densimetric Froude numbers, the gas and liquids tends to stratify. Figure 4 shows the over-report of the SONAR meter due to wetness as a function of Froude number with the wetness (LM) of each set point denoted.

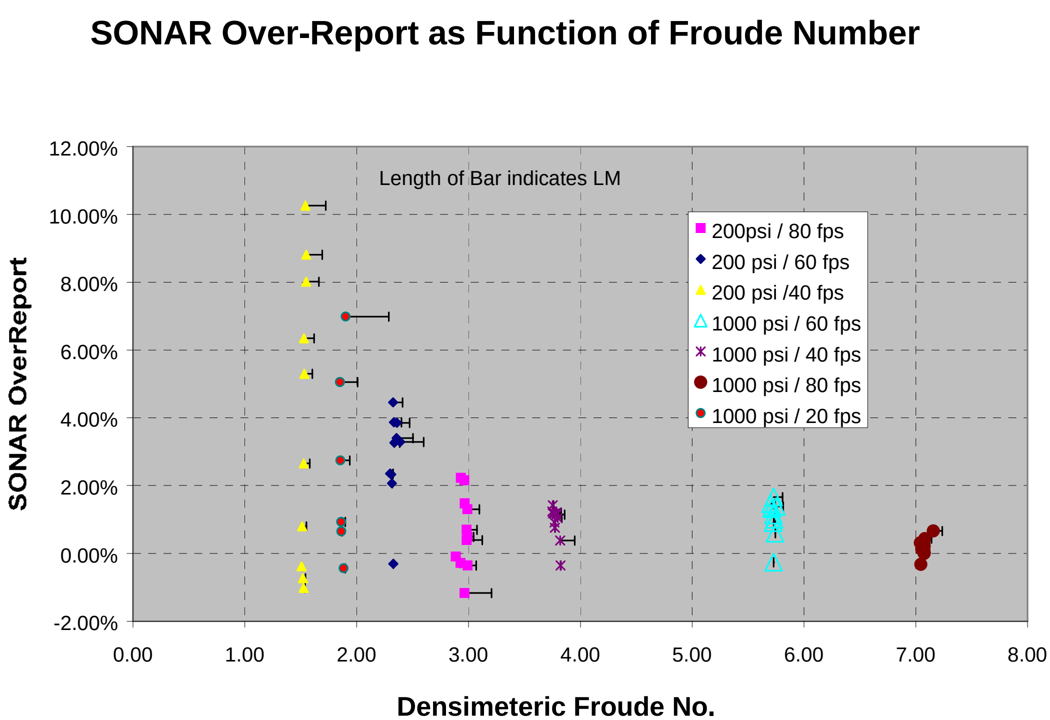

Figure 4: Over Report of SONAR meter plotted as function of Densimetric Froude Number with Wetness Denoted (Lockhardt-Martinelli Number)

For higher Froude Numbers, (FR>3), the over-report was small with little sensitivity to wetness. At low Froude numbers, while the over-report of the SONAR meter remained small compared to that of the venturi meter, the over-report increased and scaled with wetness. This effect at low Froude numbers could be attributed to the stratified liquids holding up and reducing the effective flow area of the gas and thereby increasing the velocity of the gas phase resulting in the over-report.

4.2 Venturi Meter Over Report as Function of Liquid to Gas Mass Ratio

Figure 5 shows the venturi and SONAR meters over-report data as a function of liquid to gas mass ratio. As shown, the over-report of the venturi meter appears to follow a single trend for both pressures as a function of liquid to gas mass ratio.

