Endress+Hauser
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An innovative technology for Coriolis metering under entrained gas conditions

Coriolis mass flowmeters are usually only used for single-phase fluids, i.e. either liquids or gases, since it has been found that their accuracy can be affected by two-phase flows, e.g. the existence of entrained gas in a liquid flow. It is now known that there are various sources of error, among which the significantly increased compressibility due to gas entrainment brings the most difficulty when Coriolis meters are used in the field. The authors have developed a new Coriolis sensor together with an innovative technology, Multi-Frequency Technology (MFT), which can compensate the measurement errors introduced by the increased compressibility of an entrained gas flow. The new Endress+Hauser Coriolis sensor provides a novel hardware platform so that a higher natural mode of the measuring tube can be reliably excited in addition to the basic working mode. Being driven at different frequencies, the same two phase fluid in the measuring tube can have different influences on the primary mode (i.e. the basic working mode) and the auxiliary mode (i.e. the higher tube mode). By analyzing the corresponding vibrational response of the two phase fluid at the two frequencies, the unique resonance property of this mixture can be obtained and the induced measurement errors can be compensated. In this paper, the theoretical background of Coriolis entrained gas metering is given. Afterwards, the basic principle of the MFT is explained in detail. Measurement data obtained at two independent laboratories are provided to prove the improvement brought about by this technology.

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1. Introduction

Coriolis mass flowmeters are widely accepted and used in various industries because of their high reliability and accuracy for density and mass flow rate measurements. For mass flow rate, an accuracy of ±0.1% o.r. or even ±0.05% o.r. can be reached; while for density, ±0.2 kg/m^3 has been claimed under reference conditions by some manufacturers. The distinct advantage of the Coriolis measuring principle over other meter types lies in the fact that a Coriolis mass flowmeter directly senses the true mass flow rate, whereas most of the others measure volumetric flow rates – in other words, they measure flow velocities.

The above mentioned advantages of Coriolis mass flowmeters come mainly from the measurement principle based on the Coriolis effect, which reveals the fact that a Coriolis force is generated when an object on a rotating body moves away or towards the center of rotation. This force is related to the inertia of the object and has a direction perpendicular to both the velocity of the object and the axis of the rotation body. In general, a Coriolis mass flowmeter consists of one or more measuring tubes, which in commercial designs can be of various shapes, a housing that protects the inner part as well as other components adhering to the measuring tube such as a driver for exciting the tube and sensors for sensing the tube motion, as shown in Figure 1. In a Coriolis meter, the rotation provided by the oscillation of the measuring tube together with the flow of the medium inside give rise to the Coriolis effect. This manifests itself by an anti-symmetrically distortion of the tube. As the mass flow rate is proportional to the magnitude of this distortion, it can be calculated by physically measuring the distortion with the help of two sensors located at the inlet and the outlet sections of the tube. In addition to the mass flow rate, Coriolis meters can also provide an accurate density measurement by recording the resonance frequency of the measuring tube. In order to be energy efficient, the tube is continuously excited at its natural frequency, which is defined by the tube properties and the density of the fluid inside. This correlation is thus utilized to calculate the fluid density.

Figure 1: *Inside view of a Coriolis mass flowmeter.*

In practice, Coriolis flowmeters are usually only used for single-phase fluids, i.e. liquids or gases, as it is known that their accuracy can be affected by the existence of entrained gas in a liquid flow. A number of research activities have been carried out in the past to understand the error mechanisms of Coriolis metering under two-phase conditions. It is now known that there are various error sources, among which the so-called "bubble effect" [1] and "resonator effect" [2, 3, 4] (also referred to as compressibility effect [5]) are the main ones affecting Coriolis metering.

2. Issues with entrained gas

2.1 Bubble effect

Bubble effect theory was developed and later extended to viscous bubble theory by Hemp et al [1]. The essential idea for the root cause of the bubble effect is that a gas bubble in the measuring tube of a Coriolis mass flowmeter does not strictly follow the oscillation of the surrounding liquid with the same amplitude if the liquid cannot "hold" the bubble well. This is a result of the density difference between the gas density ρ_g and the liquid density ρ_l, which generates a relative motion between the bubble and the liquid. A secondary flow (see Figure 2) around the bubble is induced by this relative motion and causes a different inertial effect from the one that Coriolis mass flowmeter utilizes to sense mass flow rate. Under such conditions, it can be proven that the oscillation amplitude of the bubble u_g is greater but in-phase with that of the measuring tube or the liquid u_l. The corresponding secondary flow around the bubble is usually in the opposite direction to the tube vibration. Consequently, a part of the inertia of the liquid that should be felt by the tube wall for a particular flow is lost. This leads to underestimation of the real density and mass flow rate of the liquid phase.

