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Paper 7.2

Multiphase Flow in Coriolis Mass Flow Meters – Error Sources and Best Practices

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nel technology for life

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1 INTRODUCTION

Coriolis mass flow meters are used throughout the oil and gas industry, from upstream allocation and net oil measurement to custody transfer of pipeline quality oil. Coriolis meters have an inherent advantage over volumetric meters in measuring pure liquid quantities in applications involving liquids with entrained gas because the mass flow rate of an aerated mixture is close to that of the liquid flow rate. Likewise, volumetric meters may be preferred for measurement of wet gas, as the volumetric flow rate of a wet gas is close to that of the gas flow rate, which is typically the desired quantity. With that in mind, multiphase flow in the context of this paper refers to any mixture of two or more components in which the base phase is a liquid. This includes bubbly liquids, particle-laden flows, slurries, emulsions, and multi-liquid mixtures.

Coriolis meters are unique in using two oscillating flow tubes to make measurements, with the assumption that the fluid moves directly with the tubes in the oscillatory direction. When multiple phases or components of different density are present, this assumption is not valid and errors result. Measurement accuracy is reduced due to various effects, and the extent of the error is a complicated function of meter design parameters, fluid properties, and flow conditions. Recent research conducted by Coriolis meter manufacturers has led to significant improvements in performance in multiphase applications. For example, modern signal processing algorithms allow resolution of flow signals even in the presence of increased flow noise. However, some multiphase errors remain. Understanding the true physical mechanisms for these remaining errors allows for development of an effective set of installation and operational best practices for multiphase applications. It will be shown that these practices can substantially reduce measurement error and make Coriolis meters a legitimate solution in multiphase applications involving relatively small gas or particle volume fractions.

The paper includes a clear explanation of the dominant error mechanism in multiphase Coriolis measurement, termed *decoupling*, which occurs when gas bubbles or solid particles move relative to the surrounding liquid during vibration of the flow tube. A theoretical analysis of decoupling, along with real-world test results, highlight the importance of several parameters including base phase viscosity, second phase particle size, vibration frequency, and density ratio between the phases. Many of these parameters, such as particle size, are directly influenced by installation and operation practices. Recommendations are made for simple practices which allow users to optimize measurement performance in the presence of entrained gas or solid particles. Several specific oil and gas applications are discussed – live oil with entrained gas, net oil, watercut, cementing, and fracture sand applications.

The paper concludes with a discussion of an important real-time diagnostic for detection of multiple phases, which is applicable to any Coriolis meter in any multiphase scenario, including water and oil measurement and solid-laden flows. Historically, density has been used for detection purposes; however, density is influenced by changes in temperature, pressure, and composition, and is not particularly sensitive to low levels of entrained gas or solid particles. Early and accurate detection of the presence of multiple phases with a Coriolis meter is best accomplished by monitoring the amount of power consumed during flow tube vibration. The same physical mechanism which causes errors in multiphase measurement, decoupling, also dramatically increases power consumption due to the relative motion between gas or solid particles and the surrounding liquid. With the use of this diagnostic, the Coriolis meter can provide an extremely sensitive detection of multiple phases. This is particularly useful in oil and gas applications in which multiphase flow is not expected and is rather a cause for alarm, for example custody transfer of pipeline quality oil or allocation measurement downstream of a separator.

1.1 How to Read this Paper

This paper is written for a diverse audience, and is accessible to anyone with a basic technical background. It is not necessary to get lost in the details of the equations in Section 3 to understand the most important information regarding how to use Coriolis meters in multiphase applications. If time is short or you're looking for an overview, please consider skimming Sections 2.3, 3.1, and 3.2, and rejoin at Section 3.3. Experienced users of Coriolis meters may want to skim Section 2.1 and rejoin at Section 2.2. The most important part of the paper is Section 4, so if you're very short on time, read Section 2.2, then skip to Section 4.

2 CORIOLIS MEASUREMENT IN MULTIPHASE FLOW

Coriolis meters are potentially more accurate than volume-based devices when gas is present in the process fluid because gas adds very little mass but a large volume. Users almost always require pure liquid or gas quantities, not mixture quantities. When 10% gas volume fraction is entrained in a flowing fluid, a volume-based device will measure about 10% high in liquid volume flow rate, while a Coriolis meter will measure nearly the correct liquid mass flow rate due to the negligible mass contribution of the gas. However, when multiple phases are present, some of the basic assumptions made in Coriolis measurement break down and errors may result. In order to study the failure modes, it is first useful to briefly review how the density and mass flow measurements are made.

2.1 Coriolis Measurement Basics

The Coriolis meter measures mass flow and density of single phase gas or liquid flows to very high accuracies. There are no complex moving parts that wear out over time and minimal installation requirements. Because mass is always conserved, pressure and temperature measurements are unnecessary and equations of state are not needed when measuring mass flow. The Coriolis meter is therefore practical in applications involving chemical reactions, which are based on a mass balance, as well as applications involving a compressible fluid or in which temperature and pressure vary significantly. However, due to their unique design, Coriolis meters do have some inherent design challenges. For example, temperature and pressure variations affect the vibrating tube by causing modulus changes and material expansion. These and other effects are usually compensated out.

A common Coriolis meter design consists of two flow tubes oscillating 180° out of phase at the natural frequency. The vibration of the tubes about fixed points yields a rotating, non-inertial reference frame in which forces such as the Coriolis force are present. As shown in Figure 1, the flow separates into two tubes after entering the meter. The tubes are driven by a magnet and coil assembly at the first bend mode resonant frequency with a periodic signal at the location marked driver. The oscillation frequency depends on the mass and stiffness of the system. If the fluid in the tubes is very dense, the tubes will be heavier, resulting in a decreased natural frequency. For a low density fluid such as a gas, the frequency will be higher. After calibration on a high and low density fluid, the density of an unknown fluid can be determined by measuring the frequency of oscillation of the tubes. The actual measurement is made using two additional magnet and coil assemblies, called pickoffs, mounted between the tubes at measurement

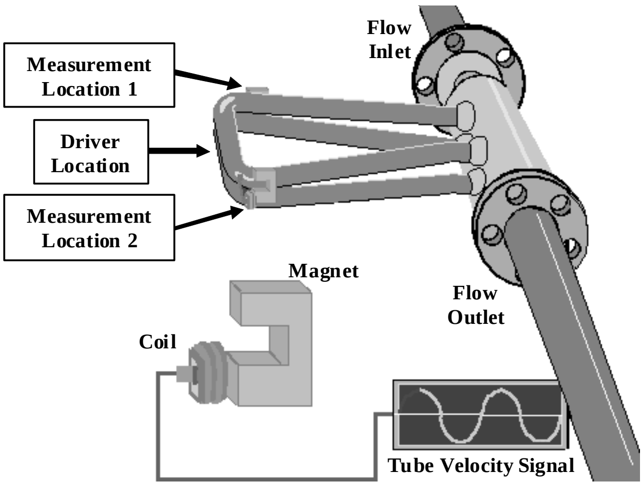


Fig. 1 - Anatomy of a Coriolis flow meter

locations shown in Figure 1. The pickoffs create a relative velocity signal which can be processed to find the oscillation frequency.

Fluid particles travelling through the oscillating flow tubes experience a Coriolis force due to the rotating reference frame. At any instant, this force applies in the opposite direction on the inlet and outlet side of the meter (see Figure 2), exciting a twist motion which is superimposed on the normal bend motion (see Figure 3). Here, a fluid parcel of mass *m* moves at velocity *V* in a flow tube with angular frequency *ω*, resulting in an applied Coriolis force, F_c, on the flow tube by the fluid. The twist motion results in a time delay, *ΔT*, between the inlet and outlet side of each tube which is measured using the signals from the two pickoffs.