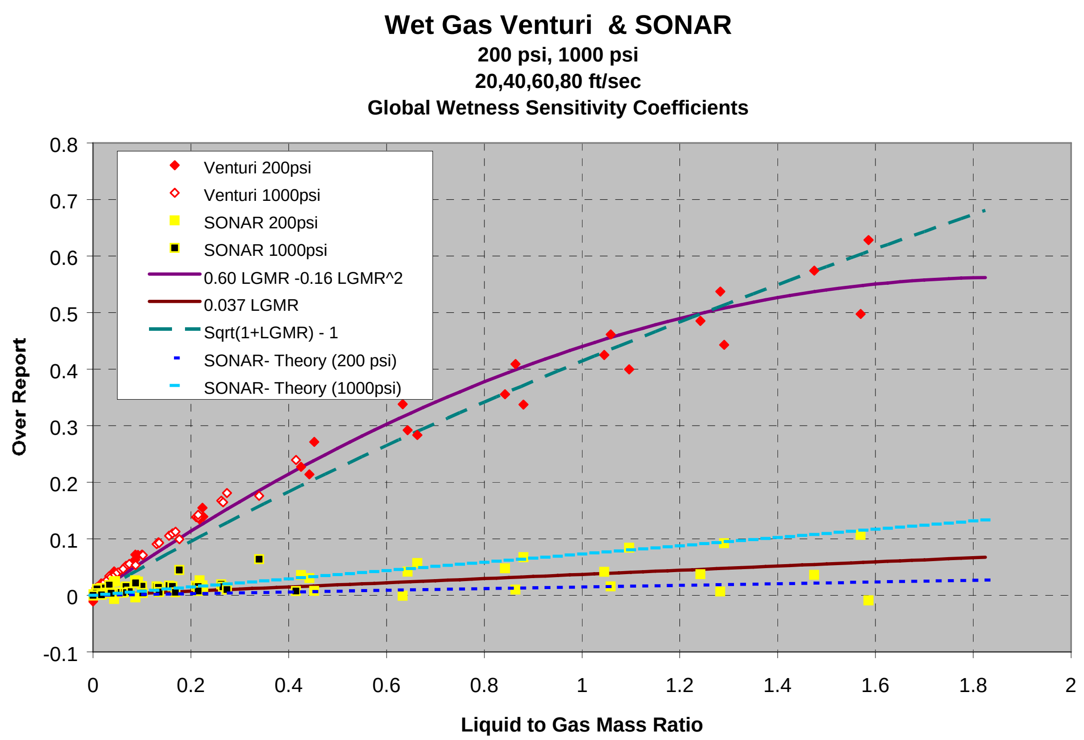

Figure 5: Over-Report of SONAR and Venturi Meters due to Wetness plotted as Function of Liquid to Gas Mass Ratio (curve fit and Theoretical result for Well mixed Model Included)

This behavior is well-predicted by the idealized, well-mixed, model of two phase flow through a venturi meter in which the over-report is a direct function of liquid to gas mass ratio, as depicted in Figure 5. As shown, the well-mixed theory represents a good approximation to the experimental over-report of the venturi over the range of Froude numbers and wetness levels tested.

4.3 Performance of Combination of SONAR and Venturi Meters

The data presented for the over-report of the SONAR and the venturi meters tested shows that the two devices have dissimilar and repeatable over-report characteristics due to wetness. To effectively utilize the combination to determine both gas rate and liquid rate simultaneously, the response of each meter to wetness requires parameterization. A schematic of the DP plus SONAR wet gas meter is shown in the Figure 6.

Although from reviewing the literature, it appears to be more standard to formulate the wetness sensitivity of the DP meter in terms of the Lockhardt-Martinelli parameter, the DP meter tested herein demonstrated a more universal response to liquid to gas mass ratio (LGMR). For this reason, it was decided to characterize the wetness sensitivity as a function of liquid to gas mass ratio in this report.

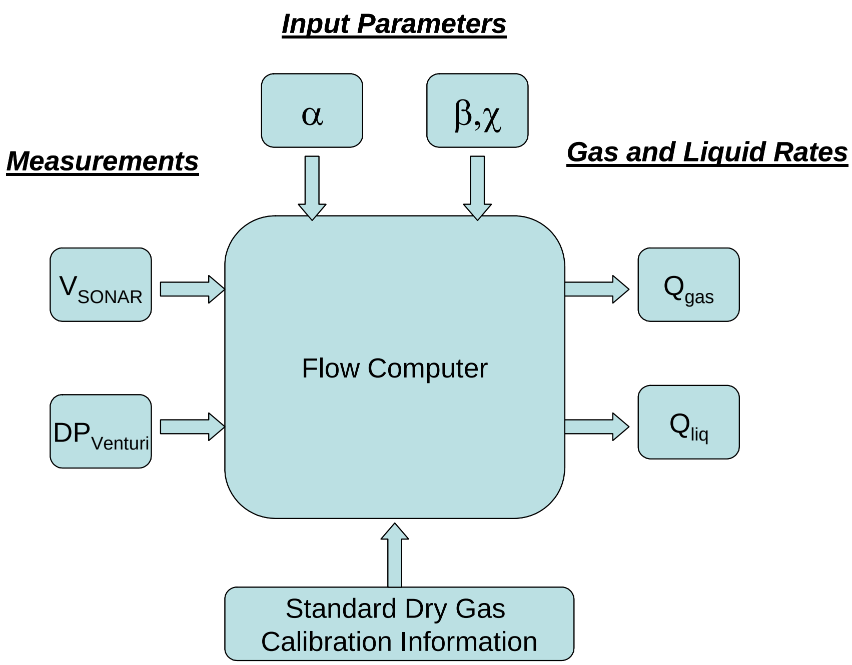

Figure 6: Schematic of the DP plus SONAR Wet Gas Metering System

4.4 Wetness Sensitivity Coefficients

In this analysis, the over-report of the SONAR and the venturi meters is parameterized as a function of a single variable, liquid to gas mass ratio. The wetness sensitivity of the SONAR meter was characterized with a linear wetness sensitivity parameter, (α), and the wetness sensitivity of the venturi was characterized with a two-coefficient (β,χ) quadratic wetness sensitivity parameters.