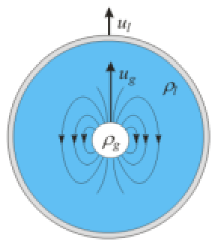

Figure 2: *Motion of a bubble in a measuring tube filled with liquid.*

Under ideal conditions of "free bubbles", in which the liquid does not exert any holding effect during the tube oscillation, it can be derived that the bubble effect error for both mass flow and density measurements is calculated by

$$E_{\rho,\dot{m}}^{\text{bub}} = \frac{-2\alpha}{1-\alpha}, \qquad (1)$$

where α is Gas Void Fraction (GVF). It can be seen that the bubble effect can only cause the same negative error for both density and mass flow measurements. If there are only ideal free bubbles and the liquid density is known, the GVF can be estimated from the drop in measured density of the Coriolis meter with respect to the liquid density. The bubble effect error can then be compensated accordingly for the mass flow and the density measurements. However, only limited success can be achieved, and then only in laboratories where ideal free bubbles are typically artificially created by injecting air or nitrogen into water flow. In real applications, however, bubble problems are more complex. One reason is that liquids are not always free of the holding effect on bubble oscillation. For example, viscosities of some oils are much higher than that of water, or the sizes of bubbles generated from an outgassing process are too small to be free in their oscillation. Based on the viscous bubble theory from Hemp, a holding coefficient is defined by the authors to describe the degree of a bubble being "free" in a liquid subject to an oscillation. This coefficient is given by

$$\delta = \sqrt{\frac{\mu}{d^2 f \rho_l}}, \qquad (2)$$

where μ, d, f and ρ_l are the viscosity of the liquid, the bubble diameter, the oscillation frequency and the liquid density respectively. With this definition, the amplitude ratio J, which is defined as the ratio of u_g to u_l, is plotted in Figure 3 as a function of δ.

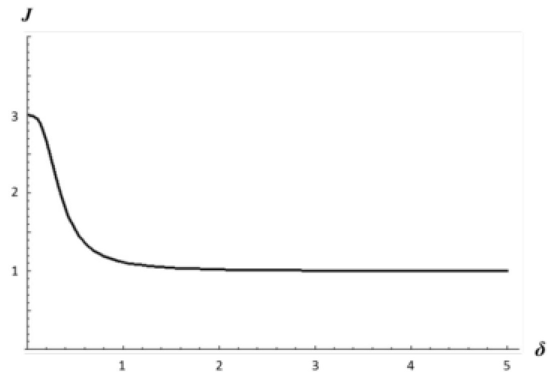

Figure 3: *Amplitude ratio as a function of δ.*

An amplitude ratio of 1 means the bubble exactly follows the liquid oscillation and no error due to the bubble effect is introduced. These types of bubble are called "suspended bubbles" in this paper. An amplitude ratio of 3 corresponds to the case of an ideal free bubble that leads to a measurement error calculated by Equation (1). An amplitude ratio between 1 and 3 is a transition region between suspended bubbles and free bubbles, where compensation for the bubble effect becomes difficult, since the exact value of δ can vary over time and process conditions. This is thus not easy to determine in real applications. It can be seen from Equation (2) that the most influence on the value of δ comes from the liquid viscosity and the bubble size, which can significantly vary compared with the liquid density and the tube frequency.