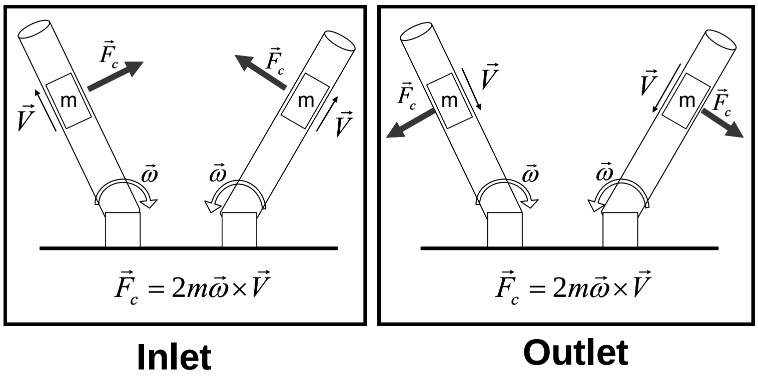


Fig. 2 - Coriolis forces on the inlet and outlet flow tubes

The magnitude of the time delay is linearly related to the mass flow rate through the meter because the Coriolis force increases linearly with the product of mass and velocity. After calibration, the Coriolis meter can measure an unknown mass flow rate using the time delay between the inlet and outlet sides of the tubes.

2.2 Decoupling Effects

A pure liquid moves in the transverse direction exactly with the flow tubes, and the center of gravity of the fluid remains fixed in the middle of the tube. However, the presence of two phases with different density causes a decoupling of the transverse fluid motion from the tube motion. For example, liquid particles and gas bubbles of the same volume will be accelerated differently due to the difference in their mass. Gas bubbles experience higher acceleration than the surrounding fluid which leads to relative motion between the bubbles and the fluid. This causes mass and density measurement errors due to changes in the location of the center of gravity of the fluid mixture inside the tube.

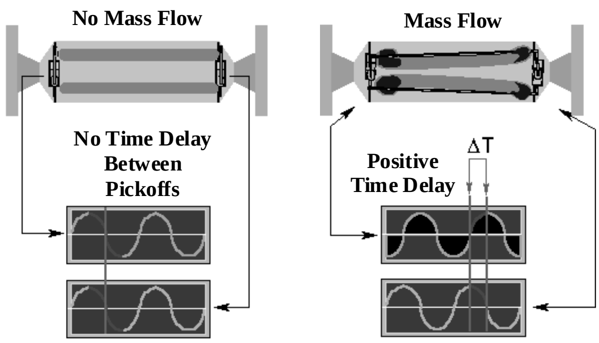


Fig. 3 - Top view of tubes showing twist mode

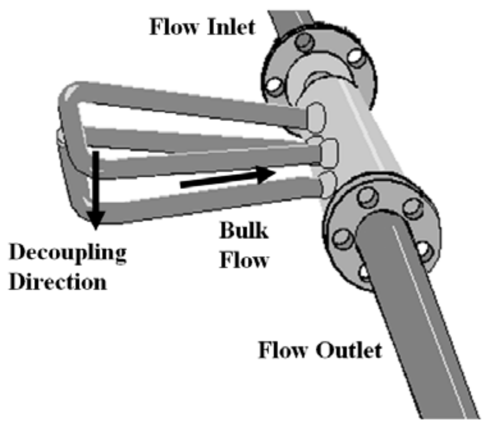


Fig. 4 - Direction of decoupling and bulk flow

The term "decoupling" refers to relative motion between two components of differing density in the direction of tube oscillation, which is perpendicular to the direction of bulk fluid flow, as shown in Figure 4. To model decoupling, it is not necessary to know exactly how the particles move through the meter, which would be very difficult due to the multiple phases and complex geometry of the flow tubes. Instead, the critical quantities are found to be the amplitude ratio and phase delay between the particle and fluid in the transverse direction.

Figure 5 shows a cross-sectional view of a single vibrating tube at two instances during a vibration cycle. At the point of maximum deflection, the bubble has moved further than the fluid by a factor defined as the decoupling ratio, A_p/A_f. The amplitudes are defined with respect to the distance from the midpoint of tube oscillation.

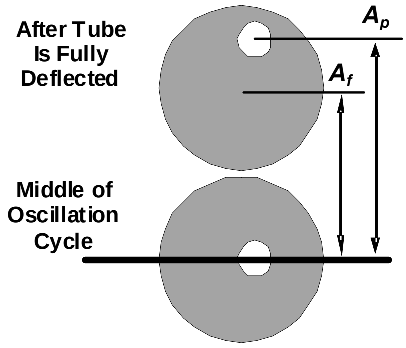


Fig. 5 - Decoupling ratio definition

Decoupling causes some of the liquid mass in the tubes to move so that it is undetected by the flow meter. This causes the density to read lower than the mixture density in the case of a bubbly fluid. For example, if a mixture consists of 10% volume fraction gas in a liquid of density 1000 kg/m^3, then the meter density should read 10% lower than the liquid, or 900 kg/m^3. However, due to decoupling, the meter erroneously measures perhaps 898 kg/m^3. The further the bubbles or particles decouple from the fluid on each oscillation of the tubes (ie. greater A_p/A_f), the larger the undetected volume of fluid will be and the larger the resulting error. Mass flow is also affected by decoupling, causing the meter to under-predict flow.

Figure 6 shows a schematic of the facility at Emerson Process Management - Micro Motion for testing entrained gas performance of Coriolis meters. Reference Coriolis meters are used for precise mass flow measurement of the separate liquid and gas streams. The reference mixture mass flow through the test meter is simply the sum of these two streams. Pressure (P) and temperature (T) measurements upstream and downstream of the test meter are used to calculate the volume fraction of the gas inside the meter, which gives mixture density. After flowing through the test meter, aerated fluid is returned to a tank and sufficient residence time is allowed for full separation of gas and liquid phases.

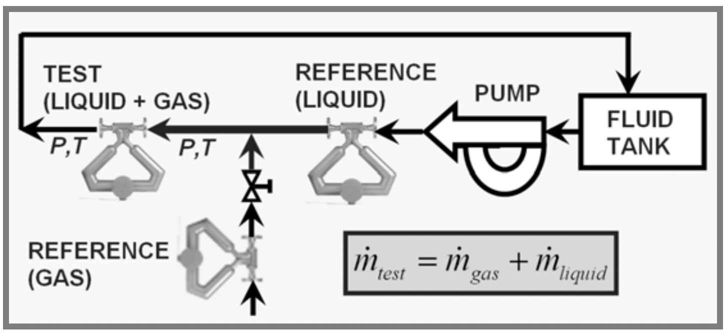


Fig. 6 - Multiphase test facility schematic

Figure 7 shows percentage mass flow error from true mixture mass flow in a Coriolis meter due to entrained gas. Pressure inside the meter is held constant at 210 kPa (30 psig) for all tests, while flow rate and the amount of gas injected are varied. For each test at constant mass flow rate, increased gas volume fraction results in increased measurement error. However, performance improves with increasing flow rate because the gas phase is broken down into very small bubbles rather than the larger slugs of gas which occur when pipeline velocities are low. This results in a more homogenous fluid mixture, and as will be shown later, smaller bubbles decouple from the fluid phase to a lesser extent.