$$V_{SONAR} = (1+\alpha LGMR)V_{S_{gas}} \qquad (8)$$

$$V_{venturi} = (1+\beta LGMR + \chi LGMR^2)V_{S_{gas}} \quad (9)$$

Here, V_{SONAR} is the output velocity from the SONAR meter and $V_{venturi}$ is the output velocity from the venturi meter. With the wetness sensitivity coefficients defined, the liquid to gas mass flow ratio can be calculated directly from the outputs of the two meters:

$$LGMR = \frac{-(\beta - \alpha \frac{V_{S\,venturi}}{V_{S_{SONAR}}}) + \sqrt{(\beta - \alpha \frac{V_{S\,venturi}}{V_{S_{SONAR}}})^2 - 4\chi(1 - \frac{V_{S\,venturi}}{V_{S_{SONAR}}})}}{2\chi} \quad (10)$$

The gas flow rate is then determined using the SONAR meter formulation,

$$V_{S_{gas}} = \frac{V_{SONAR}}{(1+\alpha LGMR)} \quad (11)$$

Knowing LGMR and gas flow rate, additional flow parameters such as liquid rate and gas-to-liquid volume flow rate parameters can be calculated in a straight-forward manner.

Figure 5 shows the over-report from the SONAR meter and the venturi meter fitted with what is termed "global wetness sensitivity parameters" – i.e. the over report data recorded from each set point, spanning a wide range of flow rates, pressures, and liquid loading characterized versus a single flow parameter. While this single global correlation provides an indication of the robustness of this approach, to evaluate the potential of the DP plus SONAR metering system to provide accurate and meaningful wet gas measurements, it was decided to use localized wetness sensitivity parameters to characterize the over-report characteristic for each gas flow rate and pressure tested.

It should be noted that more sophisticated wetness sensitivity correlations, considering, for example, other non-dimensional parameters such as Froude number, could be used and would likely expand the generality of the results. For example, the wetness sensitivity of V-cone meters are parameterized as a function of Lockhardt –Martinelli and Froude numbers by (Stevens, 2005).

Figure 7 shows the over-report data as a function of wetness at a nominal flow rate of 80 ft/sec at 1000 psi corresponding to a densimetric Froude number of 7.1. Similar data is presented for the 40 ft/sec at 200 psi (Froude = 1.5) in Figure 8. As shown, the over-report of the meters is well captured by the local wetness sensitivity parameters.

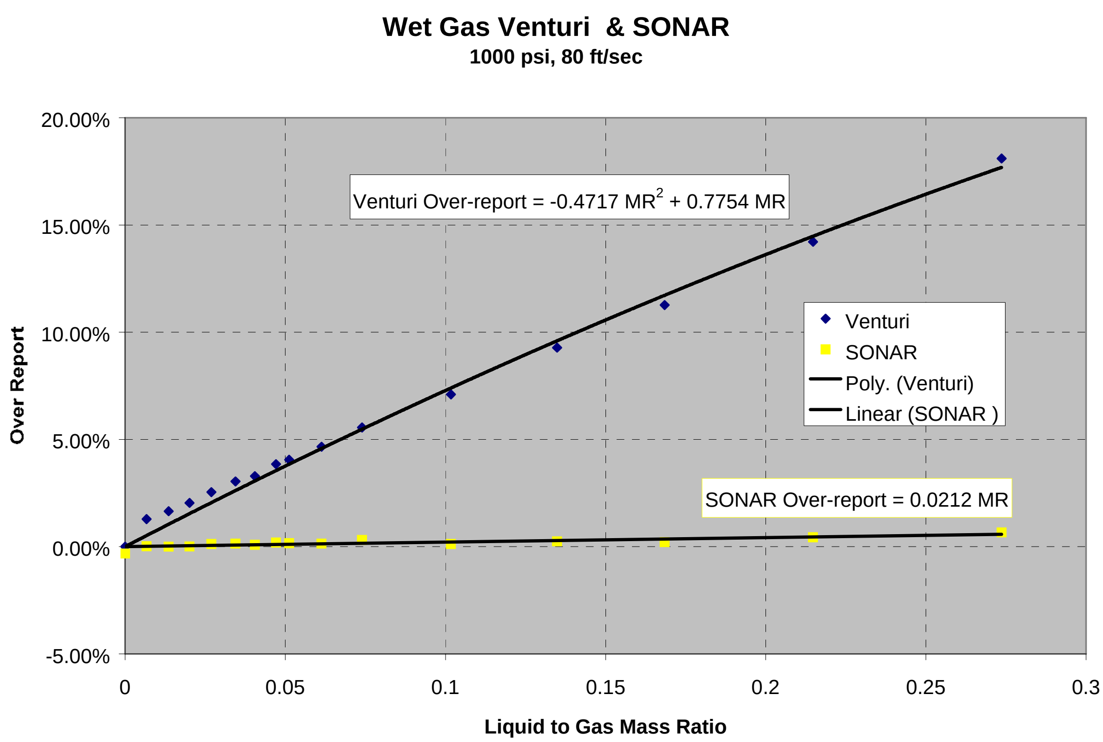

Figure 7: Over-report data as a function of wetness at a nominal flow rate of 80 ft/sec at 1000 psi (Froude number = 7.1)

