Using SONAR-based Gas Volume Fraction Meter for Improved Net Oil Rate Measurement

Daniel L. Gysling
and
Douglas H. Loose

CiDRA Corporation
Wallingford, CT USA

Abstract
The impact of entrained gases on net oil measurement is addressed and quantified for three common approaches for determining net oil: coriolis meters, resonant microwave oscillators and microwave absorption devices. Entrained gases are often encountered in the liquid leg of gas – liquid separator based measurement approaches and, if unrecognized, can result in significant error in net oil.

The measurement principles of the three types of watercut meters considered are described. Each watercut measurement device continues to provide a measurement in the presence of gas. However, the interpretation of net oil content of an oil / water mixture with free gas present can be significantly impacted without specific knowledge of the gas volume fraction. The errors in oil cut introduced by unrecognized entrained gases are outlined using simplified models for each type of watercut measurement device considered.

An approach is proposed to utilize SONAR-based gas volume fraction meters in conjunction with the watercut devices to provide accurate net oil determination in the presence of entrained gas. Laboratory and field data evaluating the proposed approach are presented, demonstrating both the impact of entrained gases on net oil measurement and the practicality of accounting for the free gas to enable accurate net oil measurement, independent of small gas volume fraction levels.

Introduction

Accurate measurement of net oil rate from individual wells is a critical component in effective oil field management, influencing production optimization strategies and financial allocation issues.

Driven by goals of reducing size and cost of conventional three phase separation approaches, many operators have adopted approaches that utilize smaller, two-phase, gas /liquid separation in conjunction with a flow and water cut measurement to measure net oil. Many techniques are used for gas / liquid separation, including level-controlled batch tank separators and continuous flow cyclonic separators (Kouba, 1995).

This paper considers the effect of free gas on three methods widely used to determine watercut and, in turn, net oil: 1) density via coriolis meters, 2) frequency of a resonant microwave oscillator, 3) absorption of microwave energy. The presence of free gas in any of these devices can result in significant over-reporting of net oil. Although gas impacts each differently, with real time knowledge of entrained gas volume fractions, each can continue to provide accurate net oil measurement.

Although most gas / liquid separator-based net oil measurement approaches are designed to eliminate gases in the liquid leq of the separator, it has proved difficult to ensure complete gas /liquid separation. Furthermore, since the fluid exits the separator at, or near, vapor pressure additional out gassing from the liquid can occur prior to measurement due pressure losses in the flowing mixture. As a result, errors in oil fraction measurement attributed to the entrained gasses can often be the single largest source of error in net oil measurement.

The first step in properly accounting for the presence of free gas on net oil measurement is to quantify the amount of free gas. An approach is presented which employs a SONAR-based gas volume fraction meter (Gysling and Loose, 2003) installed on the liquid leg of a gas/liquid separator to provide a real-time, entrained gas measurement. The real time gas volume fraction measurement is then used in conjunction with watercut devices to provide an accurate measurement of net oil. The ability to provide accurate net oil measurements in the liquids with entrained gases effectively eliminates the need for complete gas /liquid separation for accurate net oil measurement.

Data is presented from a field trial from a producing well in which presence of small, but varying, levels of entrained gases in the liquid leg of a Gas Liquid Cylindrical Cyclone separator. A density measurement from a U-tube coriolis meter was providing the watercut measurement. Data showed gas-carry under to be in the range of 0% to 5% by volume, which, when not appropriately considered in the net oil measurement, results in ~100% over-reporting of net oil.

Scope

The goal of this paper is to provide information to improve net oil measurement in the presence of free gas. The paper outlines the principle of operation of three classes of watercut measurement devices and leverages these descriptions to calculate the impact of free gas on net oil based on first principles models. A detailed analysis of each type of watercut device is beyond the scope of the paper. Readers are encouraged to consult the manufacturers of their specific watercut devices to ensure optimal performance in the presence of gas.

Net Oil Measurement

In multiphase measurement approaches that utilized gas / liquid separators, net oil volumetric flow rate, Q_{NO}, is determined by the product of net volumetric flow, Q, and oil phase fraction of the liquid leg of the separator, ϕ_O,

$$Q_{NO} = Q \cdot f_O$$

Oil phase fraction is typical determined using devices that are commonly referred to as watercut devices. Under the assumption that no gas is present, knowledge of watercut uniquely determines oil cut.

$$f_O + f_W = 1$$

With gas present, the water fraction, oil fraction, and gas volume fraction sum to unity and the direct, one-to-one relationship between water cut and oil cut is lost.

$$f_O + f_W + f_G = 1$$

In the presence of free gas, net oil production is given by the product of oil fraction of the total mixture of oil, water, and gas times the total volumetric flow rate of the mixture.