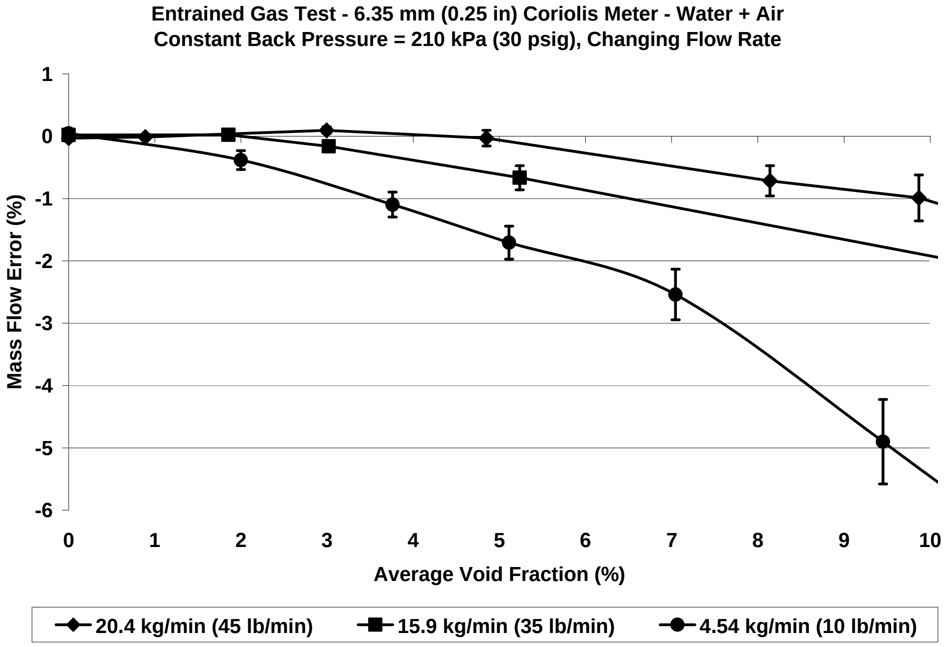


Fig. 7 - Mass flow error due to entrained gas

Density error from true mixture density is shown in Figure 8 for the same conditions. As expected, performance degrades with increasing void fraction and improves with increasing flow rate. Extensive experimental data has been obtained for a range of meters and fluids. For a definition of mixture density, see for example equation (18) in Section 4.2.

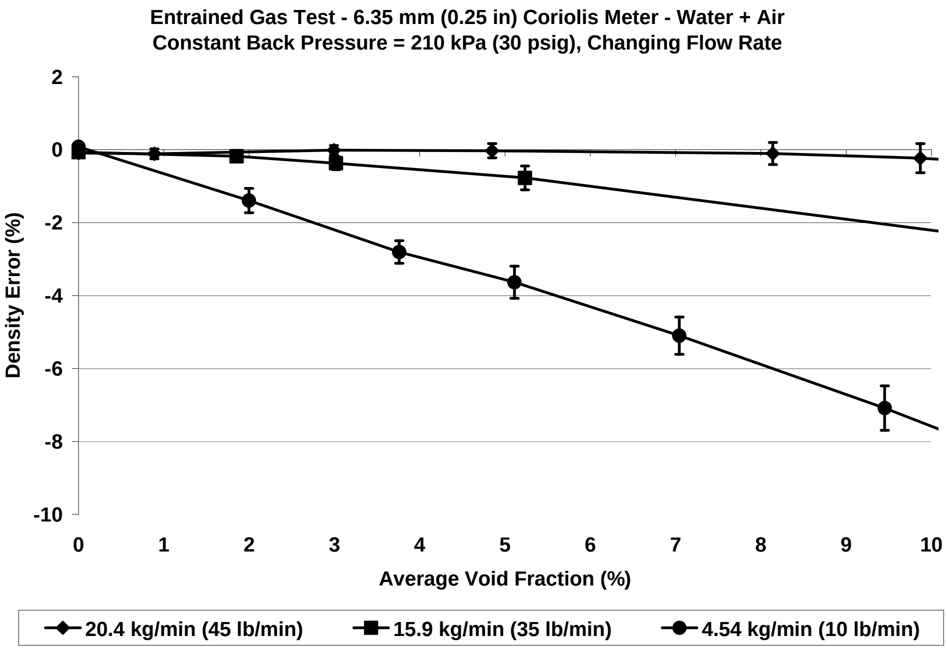
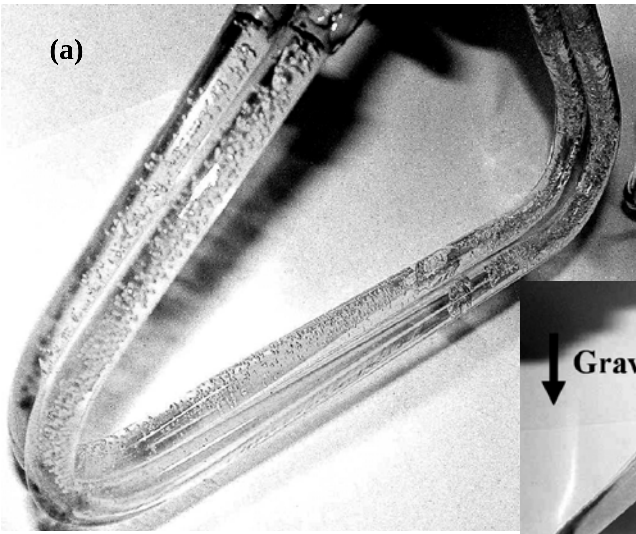


Fig. 8 - Density error due to entrained gas

In order to better understand the complicated sources of error in multiphase flow in a Coriolis meter, we constructed visualization meters out of clear polycarbonate tubing. Several sizes and shapes were made to investigate the differences between meter designs. In Figure 9, a 6.35 mm (0.25 in) dual curved tube meter is photographed with approximately 20% gas volume fraction in water with green food coloring. The flow rate is moderate in frame (a), but quite low in frame (b).



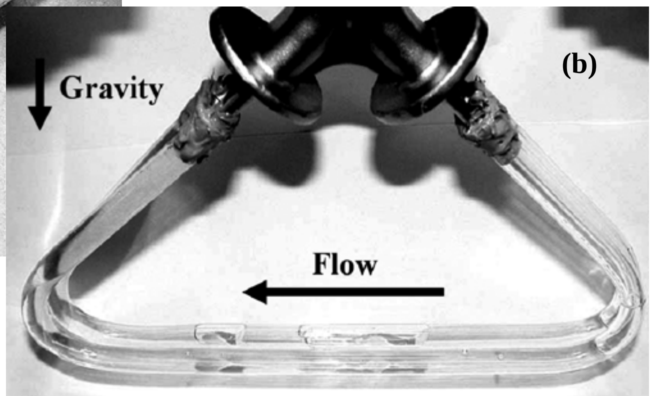


Fig. 9 - Visualization of entrained gas in a Coriolis meter; (a) high flow rate; (b) low flow rate

The bubbles are fairly well distributed within the flow tubes in frame (a) and the amount of gas in each tube is consistent. For this flow condition, errors would be small due to the homogeneity of the mixture and the small bubble sizes. However, at much lower flow rates, gas can accumulate on the inlet or outlet side of the meter depending on installation orientation and result in asymmetries along the length of the tube. Frame (b) of Figure 9 shows a scenario in which gas has accumulated on the inlet side due to positive buoyancy of the bubbles on the inlet side of the meter. Large slugs of gas are also seen near the middle of the tubes. The asymmetries in mass and damping caused by the trapped gas directly impact phase delay and cause large positive mass flow errors. If the bubbles accumulate instead on the outlet side of the meter, then the mass flow error is negative. In either case, following standard multiphase piping practices for minimum flow rates resolves these problems and results in a homogeneous mixture which is symmetric along the length of the tube.

2.3 Velocity of Sound Effects

In addition to problems caused by the relative motion of bubbles and particles, Coriolis meters experience velocity of sound effects when the sonic velocity of the measurement fluid is low or the oscillation frequency of the meter is high. Gases have lower sonic velocities than liquids, but the lowest velocities result from a mixture of the two. The addition of even a small amount of gas to a liquid results in a dramatic reduction in the velocity of sound of the mixture below that of either phase.

The oscillation of the flow tube produces sound waves that oscillate in the transverse direction at the drive frequency of the meter. When the velocity of sound of the fluid is high, as in a single phase fluid, the first acoustic mode for transverse sound waves across the circular conduit is at a much higher frequency than the drive frequency. However, when the velocity of sound drops due to the addition of gas to a liquid, the frequency of the acoustic mode also drops. When the frequency of the acoustic mode and the drive mode are close, meter errors result due to the off-resonance excitation of the acoustic mode by the drive mode. For low frequency meters and typical process pressures, velocity of sound effects are negligible with respect to the specified accuracy of the meter. However, for high frequency Coriolis meters, the velocity of sound can be low enough to cause significant measurement errors due to interaction between the drive and fluid vibration modes.