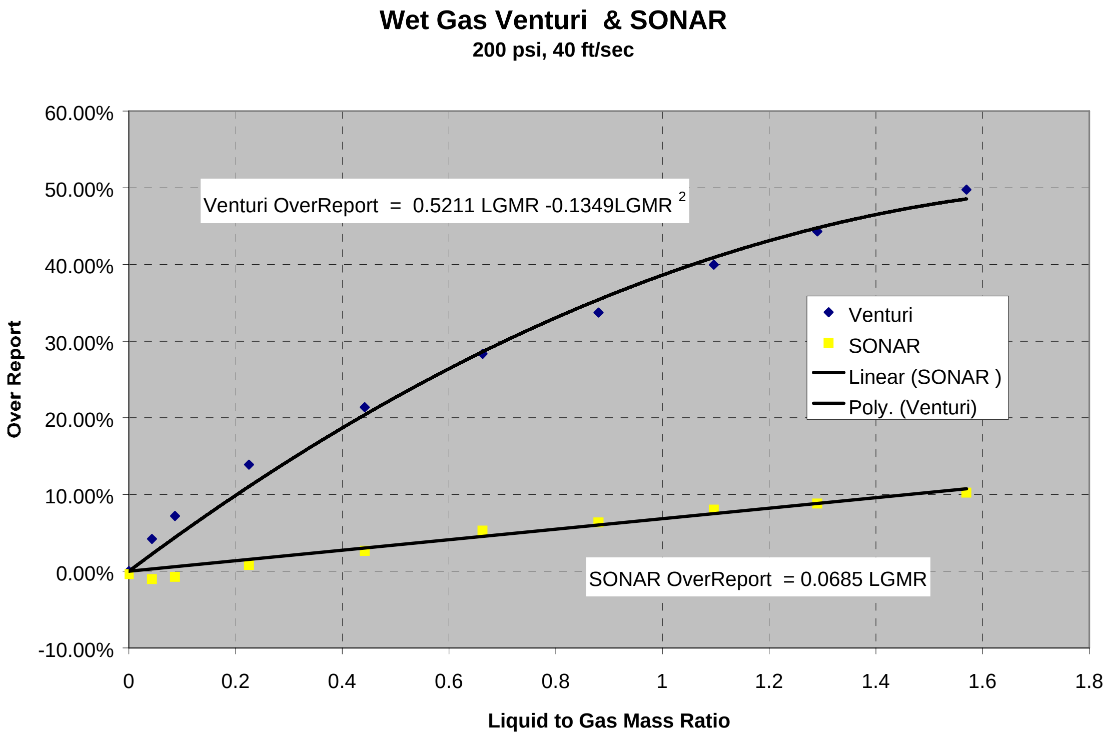

Figure 8: Over-report data as a function of wetness at a nominal flow rate of 40 ft/sec at 200 psi (Froude number = 1.5)

The global and localized wetness sensitivity coefficients determined for the testing are listed in Table 3.

Table 3: SONAR Experimentally Determined Wetness Sensitivity Coefficients

			Venturi		SONAR
			Chi	**Beta**	**Alpha**
Global Coefficients			-0.1593	-0.593	0.037
Localized Coefficients					
Pressure (psi)	Rate (ft/sec)	Fr			
200	80	2.9	-0.1449	0.6138	0.0019
	60	2.3	-0.1001	0.5245	0.0349
	40	1.5	-0.1349	0.5211	0.0685
1000	60	5.7	-0.5772	0.7794	0.0818
	40	3.8	-0.4358	0.7517	0.0379
	80	7.1	-0.4717	0.7754	0.0212
	20	1.9	-0.1178	0.5526	0.228

The gas rates measured with the venturi plus SONAR wet gas system using the localized wetness sensitivity coefficients are plotted versus reference in Figure 9. The relative gas rate error is plotted versus liquid to gas mass ratio in Figure 10. As shown, the system measures the gas rate quite accurately over the range of wetness tested, with errors of less than 2% of reference over a large range of wetness and Froude numbers. For the range of wetness tested, the venturi over-report due to wetness would have resulted in significant errors in dry gas flow rate if interpreted in isolation, exceeding 50% over-report as the liquid to gas mass ratio approached 2.0. The data demonstrates that using a clamp-on SONAR meter to augment an existing DP meter operating in wet gas service could significantly improve the accuracy of existing DP gas measurements operating in wet gas service.

