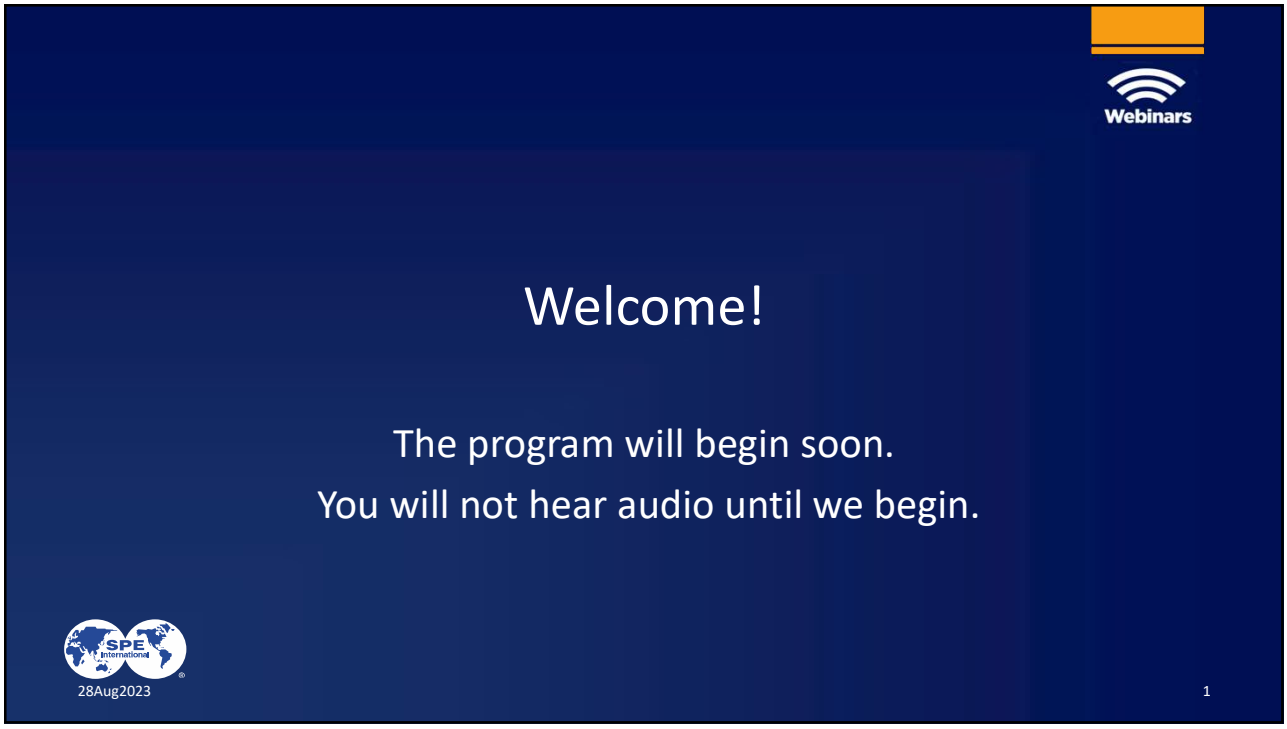
Webinars
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Webinars