A more physical explanation of velocity of sound effects in Coriolis meters is that the fluid in the tube is compressed against the outside wall of the tube on each oscillation when the compressibility of the mixture is high enough to allow for such motion. In this way, velocity of sound effects are similar to decoupling effects in that the actual error is caused by movement of the location of the center of gravity. The difference is that velocity of sound effects result in heavier fluid pushed to the outside walls of the tube while decoupling results in heavier fluid pushed to the inside walls of the tube. For this reason, velocity of sound errors are positive and decoupling errors are negative. This is confirmed by a recent model by Hemp & Kutin [1], which quantifies density and mass flow errors due to velocity of sound effects. The closed form expressions are given as percentage increases from true mixture values, where d is the inner diameter of the Coriolis meter flow tube, ω is the angular oscillation frequency, and c_m is the mixture velocity of sound.

$$\rho_{vos,err} = \frac{1}{4}\left(\frac{\omega d}{2c_m}\right)^2 \times 100 \tag{1}$$

$$\dot{m}_{vos,err} = \frac{1}{2}\left(\frac{\omega d}{2c_m}\right)^2 \times 100 \tag{2}$$

The remainder of this paper will focus on decoupling errors, which by comparison are poorly understood and are usually of greater magnitude than velocity of sound effects. For example, consider a 100 Hz Coriolis meter with 10 mm diameter tubes measuring oil with 1% gas volume fraction at low pressure. Density can be in error by up to 2% due to decoupling, but equation (1) predicts only a 0.02% error from velocity of sound effects. Also, velocity of sound effects can be easily avoided by using low frequency meters for multiphase applications, while errors due to decoupling are more difficult to eliminate.

3 OSCILLATORY PARTICLE DYNAMICS APPLIED TO CORIOLIS METERS

The motion of particles in an oscillating fluid has been investigated thoroughly, starting in the late 19th century. In this section, we apply this broad theoretical background to the specific case of multiphase measurement in Coriolis flow meters. Many multiphase applications involve viscous fluids such as soap, oil, and ice cream, but it is useful as a first step to evaluate the effects of bubble or particle motion on measurement of an inviscid flow. This analysis will illuminate the driving forces for decoupled motion and offer insight into the differences between gas/liquid, liquid/liquid, and solid/liquid flows.

3.1 Inviscid particle motion model

We begin with the Euler equations, which are found from the Navier-Stokes equations by neglecting viscosity and heat transfer. Brennen [2] gives a comprehensive overview of the solution of the Euler equations using potential flow theory for translation of a bubble or particle in an unsteady, inviscid, irrotational flow field. The total force on the particle is given by the following expression, where ρ_f refers to the fluid density and τ is the volume of the particle (f subscripts refer to the fluid, while p subscripts refer to the particle, bubble, or droplet).

$$F_{total} = F_{addedmass} + F_{buoyancy} = \frac{1}{2}\rho_f \tau \left(\frac{du}{dt} - \frac{dv}{dt}\right) + \rho_f \tau \frac{du}{dt} \tag{3}$$

Here, u and v are the fluid and particle velocities, respectively. Two forces act on a spherical particle in unsteady potential flow with the stated assumptions. The first force on the right hand side of equation (3) accounts for the added mass effect which is caused by the acceleration of the surrounding fluid due to the spherical particle which is constantly displacing fluid as it moves through the flow field. The second force in (3) is an inertial buoyancy-like force caused by the acceleration of the fluid relative to an inertial frame. The acceleration of the fluid causes a pressure gradient which produces the force term. This is similar to the force causing a bubble to rise up through water, or a slug of gas to "slip" through a pipeline with superficial velocity. Newton's Law can be applied to obtain a differential equation for particle motion, with the mass of the particle times its acceleration on the left, and the sum of the forces on the right.

$$m_p \frac{dv}{dt} = \frac{1}{2}\rho_f \tau \left(\frac{du}{dt} - \frac{dv}{dt}\right) + \rho_f \tau \frac{du}{dt} \qquad (4)$$

Given the definition of particle mass, $m_p = \rho_p \tau$, equation (4) reduces to the following:

$$\left(1 + \frac{2\rho_p}{\rho_f}\right)\frac{dv}{dt} = 3\frac{du}{dt} \qquad (5)$$

Equation (5) indicates that for a bubble of negligible density in oil ($\rho_p << \rho_f$), the bubble will have three times the acceleration of the fluid. Integrating the equation twice shows that the particle travels three times as far as the fluid per oscillation of the flow tube, as shown graphically in Figure 5. A droplet of liquid having the same density as the bulk fluid ($\rho_p = \rho_f$) will have the same position, velocity, and acceleration responses as the liquid. If the particle is more dense than the liquid ($\rho_p > \rho_f$), then the liquid will experience greater acceleration than the particle.

The liquid phase is assumed incompressible and generally to move directly with the tube. This ignores some circulation effects that occur because of the tube's circular geometry, the oscillatory motion of the pipe, and the swirl in the pipe caused by the manifold geometry. It is reasonable to neglect these effects because they do not cause changes in the location of the center of gravity of the fluid in the tube, which is the mechanism by which decoupling causes measurement errors. Given these assumptions, the fluid motion will be sinusoidal with angular frequency ω and amplitude A_f, and the particle will in general respond at the same frequency but different amplitude, A_p, and phase delay, φ.

$$\text{Fluid Displacement} = A_f \sin(\omega t) \qquad (6)$$

$$\text{Fluid Velocity} = u = \omega A_f \cos(\omega t) \qquad (7)$$

$$\text{Particle Displacement} = A_p \sin\left(\omega t + \varphi\right) \qquad (8)$$

$$\text{Particle Velocity} = v = \omega A_p \cos\left(\omega t + \varphi\right) \qquad (9)$$

It may be intuitively unclear why a bubble moves further than the bulk fluid on each oscillation of the flow tube and why a solid particle moves less. To understand this, consider the simple case of a bubble flowing with a fluid inside a pipe. Relative movement of the gas phase in pipe flow is typically known as the slip velocity, and is a measure of how fast the gas phase moves with respect to the liquid phase. This is similar to the case of decoupling in oscillatory motion, except that the acceleration is caused by a pressure gradient instead of tube motion.

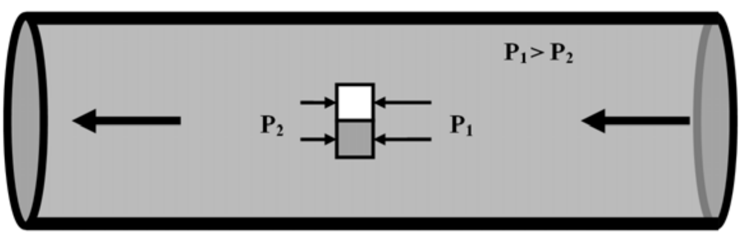


Fig. 10 - Bubble slip velocity in pipe flow

Consider two equally sized cubes of fluid flowing through a pipe as shown in Figure 10. The first cube is an air pocket and the second is a fluid of the same density as the surrounding fluid. The same pressure force is exerted on the upstream and downstream faces of both cubes, and all pressure forces exerted on faces in the direction perpendicular to flow cancel out. Therefore, with the same pressure force exerted over the same area, each cube will experience the same net pressure force in the downstream direction. Bubble slip occurs because the gas cube is less dense than the liquid cube and Newton's law requires that, under the same force, the lighter gas cube must have higher acceleration. The added mass force resists the relative motion between the gas cube and the liquid cube, but it does not completely stop the motion so long as the gas is less dense than the liquid. As will be shown later, larger bubbles experience larger slip velocities, while highly viscous fluids tend to keep slip velocities low. If the gas cube was instead replaced with a solid cube of greater density than the liquid, the solid cube would move more slowly than the liquid by the same arguments. These same effects occur in the direction of oscillation of a Coriolis meter flow tube and cause the relative motion we call decoupling.