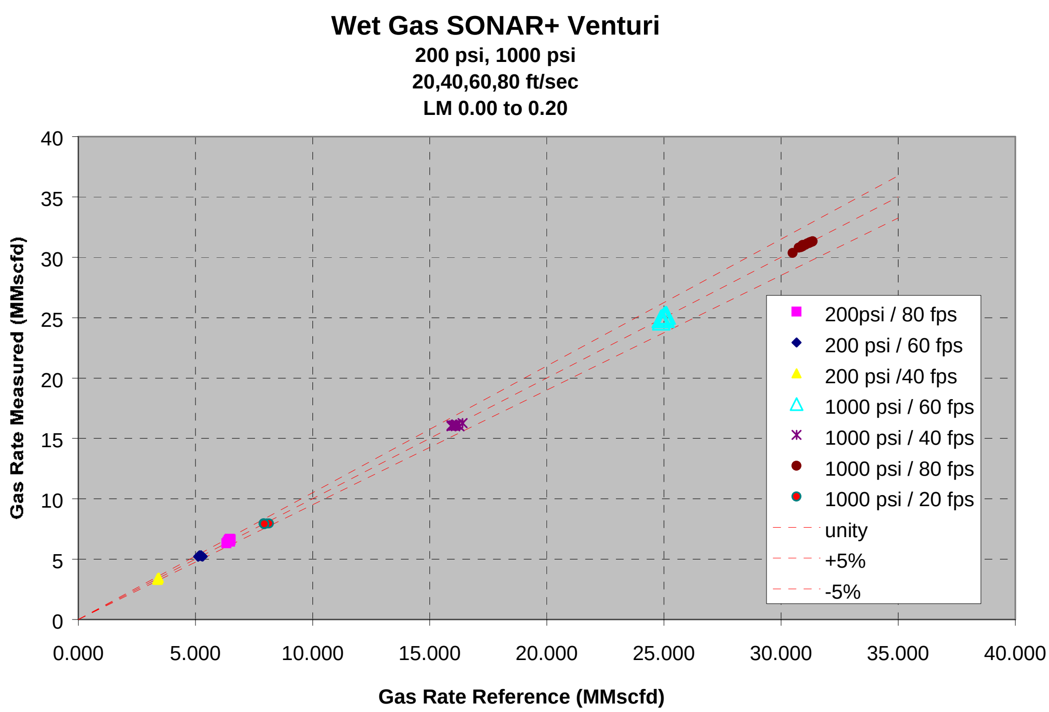

Figure 9: The gas rates measured with the venturi plus SONAR wet gas system using the localized wetness sensitivity coefficients are plotted versus reference

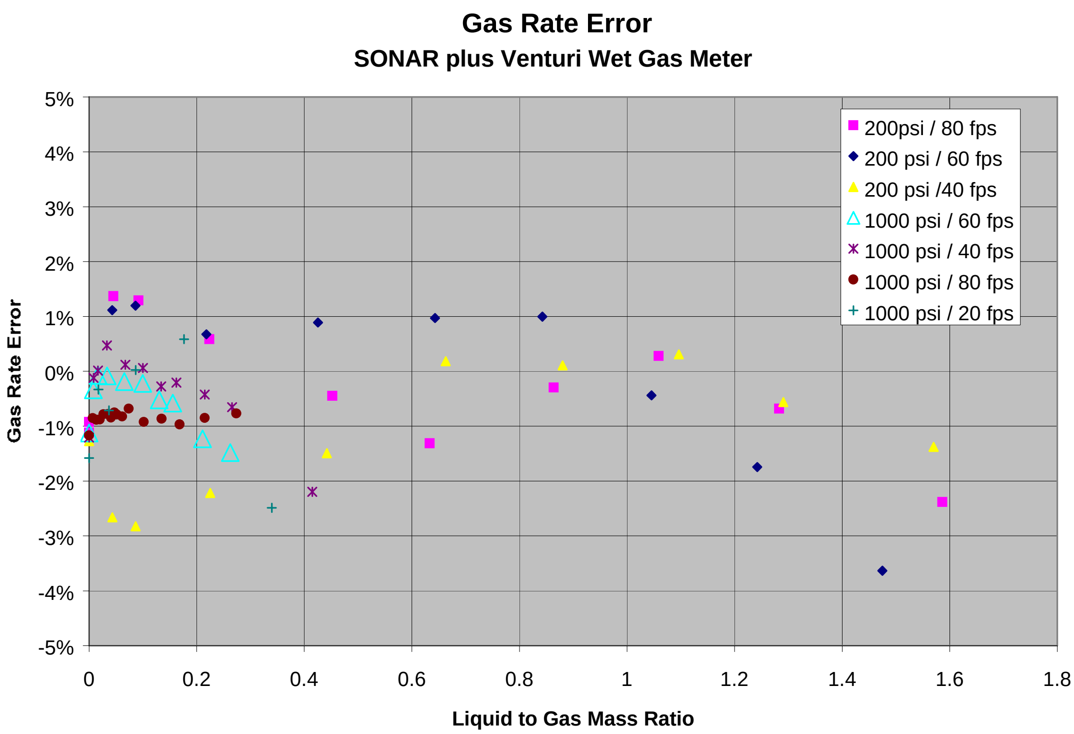

Figure 10: Relative Error in Gas rates Measured with the venturi plus SONAR wet gas system using the localized wetness sensitivity coefficients plotted versus LGMR

Similar data is presented for the measured liquid rates in Figures 11 and 12. As shown, the system provides a meaningful measurement of liquid rates, providing approximately +/-10% measurement of liquid rates for LGMR > ~0.2 (or approximately LM>0.02). The relative error in liquid rate increases significantly as the wetness approaches zero. Thus, to focus on the performance in the Type II wet gas range (LM>0.02), the axis of Figure 12 was limited to +/- 50% error, eliminating some of the higher relative error points at the low liquid loading rates.