Improving Accuracy of Coriolis Meters in Bubbly Liquids

Daniel L Gysling, PhD
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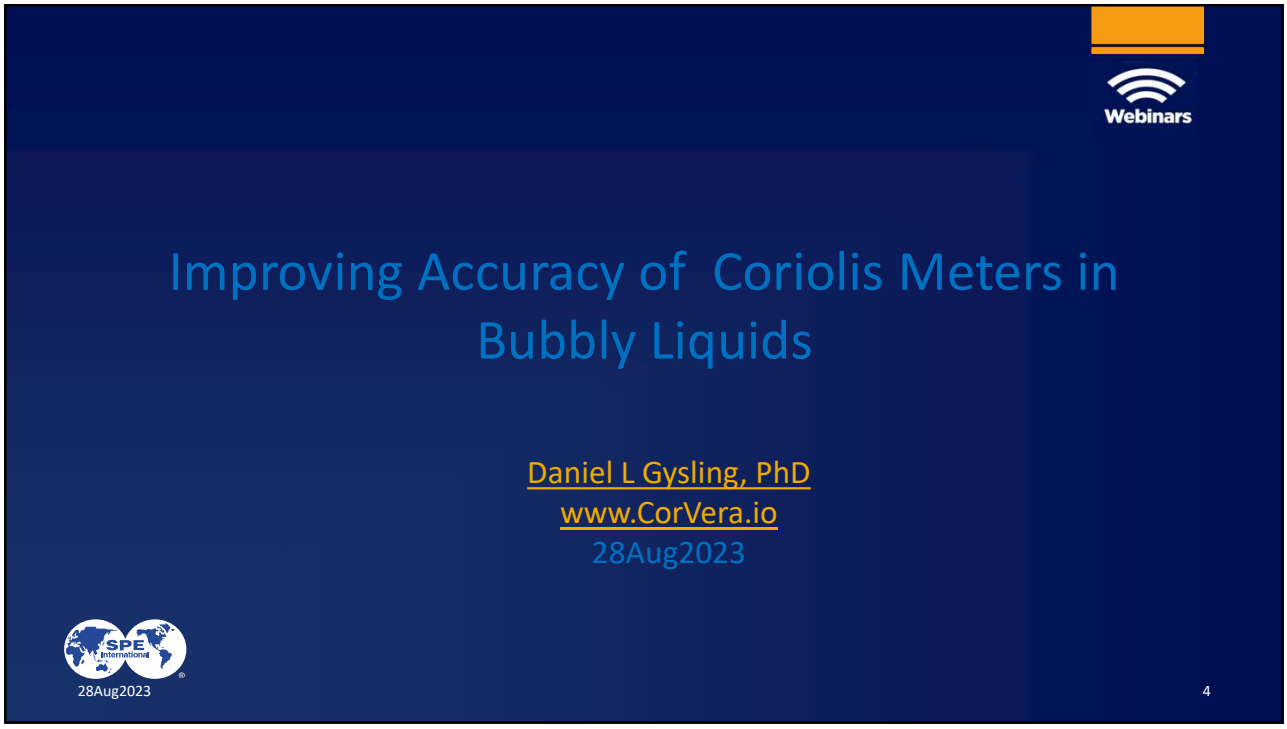
Webinars
Improving Accuracy of Coriolis Meters in Bubbly Liquids
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"Improving Accuracy of Coriolis Meters in Bubbly Liquids"

Agenda

- Overview
- Benefits of Coriolis meters in Oil and Gas
- Principle of Operation
- Coriolis meters operating in bubbly liquids
- Source of errors in Coriolis meters on bubbly liquids
- Speed of Sound (SOS) augmented Coriolis meters
- Correcting errors in mass flow, density, and volumetric flow
- Role of Speed of Sound Augmented Coriolis meters in Separator Based measurement
- Emerging Technologies
- Summary

Overview

- Coriolis meters have become the meter of choice in many Oil and Gas for their high accuracy on single-phase flows, reliability, safety advantages and low operational cost
- Historically, entrained gas is well-known to cause ***operability*** and ***accuracy*** issues for Coriolis meters
- Recent ***improvements in operability*** on bubbly liquids has resulted in Coriolis meters being applied to many applications with continuous or intermittent entrained gas, resulting in ***entrained gas*** often ***causing significant***, and often unrecognized, ***accuracy issues*** in mass flow, density, and volumetric flow
- Accuracy issues in Coriolis meters operating on bubbly liquids currently limits:
  - Utility of large installed base of Coriolis meters
  - Adoption rate of Coriolis meters in many high-value applications
- ***Speed of Sound*** augmented Coriolis technology provides a means to ***quantify gas void fraction***
- Improving the accuracy of Coriolis mass flow, density, and volumetric flow of bubbly liquids is an area of active research

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Agenda

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Benefits Coriolis Meters in Oil and Gas

- Coriolis meters have many benefits over other types if meters for many upstream oil and gas applications
- Improved accuracy over conventional turbine metering for single phase liquids
- Safety benefits associated with reduced maintenance and high turn-down ratios
- No requirement for upstream flow conditioning or meter factors
- No moving parts and tolerance of solids
- Direct mass measurement, eliminating errors associated with shrinkage factors and volumetric conversion to standard conditions
- Direct density and temperature of process fluid enabling density-based water-cut and/or composition
- Real-time diagnostics for health and process monitoring