3.2 Viscous particle motion model

In order to predict Coriolis meter performance in a wider range of multiphase flow applications, we extend the potential flow theory to incorporate viscous effects. The viscous model includes two new forces, the drag force and the history, or Basset, force. With the addition of these forces, the decoupling between the particle and fluid decreases, especially at higher viscosity. This is because the drag and history forces impede the decoupled motion between the particle and fluid. We also expect the motion of the particle and fluid to be out of phase because of the lag in deceleration and acceleration of the particle caused by the addition of the drag force.

Modeling oscillatory motion of a sphere through a viscous fluid is complicated. A viscous wake region develops behind the sphere as fluid flows past it and boundary layer separation occurs. For a particle which oscillates back and forth through its own wake, various modifications to the equations of motion must be made in order to correctly predict the physics. The theoretical basis for unsteady motion of a rigid particle in a viscous fluid is usually credited to Basset [3], though others studied the same problem independently. Through solution of the unsteady Stokes equations, Basset determined an expression for particle motion with a no-slip boundary condition, which is essentially the acceleration of a particle of mass $(4/3)\pi a^3\rho_p$ due to the summation of forces acting on the particle. Basset's solution assumed very low Reynolds numbers and a no-slip boundary condition at the surface of the sphere, but more contemporary research has led to improvements to the equation of motion to allow application at a wide range of Reynolds numbers and boundary conditions. The equation of motion for a solid sphere in an oscillating viscous fluid is given by:

$$m_p \frac{dv}{dt} = F_{drag} + F_{history} + F_{addedmass} + F_{buoyancy} \quad (10)$$

Where the force terms are defined as follows:

$$F_{drag} = 6\pi\mu_f a\left(u - v\right)\varphi(\mathrm{Re}) \quad 11)$$

$$F_{history} = 6\pi\mu_f a\left[\frac{u-v}{\delta} + \frac{\delta\rho_f a^2}{2\mu_f}\left(\frac{du}{dt} - \frac{dv}{dt}\right)\right] \quad (12)$$

$$F_{addedmass} = \frac{2}{3}\pi\rho_f a^3\left(\frac{du}{dt} - \frac{dv}{dt}\right) \quad (13)$$

$$F_{buoyancy} = \frac{4}{3}\pi\rho_f a^3 \frac{du}{dt} \quad (14)$$

Here, a, ρ_p, ρ_f, μ_f, v, and u are the particle radius, particle density, fluid density, fluid viscosity, particle velocity, and fluid velocity, respectively. On the right hand side of equation (10), the first force term is the Stokes drag law. The Stokes empirical correction factor, $\varphi(Re)$, accounts for deviation from the low Reynolds number formulation. The second term on the right hand side of equation (10) is the Basset or history force which accounts for the effects of the past motion of the particle travelling through its own wake. The inverse Stokes number, δ, represents a ratio of the oscillation time scale to the viscous diffusion time scale. This parameter is extremely important for predicting motion of an oscillating particle, and will be discussed later in detail. The third force term in (10) is the added mass force and the fourth is the buoyancy-like force that arises due to the accelerating reference frame. An excellent modern derivation and discussion of the particle motion equation can be found in Brennen [2,4], along with solutions for alternate boundary conditions.

Assumptions are made in order to apply the theory to actual multiphase flow in a Coriolis meter. Clearly, potential flow theory cannot accurately predict viscous effects, flow tubes do not constitute infinite fluid media, and bubbles or particles can potentially interact with each other during oscillation. However, for the range of conditions found in a Coriolis meter, the various forms of the force terms can be applied with high confidence in their accuracy, at least to the level needed here for formulation of best practices. For a detailed discussion of the assumptions implicit in this analytic model, please refer to Weinstein [5]. The results for decoupling ratio and phase delay between particle and fluid are also verified experimentally using a shaker table and high speed video camera in Weinstein [6].

The time plot in Figure 11 shows that, for the case of a bubble in a mildly viscous fluid such as water or light oil, the bubble oscillates slightly out of phase with the fluid, and at an amplitude approximately two times greater. With the addition of viscous effects to the model, the decoupling ratio decreases from the theoretical maximum of 3:1 down to 2:1, thus improving measurement performance.

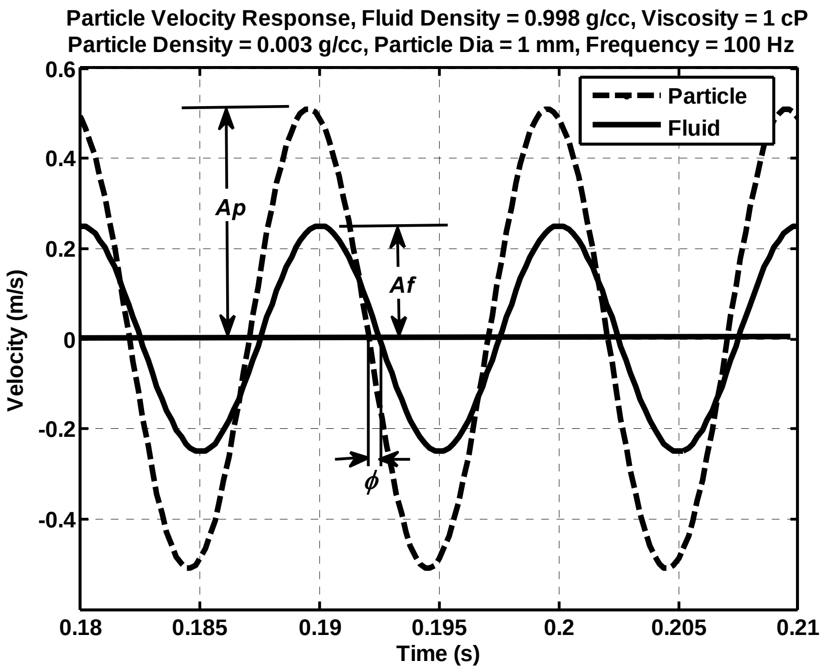


Fig. 11 - Time plot of bubble displacement for viscous model

3.3 Dimensional analysis of the particle motion equation

Nondimensionalizing the equation of motion (10) leads to a deeper understanding of the competing physical effects involved in decoupling. The details of the nondimensionalization are included in Weinstein [5]. Here we include the resulting nondimensionalized equation of motion.

$$\frac{dv}{dt} = \frac{9}{4} R\delta^2 (u - v)\varphi(\mathrm{Re}) + \frac{9}{4} R\delta (u - v) + \ldots$$
$$\frac{9}{2} R\delta \left(\frac{du}{dt} - \frac{dv}{dt} \right) + R\left(\frac{3}{2}\frac{du}{dt} - \frac{1}{2}\frac{dv}{dt} \right) \qquad (15)$$

The following nondimensional parameters are found to fully replace the original seven dimensional variables.

$$R = \text{Density Ratio} = \frac{\rho_f}{\rho_p} \qquad \delta = \text{Inverse Stokes \#} = \sqrt{\frac{2\upsilon_f}{\omega a^2}}$$
$$\text{Decoupling Ratio} = \frac{A_p}{A_f} \qquad \mathrm{Re} = \text{Reynolds \#} = \frac{2aA_f\omega}{\upsilon_f} \qquad (16)$$

The density ratio indicates the importance of the inertial difference between the phases, which is the driving force for decoupled motion. If this parameter is exactly equal to 1.0, as for a pure fluid, there is no decoupled motion. The decoupling ratio, A_p/A_f, is the desired output from the model and describes the extent to which the bubbles or particles move with respect to the surrounding liquid. Recall that if decoupling ratio is near 1.0, then measurements will be accurate, whereas decoupling ratios away from 1.0 result in errors. This term arises in equation (15) when the specific expressions for velocity and acceleration are substituted in, for example, $u = \omega A_f \cos(\omega t)$. The inverse Stokes number is an important parameter which describes the ratio of the oscillation time scale to the viscous diffusion time scale. It represents the time it takes for a disturbance created at the surface of an oscillating particle to diffuse into the surrounding flow field.