Density based water cut

Coriolis meters are widely used in net oil measurement (Wilkinson). Since Coriolis meters provide both mass flow and density, they are well-suited for net oil measurements. Although the performance of a Coriolis meters in the presence of entrained gases is, in general, dependent on its design parameters (Gysling and Banach, 2004), it is assumed that the Coriolis meters considered herein provide accurate mixture mass flow and density for the liquid and slightly aerated liquids. Specifically, this paper addresses U-tube coriolis meters, which have been demonstrated to accurately report mass flow and density on aerated mixtures.

Using a coriolis meter, net oil rate is determined by first by calculating the gross volumetric rate from the ratio of measured mass flow rate and measured density. In the absence of free gas, oil cut of oil / water mixtures is related to the mixture density through knowledge of the single component oil and water densities.

$$f_O^* = \frac{r_W - r_{mixture}}{r_W - r_O}$$

Here the asterisk is used to define oil cut and water cut inferred from measurements assuming no gas is present. The water cut is related to the oil cut through the assumption that the two components occupy the pipe:

$$f_W^* = 1 - f_O^* = \frac{r_{mixture} - r_O}{r_W - r_O}$$

The effect of free gas on density-based, oil-cut determination can be assessed by expanding the interpretation of density to include a three-component mixture of oil, water, and gas. The density of an N-component mixture is given by a volumetrically-weighted average of the individual component densities. For oil, water and gas mixtures, mixture density is thus given by:

$$r_{mixture} = f_O r_O + f_W r_W + f_G r_G$$

with $f_O + f_W + f_G = 1$

Where O, W and G subscripts refer to oil, water and gas, respectively.

Using these definitions, the oil fraction can be shown to be a function of the measured mixture density, the pure component oil and water densities, as well as the gas volume fraction.

$$f_O = \frac{r_W - r_{mixture} - f_G(r_W - r_G)}{r_W - r_O}$$

Comparing this expression for oil fraction, ϕ_O, to that derived assuming only oil and water are present, ϕ^*_O, shows how the presence of gas results in an over prediction of net oil.

$$f_O = f_O^* - f_G \frac{r_W - r_G}{r_W - r_O}$$

Figure 1 shows the error in interpreted oil fraction of the liquid stream due to the presence of a relatively small, but unknown, amount of entrained gas in oil / water stream. The example considers oil with a specific gravity of 0.85 and the water a specific gravity of 1. As discussed above, it is assumed that the coriolis meter accurately reports mixture density and the densities of the oil, water, and gas phases are known.

As shown, the presence of the free gas has a significant impact on the interpreted oil cut of the liquid stream, and hence net oil. Although still significant at low water cuts, the impact of entrained gases dominates the measurement at high water cuts. As shown, 1% entrained gas results in an approximately 2x over-reporting of net oil at 90% watercut. These errors are removed if the free gas is accurately measured and accounted for when calculating the oil fraction.

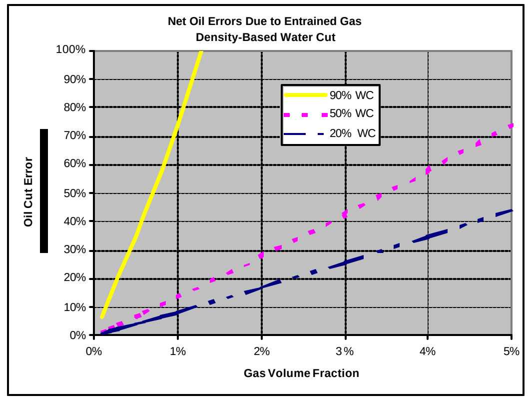

Figure 1: Effect of Free Gas on Interpreted Oil Cut using Density-based Watercut Measurement

Resonant Microwave Oscillators

Resonant microwave oscillators leverage the difference in relative permittivity between oil and water to determine water cut. Relative permittivity of a medium, ε_i, can be viewed as a measure of speed at which microwaves propagate through a given medium, V_i, compared to the speed of microwaves in a vacuum, c.