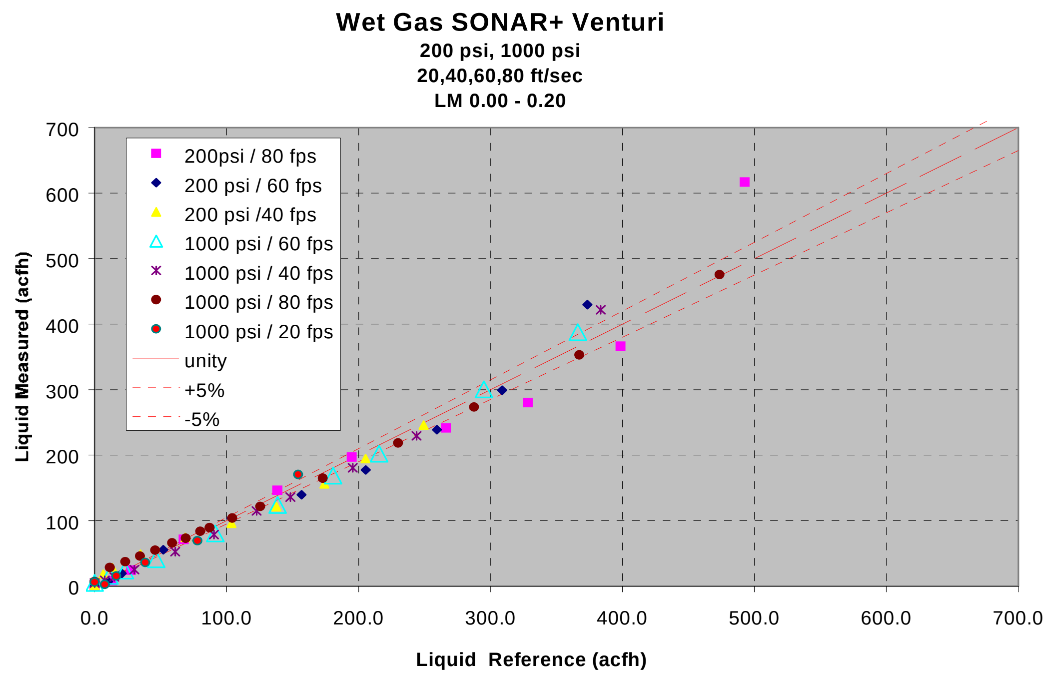

Figure 11: Liquid rates Measured with the venturi plus SONAR wet gas system using the localized wetness sensitivity coefficients are plotted versus reference

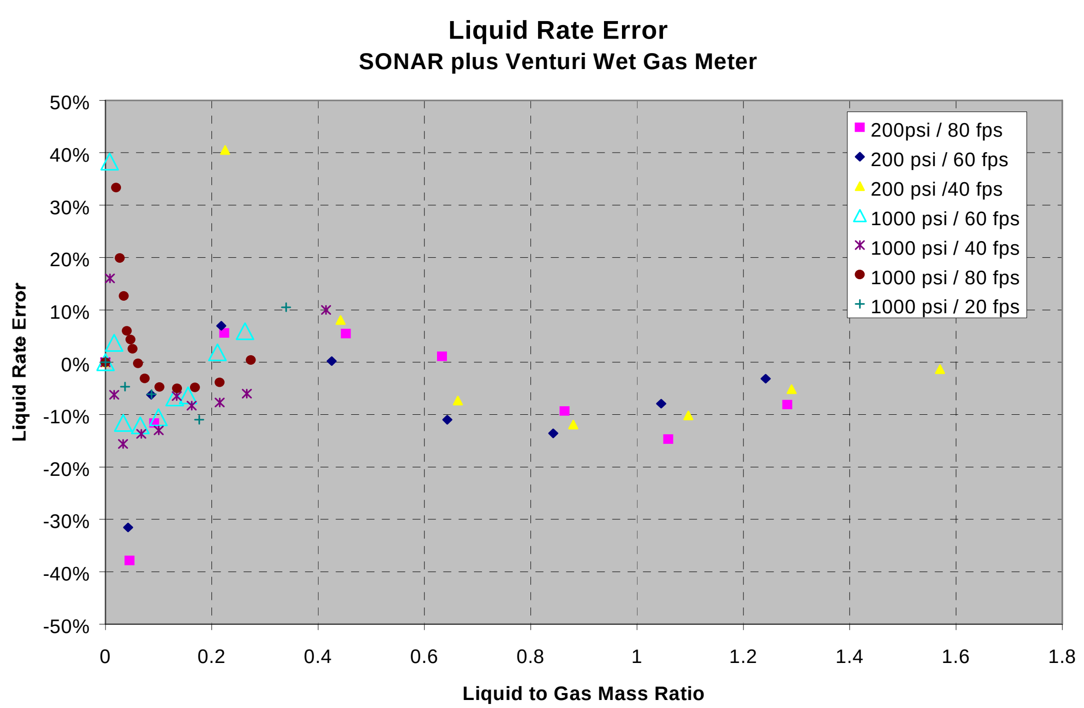

Figure 12: Relative Error in Liquid rates Measured with the venturi plus SONAR wet gas system using the localized wetness sensitivity coefficients plotted Versus LGMR

Figure 13 and 14 illustrate the ability of the DP plus SONAR system to provide a direct measurement of the gas wetness. These figures are derived directly for the gas and liquid rate data presented above. These figures further highlight the ability of the system to monitor gas / liquid ratios, an important operating parameter in many oil and gas production and processing operations. Figure 13 shows the measured versus reference gas / oil ratio calculated from the results presented above. Figure 14 shows the measured versus reference Lockhardt Martinelli number. As shown, the DP plus SONAR system provides a direct measure of wet gas wetness.