It is useful to evaluate the nondimensionalized equation (15) in the limit of low and high inverse Stokes number. Low inverse Stokes numbers occur when kinematic viscosity is low or when particle size or frequency are high. In the limit of low inverse Stokes numbers, we recover the inviscid equation of motion, equation (5), dependent only on the density ratio. Conversely, in the limit of high inverse Stokes numbers, we recover the expected result that the particle moves exactly with the fluid on each oscillation, $u = v$.

The final nondimensional parameter is the standard Reynolds number defined in terms of the fluid velocity. This parameter appears in the correction to the Stokes drag law and renders the equation of motion nonlinear. The standard Reynolds number has only a limited impact on the decoupling ratio as compared to the inverse Stokes number or density ratio.

Figure 12 gives results for decoupling ratio for density ratios between 0.1 and 1000, covering the entire range of possible conditions in oil and gas applications, including solid particles and gas bubbles. The (A), (B), and (C) markers refer to specific application examples discussed in Sections 4.1, 4.2, and 4.3, respectively. Increasing the inverse Stokes number moves the decoupling ratio closer to 1.0, indicating a reduction in relative motion. As the density ratio increases past about 50, the decoupling ratio is dependent primarily on the inverse Stokes number. This is especially important because all gas/liquid mixtures have high density ratios, usually above 100. Thus, for the most common multiphase flow conditions in a Coriolis meter, the extent of measurement error depends primarily on the inverse Stokes number. If this parameter is very small, we approach the inviscid case of 3:1 decoupling ratio, while if the parameter is large, relative motion is restricted and the decoupling ratio approaches 1:1.

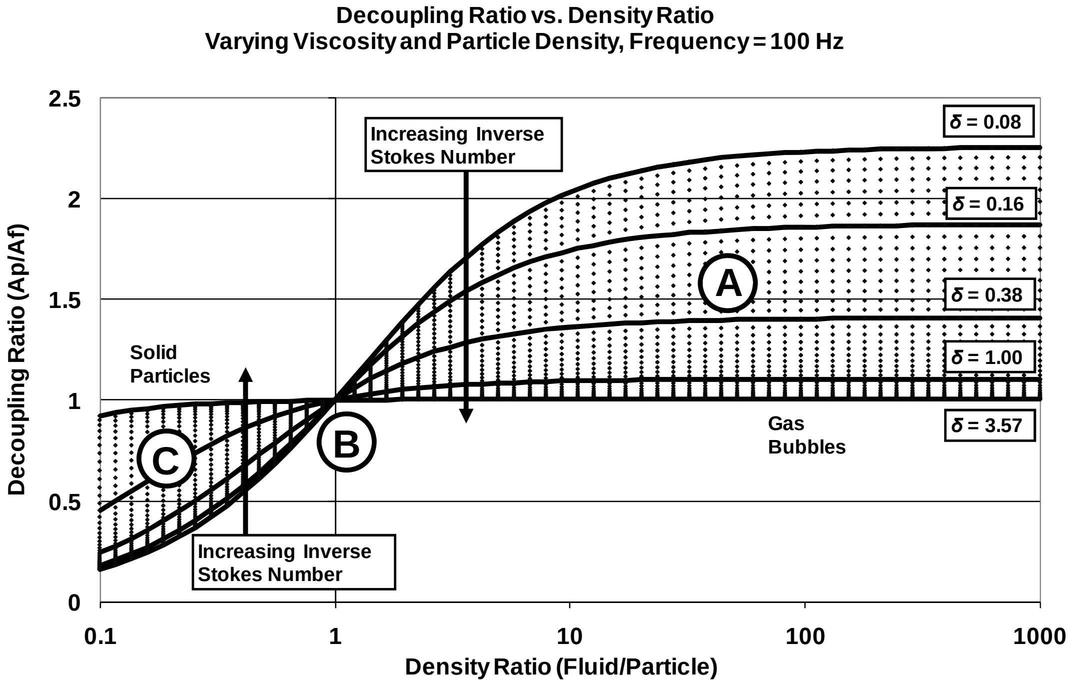


Fig. 12 - Decoupling ratio vs. density ratio, changing δ

The inverse Stokes number, δ, shows that it is the balance between fluid kinematic viscosity, particle size, and frequency that is important, not any one of these variables alone. Because bubble size is the only variable that is squared in δ, small changes in bubble size overwhelm changes in viscosity or frequency. Tests in which we steadily decrease bubble size by increasing turbulent mixing upstream of the meter using a ball valve consistently show improved accuracy in all measurements, regardless of the type of Coriolis meter used.

In the next section, we examine three common oil and gas applications for Coriolis meters – live oil with entrained gas, net oil and watercut, and cementing or drilling. In each case, we apply the theory of decoupling discussed above to establish best practices for successful operation of meters.

4 EXAMPLES OF DECOUPLING IN OIL AND GAS OPERATIONS

Coriolis meters are used extensively in oil and gas applications in which multiphase flow is present. In this section, we use the decoupling theory developed in the previous section to understand sources of error in three completely different O&G applications. In each case, we can significantly improve measurement performance by following a few simple best practices.

4.1 Live Oil Applications with Gas Breakout (A)

One of the most widespread metering challenges of live oil applications is the presence of natural gas. Depending on the pressure and temperature, the natural gas may be in liquid or gas phase, and can be dissolved in the oil or broken out into bubbles or slugs of various sizes. When gas breakout occurs in a Coriolis meter, errors due to decoupling can occur. The magnitude of the error depends primarily on the inverse Stokes number, as discussed in Section 3. The density of oil is typically between 0.8 and 1.0 g/cc, while the density of gas varies significantly with pressure between 0.001 and 0.1 g/cc. The resulting fluid to gas density ratio is between 10 and 1000. Recall that Figure 12 shows that the decoupling ratio is roughly constant over these density ratios (see marker A), but the inverse Stokes number can dramatically impact decoupling ratio, and thus meter performance. For small δ, the decoupling ratio can approach the theoretical maximum of 3:1, and for large δ, the decoupling ratio reduces to 1:1, resulting in no measurement error. The magnitude of δ is determined by the ratio of kinematic viscosity to the product of frequency and bubble size squared:

$$\delta = \text{Inverse Stokes \#} = \sqrt{\frac{2\upsilon_f}{\omega a^2}} \tag{17}$$

In order to use a Coriolis meter in live oil applications with entrained gas, it is critical to ensure that the inverse Stokes number is maximized. This can be accomplished by increasing the viscosity, decreasing tube vibration frequency, or decreasing bubble size. While the oil viscosity is usually not under the user's control, the other two parameters can be optimized by following best practices. Low frequency Coriolis meters are less prone to decoupling errors and should be used when gas entrainment is expected. This is also true for velocity of sound errors, which are minimized when tube frequency is low. Bubble size is squared in the equation for inverse Stokes number, and thus has the most pronounced effect on performance. Increasing pipeline pressure by adding a pump will decrease bubble size, and in some cases eliminate entrained gas entirely. Also, keeping pipeline velocities high and using mixing devices can effectively decrease bubble size and dramatically improve measurement performance. However, this can be a self-defeating practice, because additional gas can break out at high flow rates due to additional pressure drop across the meter. Fortunately, bubble size is typically very small with this type of gas breakout, especially when void fraction is low.

Extensive testing has shown that the best measurement performance is realized when flow rates are kept above a 5:1 turndown from "nominal," where nominal rate is defined as the flow rate at which 1 Bar pressure drop occurs with water. For example, if a water flow rate of 500 lb/min results in 1 Bar pressure drop for a particular meter, the meter should run above 100 lb/min in multiphase applications to ensure that bubbles flush out of the meter properly. For much higher viscosity fluids, for example fuel oil, this recommendation can be pushed to 10:1 turndown because viscous effects ensure that bubbles are dragged out of the flow tubes. In live oil applications, special care should be taken as a well matures, as flow meters are often sized for peak production. When a well nears the end of its life, a dump cycle can be used to keep pipeline velocities high.