Although it is difficult to determine δ for non-suspended bubbles, it is much easier to separate them when compared with the effort spent to separate suspended bubbles. Being free due to large size or low viscosity of the liquid, free bubbles tend to separate/escape from the liquid carrier phase. Therefore, the best practice to avoid the bubble effect error is to carefully design the process so as to eliminate or significantly reduce the entrainment of free bubbles in the flow that is to be measured by a Coriolis flowmeter. This can be achieved by many practical measures such as maintaining sufficient tank levels to avoid sucking in gas, installing air eliminators or settling tanks to remove large bubbles or maintaining a high enough back pressure to the meter or a small enough pressure loss upstream of the meter to avoid/suppress severe outgassing in the process. Furthermore, a high pressure or a high flow velocity is helpful to compress/break bubbles into small sizes in order to obtain suspended bubbles.

2.2 Resonator Effect

Compared with free bubbles, suspended bubbles are much more difficult to eliminate from the process. Although causing no bubble effect error, they still introduce a resonator effect as a result of the significantly increased compressibility, giving rise to density and mass flow measurement errors. It has been found in the past that suspended bubbles bring the most difficulty to Coriolis flowmeters used in the field.

A detailed explanation of the resonator effect is given in [2]. For convenience, its basic cause and theoretical treatment are briefly presented again in this paper. As a matter of fact, the speed of sound in a liquid decreases dramatically even if only a small amount of gas is mixed. This greatly reduced sound velocity reduces the resonance frequency of the mixture in the tube, which approaches the driving frequency of the oscillating tube and causes a resonator effect (driven out of resonance) that cannot be neglected during measurement.

Considering speed of sound in a two-phase fluid, the following equation gives the relation to GVF and pressure:

$$c = \left(\frac{\alpha}{c_g^2} + \frac{(1-\alpha)^2}{c_l^2} + \frac{\alpha(1-\alpha)\rho_l}{\gamma p}\right)^{-\frac{1}{2}}, \qquad (3)$$

where γ and p are adiabatic constant and pressure respectively. Sound velocities in the gas, fluid and mixture are denoted as c_g, c_l and c. Figure 4 shows how fast speed of sound can decrease with the introduction of air into water. For an ideal two-phase medium, assuming that the gas phase is evenly distributed in the liquid phase, the acoustic resonance frequency of interest in the measuring tube can be calculated from the lowest acoustic resonance mode (standing wave, approximately half wavelength in the tube) of the tube cross-section, as given by the following equation:

$$f_0 = c\frac{\lambda_1}{2\pi R_0}, \qquad (4)$$

where λ_1 = 1.842 and R_0 is the radius of measuring tube.

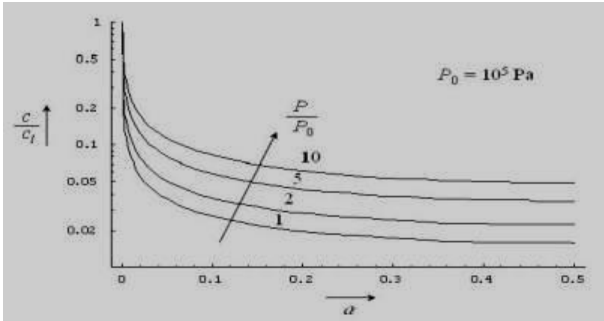

Figure 4: *Dependence of velocity of sound on GVF and pressure.*

Once the acoustic resonance frequency is determined, it is possible to calculate quantitatively the influence of the resonator effect on Coriolis density and mass flow rate measurements. As a simplified version, the density error and the mass flow rate error caused by resonator effect can be calculated as:

$$E_\rho^{\text{res}} = \left(r_0 + r_1\frac{1}{1-\frac{f^2}{f_0^2}}\right) - 1, \qquad (5)$$

$$E_{\dot{m}}^{\text{res}} = k_{\text{res}}E_\rho^{\text{res}}, \qquad (6)$$

where k_{res} is the magnitude factor of mass flow rate error to density error. This has a value of about 2 or alternatively can be precisely calculated by the method described in [2]. r_1 (=0.837) is the portion of the fluid mass in the measuring tube that is active for the resonator model being discussed, while r_0 (=0.163) is the inactive part. The detailed explanation is given in [2]. It can be concluded from Equations (3)-(6) that since the tube driving frequency is typically far below the acoustic resonance frequency, the resonator effect almost always leads to positive measurement errors - which is opposite to the bubble effect. Although a low tube driving frequency generates a smaller resonator effect error according to Equations (5) and (6), the finite physical dimension of a Coriolis meter determines that the lowest driving frequencies are still of the order of 100 Hz. Moreover, for a given driving frequency, a larger measuring tube diameter results in a lower acoustic resonance frequency of the fluid f_0 in measuring tube and consequently a more significant resonator effect according to Equations (4) and (5). This means that larger size meters suffer more from the resonator effect and it is not of practical value or is even impossible to design them with extremely low frequencies (e.g. to the level of a few Hz) to eliminate the errors induced by it.