$$V_i = \frac{c}{\sqrt{e_i}}$$

Thus, the speed of propagation of microwaves decreases in media with increasing permittivity. For multi-component mixtures, an approximate model for the average propagation velocity is given as volumetrically-weighted function of the propagation velocities of the components.

$$V_{mix} = \frac{1}{\sum \frac{f_i}{V_i}} = \frac{c}{\sum f_i \sqrt{e_i}}$$

A more formal treatment of the permittivity of mixtures can be found in the literature (Tuncer, 2001). Water typically has a relative permittivity of 68-80, with crude oil typically ranging from 2.2 to 2.6. (Scott, 1993). Since the water phase has the largest relative permittivity, microwave propagation velocity decreases with increasing water cut.

For a fixed geometry resonant cavity, the resonant frequency is proportional to speed of propagation of microwaves inside the cavity. Thus, for a cavity filled with a mixture of oil and water, increasing water cut, decreases the propagation speed, and in turn, decreases the resonant frequency. Thus, once calibrated, the frequency of the resonant microwave cavity is a measure of the speed of propagation and thus the relative permittivity of the mixture inside the cavity, ε_{mix}. The oil cut of an oil / water mixture can be related to the measured permittivity and the permittivities of the water and oil components:

$$f_O^* = \frac{\sqrt{e}_W - \sqrt{e}_{mixture}}{\sqrt{e}_W - \sqrt{e}_O}$$

Again, under the no gas assumption, there is a direct relation between the interpreted oil cut and water cut.

$$f_W^* = 1 - f_O^* = \frac{\sqrt{e}_{mixture} - \sqrt{e}_O}{\sqrt{e}_W - \sqrt{e}_O}$$

Similar to density-based watercut devices, resonant microwave oscillators continue to operate in the presence of gas, with their ability to independently determine watercut degraded. The effect of gas can be incorporated by allowing for the presence of a third component in the analysis. Gas has a relative permittivity of ~1, an as such, free gas appears similar to oil and results in the resonant microwave oscillator over-reporting the actual oil cut.

Using the above relations, the relationship between the actual oil cut, ϕ_o, and that interpreted assuming no gas, ϕ_o*, is given below.

$$f_O = f_O^* - f_G \frac{\sqrt{e}_W - \sqrt{e}_G}{\sqrt{e}_W - \sqrt{e}_O}$$

Figure 2 shows the error in interpreted net oil cut that would be incurred by a resonant microwave oscillator due to the presence of a small, but unknown, amount of gas. The relative permittivity of the water, oil and gas phases were assumed to be 66, 2.2, and 1 respectively, in this example. The error is calculated using the equation developed above. Despite a relatively simplistic model for mixture permittivity, the predicted errors, are broadly consistent with those given in the literature (Scott, 1993). Although the resonant microwave oscillators are typically less sensitive to free air than density based devices, the effect on net oil can be significant, with the largest proportional errors due to unrecognized free gas occurring at the highest watercuts.

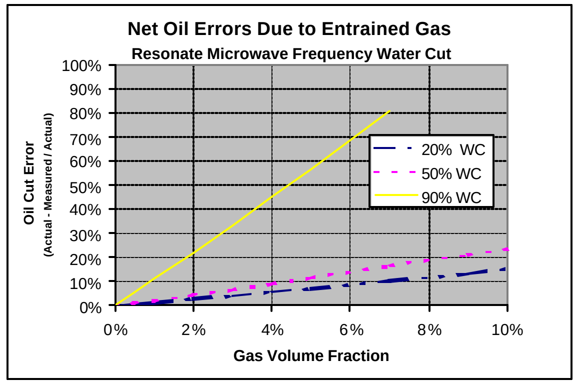

Figure 2: Effect of Free Gas on Interpreted Oil Cut Using Resonant Microwave Cavity Devices

Microwave Absorption

The third type of watercut device considered is the microwave absorption watercut device. Water molecules efficiently absorb microwave energy, whereas hydrocarbons typically do not. Thus, the amount of microwave energy absorbed by a given volume of a mixture of hydrocarbons and water is primarily determined by the watercut of the mixture. Thus, watercut can be determine by a calibrated measure of microwave absorption, α, as follows:

$$f_W^* = F(a)$$

Again, assuming no gas is present, oil cut is determined directly from the water cut.