Coriolis Meter Applications in Oil and Gas

Webinars

Wellhead

Test Separator

Production Separator

LACT unit

Drilling

Export Pipeline

Coriolis meters are offered with a variety of tube geometries and sizes ranging from fractions of inches to 16”

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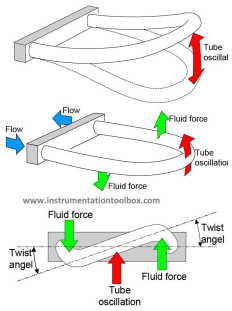
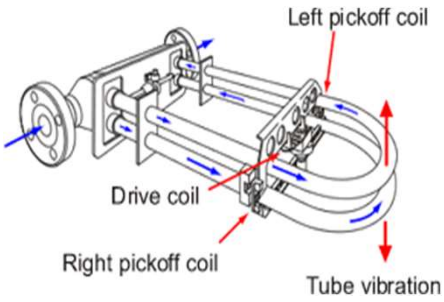
Principle of Operation

Coriolis measurement principle



Key Coriolis Components



- ***Coriolis meters measure the effect of the process fluid on the vibrational characteristics of fluid-conveying flow tubes***
- ***Flow tubes are driving with a drive coil, and the vibration of each leg of the flow tubes is measured with a pick-off coil***
- ***Flow tube twist determines mass flow and flow tube natural frequency determines density***

Theory of Operation Video

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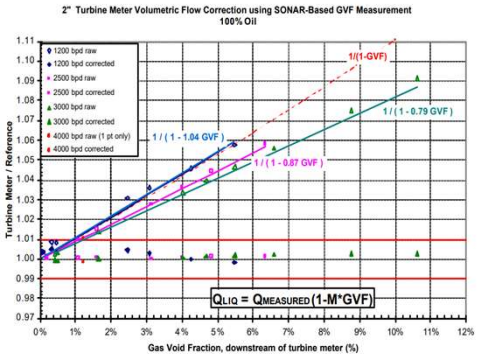
Impact of Entrained Gas on Flow Meters

- Entrained gas presents measurement challenges to all types of volumetric flow meters
- Separator outlets are typically equipped with single phase metering devices
  - majority of separators use turbine meters on liquid outlets
- When present, gas void fraction is typically unknown and impacts accuracy
- Turbine meters do not distinguish the volume of the liquid from the volume of the entrained gas
- Under ideal, well-mixed, bubbly flow conditions, turbine meters operating with unknown gas void fraction will typically over-report the liquid volume flow rate by the gas void fraction

$$Q_{meas} = Q_{liq}(1 + GVF)$$



SPE-102962-PP

Accurate Volumetric Flow Rate and Density Based Water-Cut Measurement in Bubbly Liquid Hydrocarbon Flow

Richard Volz, BP
Daniel Gysling, SPE, and Douglas Loose, SPE, CiDRA Corp.

Impact of Entrained Gas on Coriolis Meters

Under ***ideal*** bubbly flow conditions, bubbles are fully-coupled to the liquid and mixture is effectively incompressible

- Coriolis meters accurately measure the mixture mass flow and the mixture density of bubbly liquids

$$\dot{m}_{meas} = \dot{m}_{liq} \quad \text{and} \quad \rho_{meas} = \rho_{liq}(1 - \text{GVF})$$

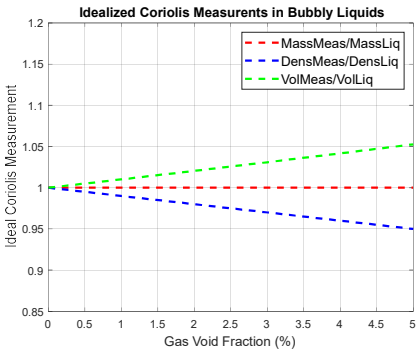
- Coriolis meters calculate volumetric flow as the ratio of the measured mass flow to the measured density

$$Q_{meas} = \frac{\dot{m}_{meas}}{\rho_{meas}} = Q_{liq}(1 + GVF)$$

- the over-report of liquid volumetric flow rate reported by the Coriolis meter matches that reported by turbine flow meters
- Since GVF is often unknown and may be significant, Coriolis errors in volumetric flow and density can still be significant under ideal bubbly flow conditions