Figure 13 shows the influence of fluid viscosity and bubble radius on the density error expected in a 100Hz Coriolis meter with a density ratio representative of that found in a live oil application. Note that density error is defined as the percentage deviation from true mixture density. The derivation of an analytical expression for density error due to decoupling in a Coriolis meter can be found in Weinstein [5]. Density errors are reported here because of the availability of a closed-form expression, however testing has shown that similar trends exist for mass flow.

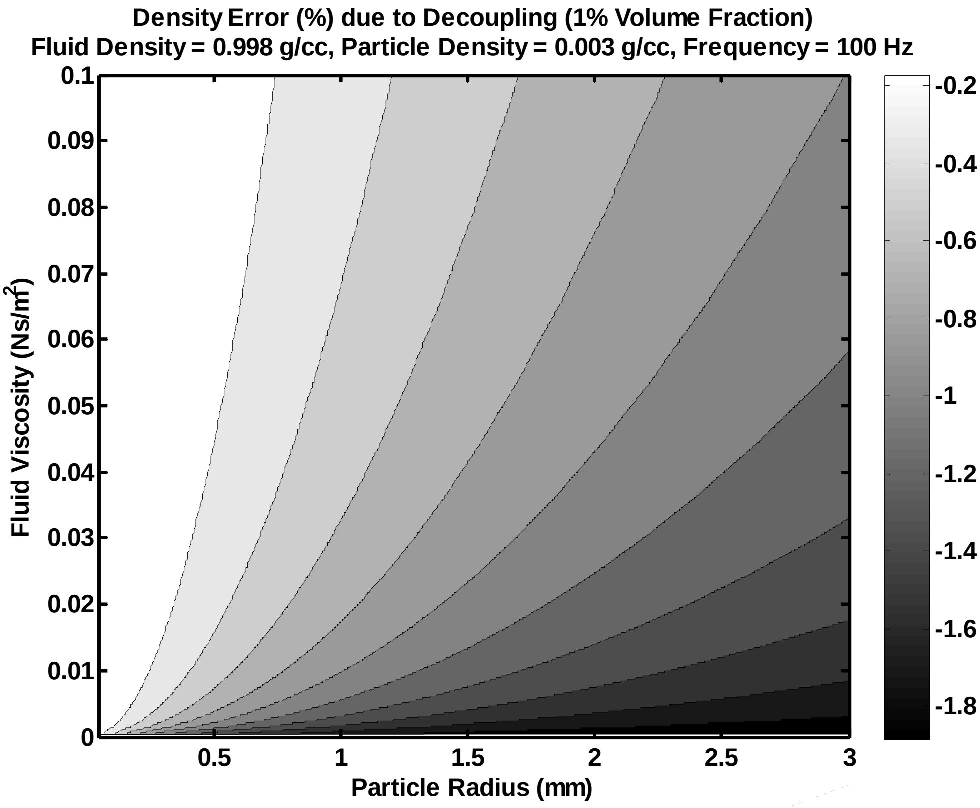


Fig. 13 – Density error as a function of fluid properties

As shown in the figure, errors in a live oil application can vary significantly depending on the value of the inverse Stokes number. For best performance, ensure that the fluid mixture is homogeneous with small bubble sizes, and use a low frequency Coriolis meter if possible.

4.2 Net Oil and Watercut Measurement (B)

Net oil measurement with a Coriolis meter allows a user to simultaneously determine watercut, oil flow rate, and water flow rate from a single device. The meter provides mixture density and mass flow measurements, which can be used along with known base densities for water and oil to determine the unknown water and oil volume fractions.

$$\begin{aligned} &\rho_m = \rho_w \phi_w + \rho_o \phi_o \\ &\phi_w + \phi_o = 1 \\ &\dot{q}_o = \dot{q}_m \phi_o \quad ; \quad \dot{q}_w = \dot{q}_m \phi_w \end{aligned} \tag{18}$$

Here, the (*m*), (*w*), and (*o*) subscripts represent “mixture”, “water”, and “oil” quantities, respectively. The density of the oil and water are known in advance, and the Coriolis meter provides mixture density, ρ_m, and mixture flow rate, q_m. The first two equations are solved simultaneously for the oil and water volume fractions, φ_o and φ_w, and the oil and water flow rates are then calculated using the known volume fractions. The flow rate can be either a volume or mass flow rate, as a Coriolis meter can measure both.

Error due to decoupling is usually negligible for net oil applications because the density ratio is so close to 1.0. Recall from Figure 12 that a density ratio near 1.0 results in a decoupling ratio that is also near 1.0 (see marker B). For a mixture of two fluids with the same density, the density ratio is exactly 1.0 and decoupling errors do not occur because there is no buoyant force to cause the relative motion between the two fluids. With a density of 1.0 g/cc for water and 0.85 g/cc for oil, the density ratio for a net oil application is 1.18. At a density ratio of 1.18, the error due to decoupling is negligible as long as the flow rate is high enough to keep the water and oil moving through the meter.

For net oil applications, it is recommended that the meter be operated at flow rates above 20:1 turndown from nominal, where nominal rate is defined as the flow rate at which 1 Bar pressure drop occurs with water. As with live oil applications, special care should be taken as the well matures, as flow rates drop well below peak production levels. At extremely low flow rates, it is possible to “hold up” oil or water inside the flow tubes, which results in an artificially high or low net oil measurement because the meter simply measures the density of the mixture currently inside the flow tubes. If some oil gets stuck on the inlet side of the meter, then the meter will register a lower mixture density than the density representative of the actual pipeline, and will over-report oil production. Another similar issue is pipeline “slip” velocity, discussed at the end of Section 3.1, which occurs when the oil phase moves faster than the water phase through the pipeline. For net oil applications, these issues can be completely avoided by proper meter sizing to ensure a well-mixed fluid. This topic was investigated experimentally by TUV NEL and presented at a prior North Sea Workshop [7].

So far, we have only considered net oil applications in which water and oil are the only components present in the pipeline. When gas bubbles are present, the Coriolis meter correctly measures the lowered mixture density, ρ_m. However, the reduction in density is misinterpreted by the net oil equations (18) as an increase in oil output. Because the density of the gas is so low, even a small amount of gas can represent a large amount of oil. For example, consider a mixture of water and oil with 50% volume fraction of each component. If the density of water and oil are 1.0 g/cc and 0.8 g/cc, respectively, then the Coriolis meter will measure 0.9 g/cc and the net oil equations will output 50% watercut. However, if 5% gas volume fraction is added to the mixture, then the Coriolis meter will again measure the correct mixture density, now roughly 0.85 g/cc, but the net oil equations will indicate 75% watercut even though the true watercut is 50%.

Coriolis meters offer extremely accurate measurements in net oil applications, so long as the meter is properly sized and entrained gas is avoided. When occasional gas is unavoidable, the Coriolis meter provides a robust detection capability, tube excitation power, as discussed in Section 5. This enables the user to confidently use the net oil outputs from a Coriolis meter when conditions are stable, and quickly identify and fix problems with separators or other equipment when process upsets occur.

4.3 Cementing and Drilling Mud Applications (C)

Many oil and gas applications involve particle-laden fluids, such as cement, drilling mud, or fracture sand. The decoupling models described in Section 3 are equally applicable for solid particles as for gas bubbles, and the mechanism for measurement error is the same - decoupling. A solid particle is typically denser than the fluid, so it moves to a lesser extent on each oscillation cycle than the surrounding fluid. This causes the center of gravity to move backwards with respect to the center of the tube (ie. the center of gravity of the fluid mixture inside the tube moves less far than the center of the tube). This also occurs in the case of a gas bubble, which moves further on each oscillation than the surrounding fluid, but because the surrounding fluid is heavier than the bubble, the shift in center of gravity is still backwards with respect to the direction of oscillation. For this reason, measurement errors due to decoupling are negative regardless of the density of the inclusion.