$$f_O^* = 1 - f_W^* = 1 - F(a)$$

From a microwave absorption perspective, gas and crude oil are both, non-absorbing components. Therefore, a microwave absorption device will continue to accurately report watercut (i.e. water fraction) in an oil / water mixture with a small but unknown amount of gas. However, although the watercut is reported accurately, the presence of gas still can result in significant over-reporting of net oil cut.

$$f_O = 1 - f_W - f_G = 1 - F(a) - f_G = f_O^* - f_G$$

For example, consider a non-aerated 90% water, 10% oil stream. A properly calibrated microwave device would accurately report 90% water cut. If this same liquid mixture is then aerated with 10% entrained gas, the resulting mixture would then consist of 81%

water, 9% oil and 10% gas by volume. A microwave absorption device would then accurately report a water cut of 81%. However, without knowledge of the amount of gas present, one would then conclude that the mixture was 19% oil, resulting in approximately 2X over-reporting of the oil cut of the stream. Figure 3 shows the errors in oil cut interpreted using an absorption-based microwave device due to an unrecognized presence of gas as a function gas volume fraction for a range of watercuts.

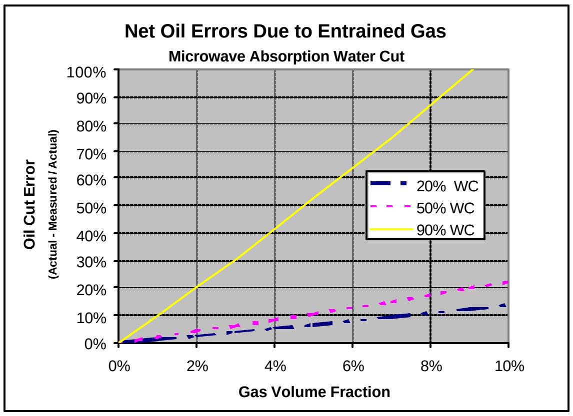

Figure 3: Effect of Free Gas on Interpreted Oil Cut Using Microwave Absorption Devices

Summary of Effect of Free Gas on Oil Cut

Table 1 summarizes the quantifiable impact of free gas on the interpreted net oil measured from each of the three types of water cut devices considered.

Table 1: Effect of Gas Volume Fraction on Three Types of Watercut Devices

Watercut Device	Effect of Gas on Oil Cut (add to Oil Fraction Calculated Assuming No Gas)
Coriolis Density	$-f_G \dfrac{r_W - r_G}{r_W - r_O}$
Microwave Resonant Cavity	$-f_G \dfrac{\sqrt{e_W} - \sqrt{e_G}}{\sqrt{e_W} - \sqrt{e_O}}$
Microwave Absorption	$-f_G$

The correction factors listed in Table 1 can be summed directly with the output of existing, installed watercut devices to yield a more accurate determination of the oil cut in the presence of free gas. The constants required to implement the correction factors, with the exception of the gas properties are common to those required for the base-line calibration of measurement.

Laboratory Evaluation of Coriolis Meter

Experiments were conducted to verify the ability to accurately measure the density of aerated mixtures using the combination of coriolis density and SONAR-based gas fraction measurements. The test consisted of a water flow loop with a 2-inch Micro Motion CMF200 coriolis meter installed in a vertical upward flowing orientation ("flag" mount) with a CiDRA *SONARtrac*™ gas volume fraction meter and pressure sensor installed just downstream of the coriolis outlet. Air was injected upstream of the test section.

Figure 4 shows the measured mixture density and the corrected liquid-density measured by the combination of the coriolis and SONAR-based meters. The results confirm that 1) the coriolis meters can continue accurately report mixture density in the presence of gas and 2) the real time measurement of gas volume fraction enables the combination to continue to report liquid density.

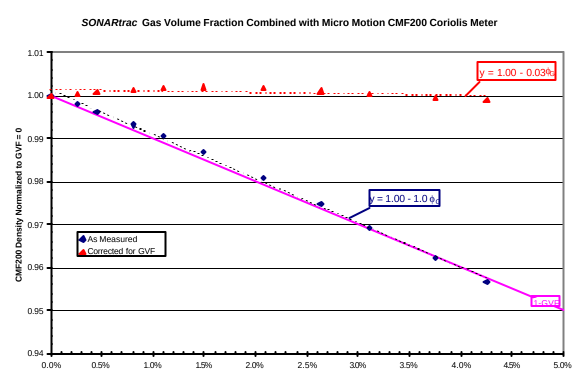

Figure 4: Density of Aerated Water as a Function of Gas Volume Fraction as reported by Coriolis Meter with SONAR-based GVF Measurement