3. Multi-Frequency Technology (MFT)

To compensate the measurement errors induced by the resonator effect, MFT has been researched and developed based on the vibrational properties of the Coriolis sensor and advanced further with respect to the Two-Mode Compensation proposed in [2]. When a Coriolis meter measures a liquid with suspended bubbles, the measured density error is defined as

$$E_\rho^{\text{res}} = \frac{\rho_a - \rho}{\rho}, \qquad (7)$$

where ρ_a and ρ are the apparent density reading from the meter and the true density of the two-phase mixture respectively. Combining Equations (5) and (7) gives

$$\rho_a = \rho\left(r_0 + r_1\frac{1}{1-\frac{f^2}{f_0^2}}\right). \qquad (8)$$

A conventional Coriolis sensor oscillates typically at the first natural mode of the measuring tube, which is a bending mode as shown in Figure 5 (only a half model is shown). Therefore, only one equation, namely Equation (8) can be established, which is not sufficient to determine the two unknowns, ρ and f_0.

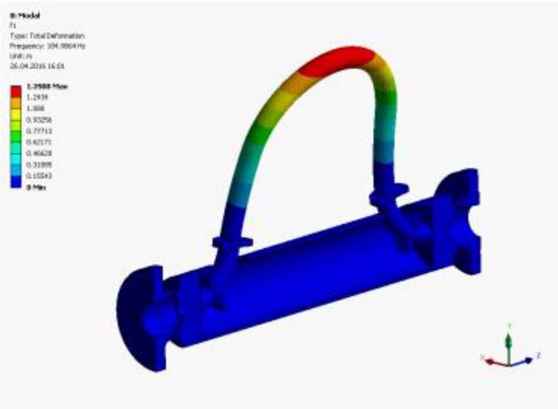

Figure 5: *Modal shape of the first natural mode in numerical simulation.*

During the new sensor (Promass Q) design, the authors have given special consideration to ensuring that the oscillation of the measuring tube is not only well balanced for the basic working mode, but also for a higher mode, the third mode of the measuring tube, as shown in Figure 6. A good balance for tube oscillation is critical for the design of a Coriolis meter to ensure that the tube vibration is isolated from the external process connection. Then, a reliable density measurement can also be realized with the third mode, which provides an independent density reading ρ_{a3} from that of the first mode and therefore can give additional information about the resonance properties of the fluid. The reason for relying on the third mode instead of the second mode of the tube lies in the fact that the second tube mode is anti-symmetric with respect to the driver, so that this mode cannot be excited by the existing driver shown in Figure 1. In addition to mode shape, the third mode differs from the basic working mode by having a much higher resonance frequency, typically by a factor of 5-6. It should be noted that the two tube modes can be driven simultaneously with the same driver. The mechanical motions and the corresponding signals of the two modes are then superimposed. With the modern electronics developed for this purpose, the combined signal can be simultaneously processed and two independent vibrational properties of the two modes can be obtained accordingly.

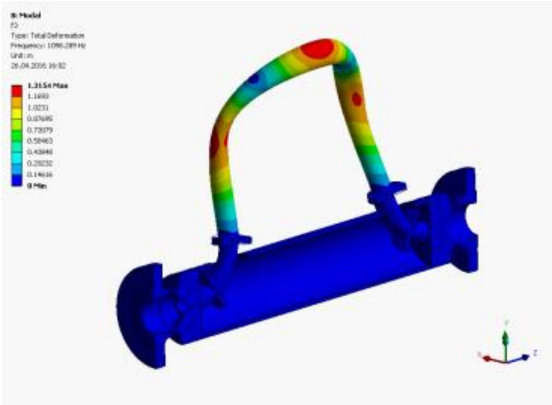

Figure 6: *Modal shape of the third natural mode in numerical simulation.*

With the same two-phase fluid being driven at two frequencies, two equations, taking the same form as Equation (8), can be established as follows:

$$\rho_{ai} = \rho\left(r_0 + r_1\frac{1}{1-\frac{f_i^2}{f_0^2}}\right), \qquad (9)$$

where i = 1 and 3, correspond to the first mode and the third mode of the measuring tube, respectively. With the above two equations, the unique resonance property of the entrained gas in the measuring tube can be determined. In other words, the two unknowns, ρ and f_0 can be solved. Therefore, the first measured parameter, the density of the two-phase fluid unaffected by the resonator effect, is already obtained. With the known f_0, the mass flow error caused by the resonator effect can be calculated with the help of Equations (5) and (6). Once the mass flow error is determined, the actual mass flow measured by the device $\dot{m}_a$ can then be compensated accordingly with the following equation:

$$\dot{m} = \frac{\dot{m}_a}{E_{\dot{m}}^{\mathrm{res}} + 1}, \qquad (10)$$

Since f_0 is obtained from MFT, it is straightforward to calculate the speed of sound based on Equation (4) as the radius of the measuring tube is known. This is not only possible for a liquid with entrained gas, but also for a pure gas. Research work conducted by the authors has shown that speed of sound of various gases can be measured with MFT, provided the resonator effect of the gas can introduce a sufficient difference between the apparent densities measured by the first mode and the third mode of the measuring tube respectively. Typically, this can be achieved by having a high enough gas pressure (e.g. ≥5 barg). As this does not concern the subject of this paper, no further detail is given.

4. Application of MFT

There are numerous entrained gas applications to which MFT can be applied, such as heavy oils that can hold bubbles because of high viscosity, dairy products that contain micro-bubbles due to product nature, etc. Targeted for one interesting type of application, Promass Q with MFT was tested with outgassing from produced water at Schlumberger in Porsgunn, Norway. The test setup is shown in Figure 7. A reference Coriolis meter was installed in the high pressure section, where the production water saturated with nitrogen was single phase (shown in the left picture of Figure 8), which the reference Coriolis meter measured with an uncertainty of ±0.1%. The test Coriolis meter with MFT was installed in the low pressure section, where outgassing was created to generate a gas-liquid two phase flow, as shown in the right picture of Figure 8. As can be seen there, a homogeneous micro-bubble flow regime was produced by the outgassing.

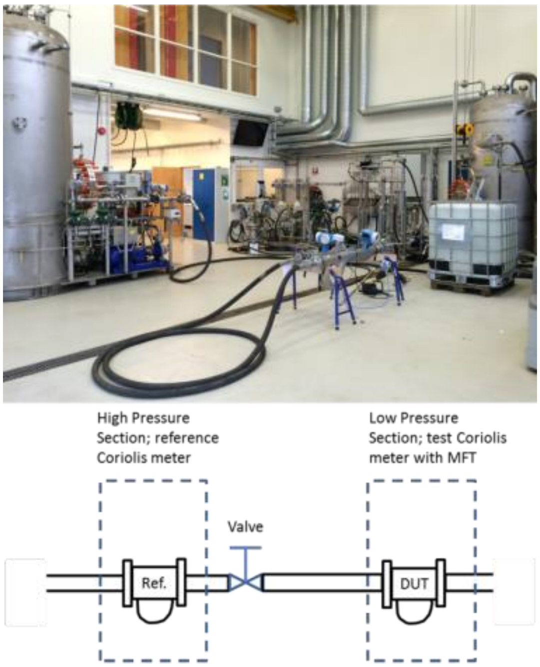

Figure 7: *Outgassing setup for Promass Q with MFT at Schlumberger and corresponding schematics.*

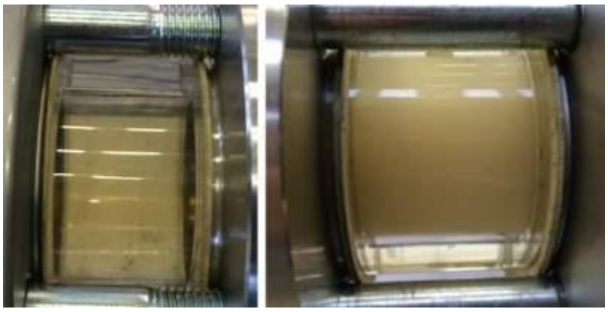

Figure 8: *Single phase flow in the high pressure section (left) and two-phase flow in the low pressure section due to outgassing (right).*

The test conditions are given in Table 1, and the test result is shown in Figure 9.