Consulting Figure 12 for density ratios of less than 1.0 (see marker C), we again find that decoupling ratio is further from 1.0 for density ratios further from 1.0. Also, decoupling ratio is further from 1.0 when inverse Stokes number is small. Therefore, the same recommendations from live oil and net oil applications still apply. Lower frequency Coriolis meters will outperform higher frequency meters because decoupling is reduced, and small sand or rock sizes will result in dramatically improved performance over large sizes. Experimental results from a fracture sand test verified the influence of both of these factors, frequency and sand size. The best density measurement was found using a low frequency Coriolis meter on the smallest sand size. On the other hand, performance was unacceptable using a high frequency Coriolis meter, with small or large sand sizes.

5 MULTIPHASE DETECTION USING TUBE EXCITATION POWER

In many oil and gas applications, entrained gas is an unexpected process upset that is avoided under normal operating conditions. For example, custody transfer of pipeline quality oil, or allocation measurement downstream of a separator. Coriolis meters provide an extremely useful diagnostic output, tube excitation power, which can be used as an indicator of entrained gas or solid particles in the process fluid. For example, tube excitation power can be monitored to keep a separator's level at the proper height for optimal separation.

The Coriolis flow meter relies on limited power to maintain tube oscillation. The flow tubes are driven on resonance in the first bend mode, so very little energy is needed to keep the tubes oscillating. In fact, the structural damping in a Coriolis meter is minimized during the design process so that excitation power is low enough to meet safety regulation limits. The low power requirement is usually not an issue because single phase liquids and gases do not significantly increase damping of the flow tubes. Increasing viscosity causes only slight increases in energy requirements.

On each oscillation, the tube does a certain amount of work on the fluid. For single phase flows, very little work is required to keep tubes oscillating. However, when multiple phases are present, much of the input energy is used to create the relative motion between the particles and the fluid we call decoupling. As shown in Figure 14, the drive power required increases dramatically with gas entrainment until the maximum allowable values for voltage and current are reached. This occurs at surprisingly low void fractions, generally around one percent as determined from testing of Coriolis meters with entrained gas. If additional power dissipation occurs, for example by the addition of more gas, then the amplitude of tube vibration begins to decrease because drive power is limited.

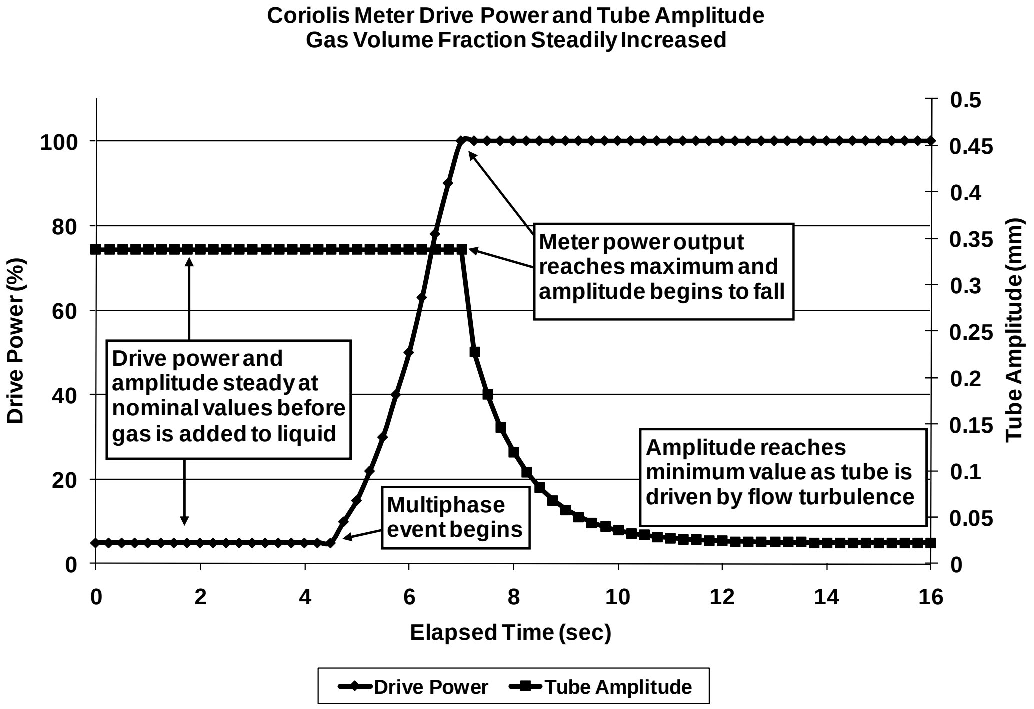


Fig. 14 – Drive power and tube amplitude response during multiphase event

With increasing gas entrainment, the tube amplitude eventually reaches a minimum value for which the turbulence in the flow actually keeps the tubes vibrating. If signal processing algorithms are carefully designed, it is possible to continue measuring accurately at very low amplitudes, although the signal to noise ratio is low and measurements can be noisy.

Increased drive power is a very useful indicator of entrained gas or solid particles, however it cannot be used to predict how much measurement error is occurring due to multiphase effects. The reason for this is that drive power is far more dependent on the phase difference between the particle and the fluid, rather than the amplitude ratio. Still, for most applications, a reliable detection of entrained gas is the most critical requirement.

6 BEST PRACTICES AND CONCLUSIONS

Understanding of the sources of error in a Coriolis meter in multiphase flow is improving, although complete compensation for decoupling errors is unlikely due to the complexity of the physics and the fact that bubble size is generally unknown. These challenges also make it difficult to predict exact measurement error magnitude for specific applications. However, extensive testing has shown that Coriolis meters perform well in multiphase applications in which certain conditions are met, and frequently outperform other flow measurement technologies, such as volumetric meters, which over-report liquid-only quantities due to the increased flow volume associated with bubbly mixtures. In addition, Coriolis meters provide a dependable diagnostic for detection of entrained gas or solid particles in a fluid, which can be used to quickly fix process problems such as poorly tuned separators or leaking pump seals.

Trends for decoupling and other errors discussed in this paper allow for better recommendations to users regarding how to install and operate Coriolis meters when multiple phases are present. Dimensional analysis of the particle motion equation yields several important parameters, including the density ratio and the inverse Stokes number. Analysis of these parameters explains Coriolis meter performance in diverse multiphase applications, such as live oil, watercut measurement, and fracture sand operations.

Assuming that fluid properties are pre-defined for a given application, the most important operational practices for achieving good performance with a Coriolis meter are (1) choosing a low frequency Coriolis meter for multiphase applications, (2) minimizing bubble or particle size through mixing and increased pressure, and (3) keeping flow rates high enough to prevent holdup and flow tube asymmetry.

Future Coriolis meter design improvements can be made by reducing drive frequency, as a very low frequency meter would be essentially immune to multiphase effects, including decoupling and velocity of sound. While complete compensation of multiphase errors in a Coriolis meter may never be possible, following a set of simple guidelines is effective for reducing measurement errors to acceptable levels. With these best practices, Coriolis meters will remain a leading solution for inline measurement of process fluids prone to small amounts of entrained gas or solid particles.

3 NOTATION

a	Particle radius
A_f	Amplitude of fluid oscillation
A_p	Amplitude of particle oscillation
c	Velocity of sound
d	Tube diameter, VOS model
$f_{(sub)}$	Subscript indicates “fluid”
F_c	Coriolis force
$m_{(sub)}$	Subscript indicates “mixture”
m_p	Mass of particle
$p_{(sub)}$	Subscript indicates “particle”
R	Fluid to particle density ratio
Re	Reynolds number
u	Velocity of fluid
v	Velocity of particle
δ	Inverse Stokes number
μ_f	Dynamic viscosity of fluid
ν_f	Kinematic viscosity of fluid
ρ_f	Density of fluid
ρ_m	Density of mixture
ρ_p	Density of particle
τ	Volume of particle
φ	Phase angle, particle vs. fluid
φ	Component volume fraction
$\varphi(Re)$	Correction to Stokes drag law
ω	Angular frequency fluid oscillation

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