Oil Field Test Data

A SONAR-based gas volume fraction meter was installed on the outlet of a coriolis meter on the liquid leg of a continuous-flowing, gas/liquid cylindrical cyclone (GLCC) two-phase separator. Both meters were mounted in a vertical orientation with upward flowing liquid similar to the experimental test section as described above. The mass rate, density and drive gain from the coriolis meter and the gas volume fraction from the SONAR-based meter were output to a programmable logic controller (PLC) where the data could be stored and later retrieved. The pressure at the outlet of the coriolis meter was also output to the PLC. Figure 5 shows the gross flow rate and coriolis measured density during the 9 ½ hour well test. The gross rate was calculated by dividing the mass flow rate by the density, both directly measured by the coriolis meter.

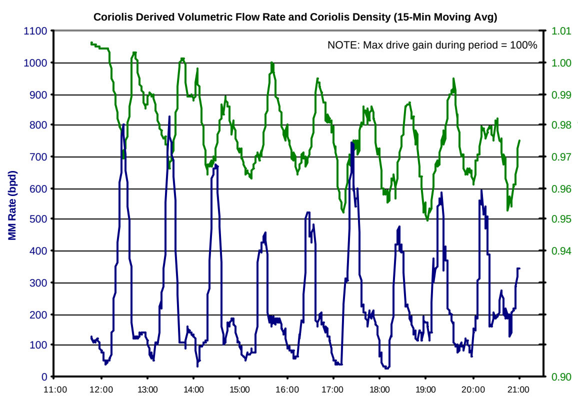

Figure 5: Coriolis Mass Flow and Density Reported During Well Test

Figure 6 shows the measured gas volume fraction and coriolis measured density. The gas volume fraction ranged from 0 to approximately 4%, varying significantly over the test period.

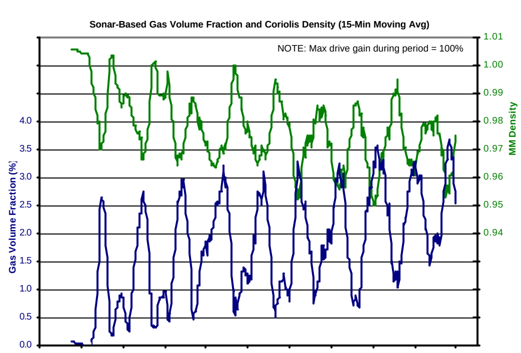

Figure 6: Coriolis Density and SONAR-based Gas Volume Fraction Reported During Well Test

Figure 7 shows 1) the measured density and 2) the coriolis drive gain plotted versus gas volume fraction. The measured density and the measured gas volume fraction show good correlation, with the decreases in measured density corresponding to increasing in gas volume fraction. However, unlike the laboratory experiment in which the liquid density was constant, the density of the liquid phase in the well test also varied due to changes watercut throughout the well test period. Time history data (Figure 6) shows that the gas volume fraction tends to increase with oil fraction. This effect would cause the density of the mixture to decrease more with gas volume fraction than it would if the liquid density were held constant. As shown, a best straight line fit through the data shows a mixture density decreasing at ($1.0\text{-}1.2^*\phi_G$), very close to theoretical $1-\phi_G$ for liquid / gas mixture with constant liquid properties.

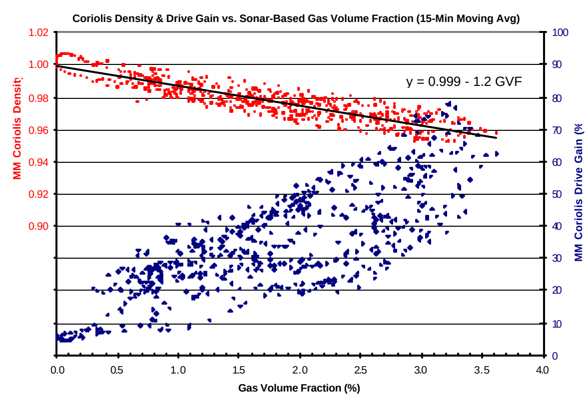

Figure 7: Coriolis Density and Drive Gain Plotted vs. SONAR-based Gas Volume Fraction During Well Test