Table 1: *test conditions.*

Salinity	3.7%
Temperature (°C)	50 °C
Flow rates (kg/h)	7000–18000

As can be seen in Figure 9, MFT significantly improved the measurement accuracy from up to 2% error to an accuracy level about 0.3%. Based on the setup and the fluid, GVF could reach about 3% in this test. In Figure 9, the calculation done for the case "without MFT" was based on the recorded internal parameters of the same test meter and errors were calculated offline after the test. It is interesting to see that the calculated speeds of sound in this test ranged from 78 to 260 m/s, which are lower than the speed of sound in either water or nitrogen.

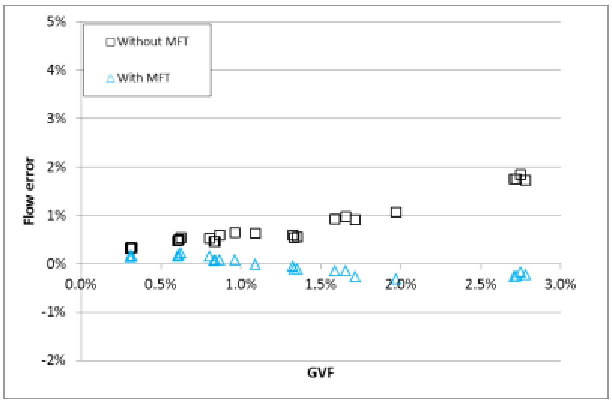

Figure 9: *Measurement accuracy as a function of GVF.*

5. Further application of MFT

In addition to the compensation of density and the mass flow errors induced by the resonator effect, MFT enables the measurement of more compressible fluid parameters, such as the speed of sound in this fluid and GVF in a gas-liquid two-phase fluid.

For a gas-liquid two-phase fluid, once the speed of sound is known, GVF can be calculated from Equation (3) with the knowledge of the process pressure in the device and the basic thermodynamic properties of the gas phase and the liquid phase, respectively. It should be noted that analyzing the weighting factors of different terms on the right hand side of Equation (3) suggests that an exact knowledge of c_g and c_l is not strictly required since the their contribution to c is much smaller than α and P, at least for most common applications where α and P are relatively small. Furthermore, the following equation

$$\rho_l = \frac{\rho - \alpha\rho_g}{1-\alpha} \qquad (11)$$

generally holds for a gas-liquid two-phase fluid. For most applications of interest here, the term $\alpha\rho_g$ is much smaller than ρ. Therefore, it can be simplified to

$$\rho_l = \frac{\rho}{1-\alpha}\,. \qquad (12)$$

Combining Equations (3) and (12) gives the solutions to GVF and liquid density. The latter is of particular interest for some applications, where the liquid phase consists of two components e.g. water and oil, and the Coriolis meter is expected to measure this liquid mixture density to determine the phase volumetric concentrations such as Water Cut (WC, water volume fraction in oil). With MFT, the measurement for three phase volume fractions is enabled, which is otherwise impossible with only a conventional Coriolis meter.

A test of this function was performed at an independent laboratory, DNV GL, where outgassing conditions were generated to introduce the third phase (i.e. gas) in the water-oil two phase flows with various WCs (see Figure 10). The oil used in the test was Exxsol D120 with a viscosity of about 4-5 cSt and a density of about 0.82 g/ml. The test pressure ranged from 8-14 barg. Figure 11 shows the calculated GVFs with MFT compared to the ones derived from the Coriolis density measurement, knowing the liquid phase densities from the lab. It should be pointed out the latter method for the GVF calculation is based on the assumption that the Coriolis density measurement is precise. Therefore, it cannot be strictly taken as the reference and the comparison made in Figure 11 is only qualitative.