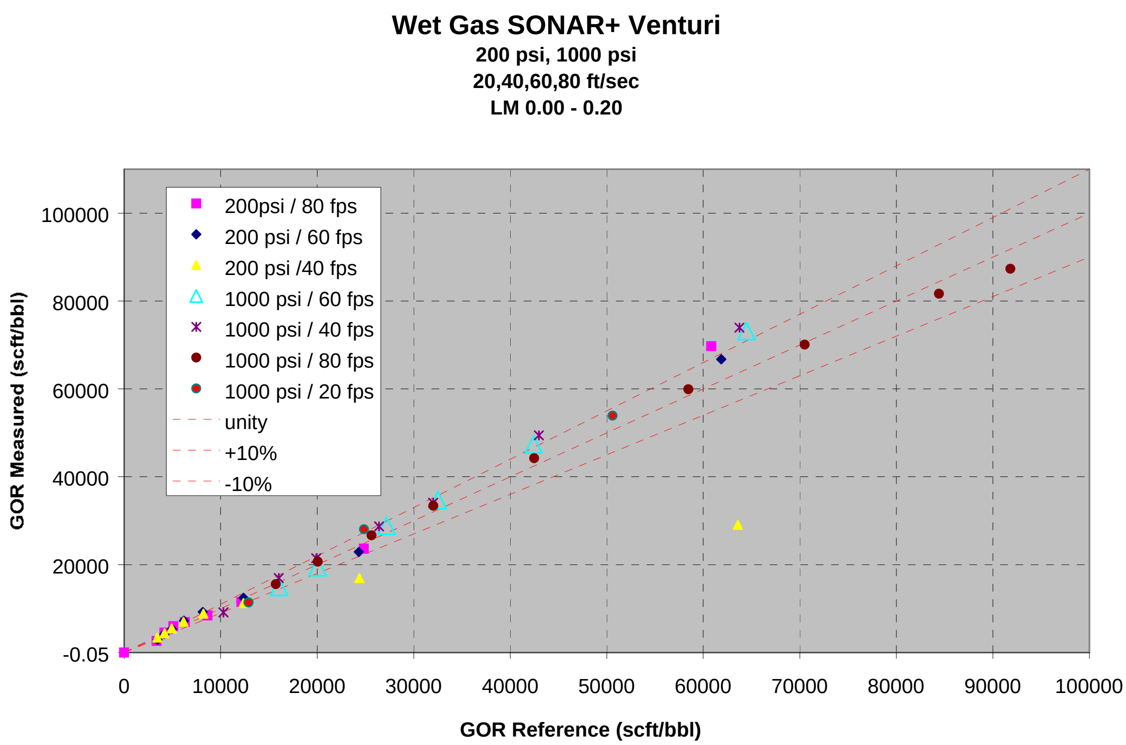

Figure 13: Measured Gas Oil Ratio with the venturi plus SONAR wet gas system using the localized wetness sensitivity coefficients versus Reference GOR