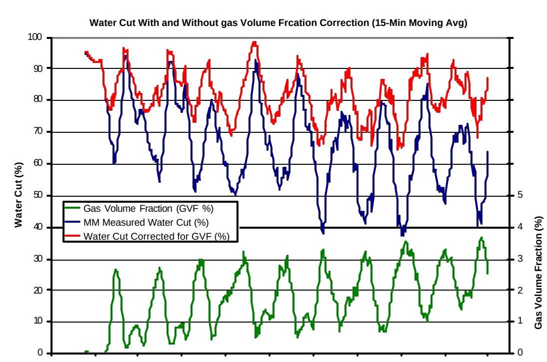

Figure 8: Reported and Corrected Coriolis Watercut and Gas Volume Fraction During Well Test

The cross-plot of the drive gain versus gas volume fraction is also shown. Although there appears to be a qualitative correlation, this data indicates that drive gain would not provide a quantitative measured of gas volume fraction. The water cut with, and without, the knowledge of the gas volume fraction is shown in Fig. 8.

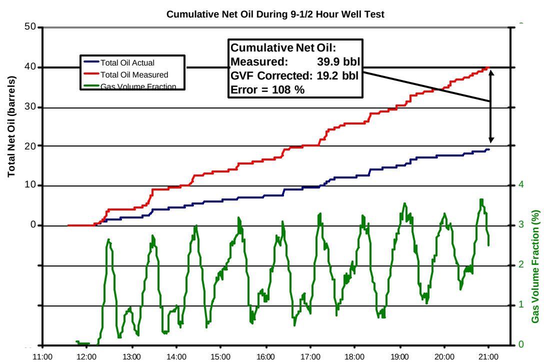

Figure 9: Cumulative Net Oil, Reported and Corrected, and Gas Volume Fraction During Well Test

Figure 9 shows the cumulative net oil over the well test period for the two cases. Using knowledge of the gas volume fraction when calculating the oil fraction yields a total oil of 19.2 barrels for this 9-1/2 hour well test. If the gas volume fraction were not known an assumed to be negligible, the total oil for this test would be reported as 39.9 barrels. This is an overstatement of the total oil by 20.7 barrels or 108% (Fig. 9).

Summary

Entrained gases can have a significant impact on the accuracy of net oil measurements. Specifically, net oil measurement determined using a gas /liquid separator in conjunction with a watercut and flow rate measurement on the liquid leg of the separator. The impact of entrained gases was analyzed for three common types of watercut devices, coriolis density meters, microwave resonant cavity devices and microwave attenuation devices. Correction factors to account for the presence of free gas were developed and presented for each device.

Laboratory data confirming the ability of the proposed approach of coupling SONAR-based gas volume fraction meter with watercut devices to provide accurate net oil was presented. The data demonstrates the ability of a combination of SONAR-based gas volume fraction meters and a U-tube Coriolis meter to accurately report liquid density in the presence of 0-5% gas volume fraction.

Well test data from a gas / liquid separation based net oil measurement approach was presented. The data shows the presence of 0-4% free gas in the liquid leg of the separator. Analysis of this data shows that presence of gas resulted in a roughly 2X over-reporting of net oil over the 9 ½ hour well test period.

References

Kouba, G. K. et al, " Design and Performance of Gas Liquid Cylindrical Cyclone Separators", BHR Group 7th International Conference on "Multiphase 95", 1995.

Tuncer, E. et al, " Dielectric mixtures – electrical properties and modeling", IEEE Transactions on Electrical Insulations and Dielectrics, 2001.

Scott, B.N. et al, "Technology for Full-Range Water-Cut Measurements", Off Shore Technology Conference, Paper No. 7233, presented at the 25th Annual OTC in Houston, Texas, 3-6 May, 1993.

Wilkinson, C., "Net Oil Measurement at the Separator (Coriolis)", Class #45 Liquid, Presented at the Canadian School of Hydrocarbon Measurement,

Gysling, D. L. and Loose, D. H., "Sonar-based Volumetric Flow and Entrained Air Measurement for Pulp and Paper Applications", presented at the TAPPI Spring Technical Conference, Paper 58-1, Chicago, IL, May, 2003.

Gysling, D. L. and Banach, T., "Enhanced Density Measurement using Speed-of-Sound Augmented Coriolis Meters," Presented at ISA, Houston, TX, October, 2004.