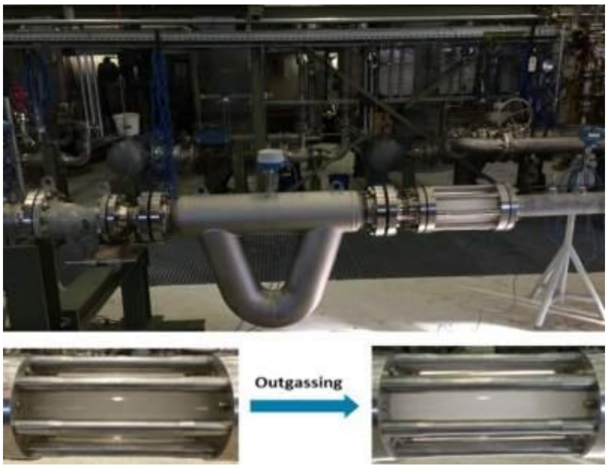

Figure 10: *Outgassing test of Promass Q with MFT at DNV GL.*

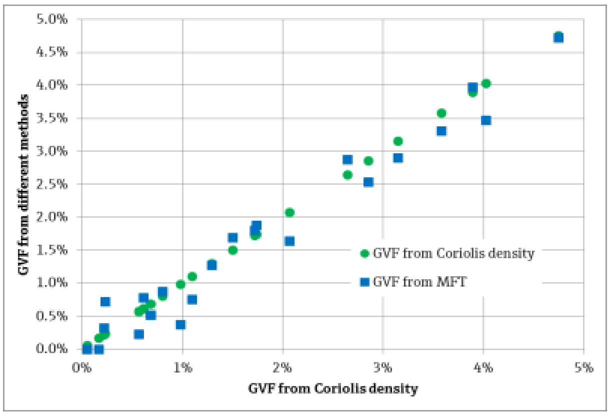

Figure 11: *Calculated GVF with MFT compared with that derived from the Coriolis density measurement.*

However, the reference for the actual WC provided by DNV is highly reliable since water and oil single phase flows were separately measured before they were mixed together. The results of the enhanced WC measurement with MFT are given in Figure 12. They are compared to the results from the straightforward method, with which the Coriolis density drop caused by the entrained gas was simply wrongly regarded as a higher concentration of oil, the density of which is lower than water.

It can be seen from the figure that the WC measurement is significantly improved by correcting the effect of entrained gas with the help of MFT.

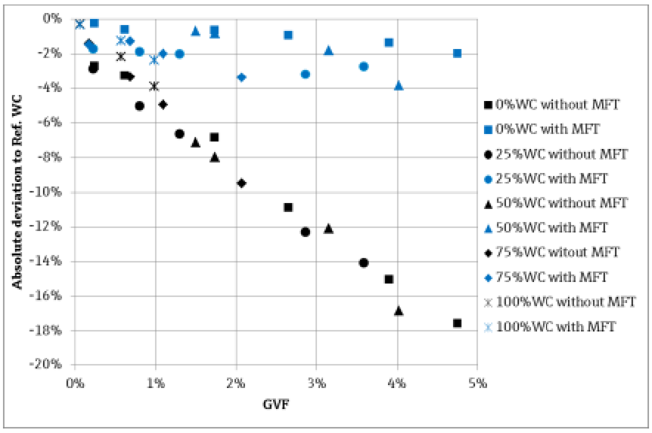

Figure 12: *WC measurements by MFT corrected with GVF.*

6. Conclusion

The bubble effect and the resonator effect are the main error sources for Coriolis metering under entrained gas conditions. As the best practice, the bubble effect due to the existence of free bubbles should be suppressed by eliminating the free bubbles with the help of the process optimization, e.g. using gas eliminators or creating high turbulence to break free bubbles into small size suspended bubbles. The resonator effect is the major issue in the field since suspended bubbles are much more difficult to remove. To cope with this, an innovative technology, MFT, which makes use of multiple oscillation modes of the measuring tube to compensate the resonator effect for both density and mass flow measurements, has been introduced in this paper. The measurement of speed of sound in a gas or an entrained gas fluid is enabled with the help of MFT. In combination with a pressure measurement, MFT can further calculate the GVF in an entrained gas fluid, which allows the measurement of the volume fractions for a three-phase fluid. Two lab tests with outgassing, where homogeneous suspended bubbles were generated, are also shown as validation tests for this technology.

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