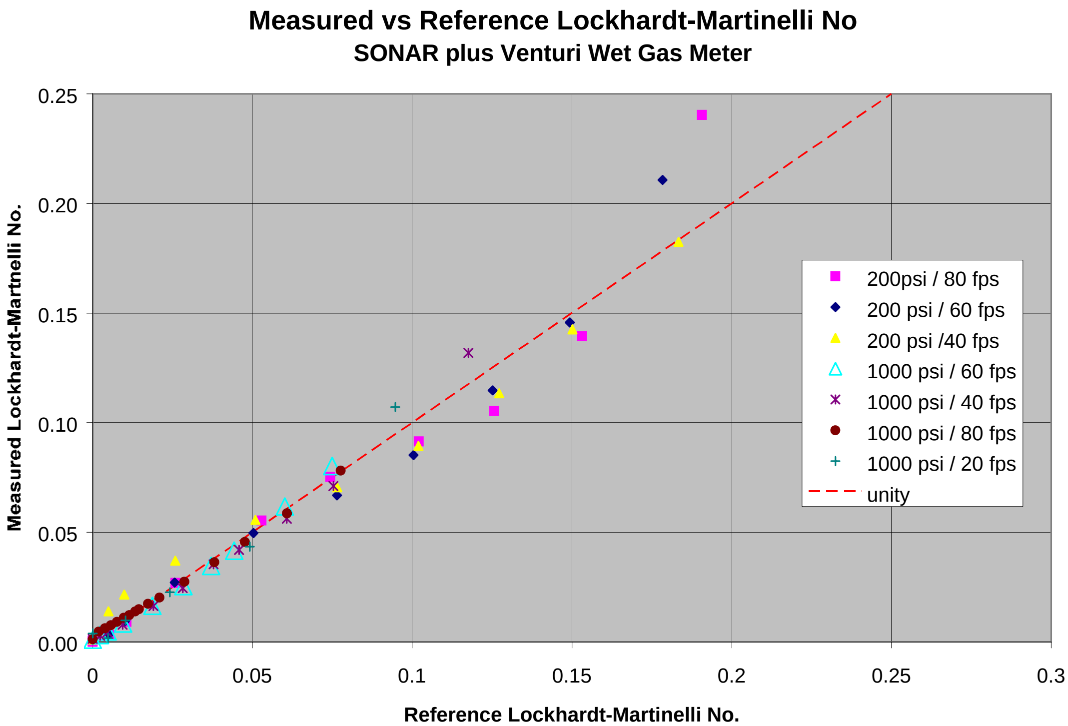

Figure 14: Measured Lockhardt-Martinelli with the venturi plus SONAR wet gas system using the localized wetness sensitivity coefficients versus Reference Lockhardt-Martinelli

5. SUMMARY

A method to measure the gas rates and liquid rates of wet gas flows was presented. The approach combines any differential pressure-based gas flow meter of known wetness sensitivity with a SONAR-based flow measurement. The two independent measurements have repeatable and distinct wetness sensitivity and can be used to accurately determine gas and liquid flow rate.

Experiments were conducted to validate the ability of a DP plus SONAR metering system to measure gas and liquid rates of wet gas flows. The over-report due to wetness of a 0.6 beta ratio venturi meter and a clamp-on SONAR-based flow meter were measured and characterized over a wide set of flow conditions representative of oil and gas production and processing conditions. The experimentally determined over-report due to wetness of each was in good agreement with theoretical models of the over-report associated with well-mixed gas / liquid mixtures. The over-report characteristics of both the venturi meter and the SONAR meter were correlated with the liquid to gas mass ratio of the wet gas flow.

The ability of the combination of the venturi plus SONAR system was evaluated using experimentally determined wetness sensitivity coefficients to solve for the gas and liquid rates based on the outputs of the venturi and SONAR installed in series on the test loop. The combination was shown to accurately measure gas flow rates to within ~+/- 2% and liquid rates to within +/-10% over a wide range of wet gas flows.

The results of these experiments suggest that the addition of a clamp-on SONAR-based flow meter to a differential pressure-based device is a viable means to provide both liquid and gas flow rates of Type I and II wet gas flows.

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7. REFERENCES

Murdock, J. W., "Two Phase Flow Measurement with Orifices", Journal of Basic Engineering, December, 1962.

Nederveen, N., et al, "Wet Gas Measurement", SPE Paper 19077, Presented at the SPE Gas Technology Symposium, Dallas, TX, June, 1989.

Mehdizadeh, P., et al, "Wet Gas Metering: Trends in Application and Technical Developments", SPE Paper 77351, Presentated at SPE Annual Technical Conference, San Antonio, September, 2002.

Stewart, D., "The Evaluation of Wet Gas Metering Technologies for Offshore Applications, Part 1 – Differential Pressure Meters" Flow Measurement Guidance Note No. 40, National Engineering Laboratory, Glasgow, UK, February, 2003.

Agar, J. and Farchy, D., "Wet Gas Metering Using Dissimilar Flow Sensors: Theory and Field Trial Results", SPE Paper 77349, Presented at SPE Annual Technical Conference, San Antonio, September, 2002

Stevens, R. et al, "An Update on V-Cone Meter Wet Gas Flow Metering Research", Flomeko 2005, 13th International Flow Measurement Conference, NEL, June 2005.

Gysling, D. L. and Loose, D. H., "Using SONAR-based Gas Volume Fraction Meter for Improved Net Oil Rate Measurement", Presented at the 2005 Canadian School of Hydrocarbon Measurement, Calgary, AB, March, 2005.

Kragas, T. K., et al., "Downhole, Fiber Optic Multiphase Flow Meter: Field Installation" Presented at the Society of Petroleum Engineers Annual Conference, SPE Paper #77654, September 2002.

Kragas, T. K., et al., "Downhole Fiber-Optic Multiphase Flowmeter: Design, Operating Principle, and Testing," Presented at Society of Petroleum Engineers Annual Conference, SPE Paper #77655, September 2002.

Gysling D.L. and Loose, D.H., "SONAR-based, Clamp-on Flow Meter for Gas and Liquid Applications", Presented at 2003 ISA Show, Houston, TX, October, 2003.

Gysling D.L., Loose, D.H., van der Spek, " Clamp-on, SONAR-based, Volumetric Flow and Gas Volume Fraction Meter Industrial Applications", presented at the 13th International Flow Measurement Conference, organized by the National Engineering Laboratory, East Kilbride, Scotland, UK, June 2005.