Under ***non-ideal*** bubbly flow conditions, bubbles become decoupled from liquid and/or mixture is effectively compressible

- Interaction of the bubbly fluids and structure is more complex than single phase liquids
- Coriolis meters can typically over-report and/or under-report mass flow, density, and volumetric flow in the range of +/- several times the gas void fraction
- Errors in Coriolis meters are often unrecognized and unquantified

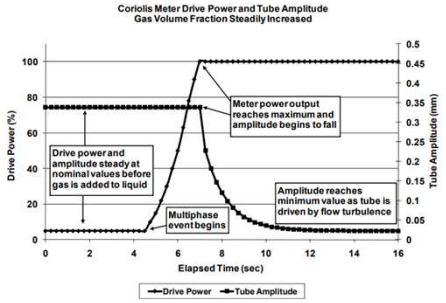


Why Bubbly Liquids in Coriolis meter are more Complex

- Coriolis Meters are “aeroelastic” flow meters and determine the ***mass flow and density*** of a process fluid by measuring and ***interpreting the influence of the process fluid*** on the ***vibrational characteristics*** of fluid-conveying vibrating ***flow tubes***
- Under ***single-phase conditions***, the process liquids are essentially homogeneous and incompressible and the center of mass of the ***liquid remains closely-aligned with*** geometric center of the vibrating ***flow tube***
- Under these conditions, the ***measured vibrational characteristics*** can be ***precisely calibrated*** in terms of the ***mass flow and density*** of the process fluid
  - Twist determines mass flow rate / Frequency of vibration determines density
- Under ***multiphase conditions***, the fluid is no longer homogeneous and is significantly more compressible than single phase fluids resulting in the ***center of mass of a bubbly liquid departing*** from the ***geometrical center of the vibrating flow tube***
- This ***departure*** modifies the interaction of the process fluid and the vibrating flow tube and ***results in errors*** in the reported mass flow, density and volumetric flow when single-phase calibrations are applied to Coriolis meters operating bubbly liquids
- Coriolis mass flow, density, and volumetric ***errors*** on bubbly liquids can ***scale with up to +/- several times the gas void fraction***

Coriolis meters Diagnostics and Entrained Gas

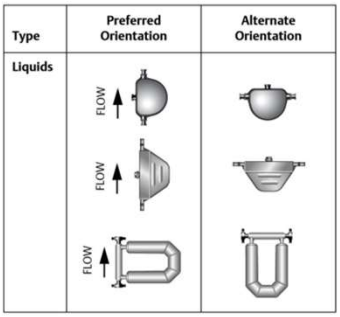
- Coriolis meters typically provide diagnostic information regarding the ***excitation energy*** (EE)and tube vibration amplitude (VA) which provide ***qualitative indications of entrained gas levels***
- Modern Coriolis meters can typically maintain operability and report mass flow, density, and volumetric flow on bubbly liquids often in excess of 20% gas void fraction
  - In most applications, amount of entrained gas is unquantified
- Excitation Energy (EE) metrics provides a measure of the amount of energy required to maintain the vibration of the flow tubes
- Typically, EE increases with gas void fraction until it saturates at the design limit
- Once saturated, the amplitude of vibration (VA) of the flow tubes begins to decrease with increasing gas void fraction
- Once the vibration amplitude falls below value at which the Coriolis meter can no longer report a "statistically meaningful" mass flow measurement, the Coriolis meter is said to have "stalled"



Weinstein, J., Multiphase Flow in Coriolis Mass Flow Meters – Error Sources and Best Practices, 28th International North Sea Flow Measurement Workshop 26th – 29th October 2010

Best Practices to Mitigate Impact of Bubbly Liquids

- Coriolis manufacturers offer “Best Practices” advice to mitigate errors due to entrained gas
- “Best Practices” advice is intended to create conditions within the Coriolis meter to minimize errors due to entrained gas which include
  - Minimizing or eliminating entrained gas from the process
  - Using specific meter orientations,
  - Maintaining high pressures and high flow velocities
  - Utilizing relatively low-frequency, bent-tube Coriolis meters
- Best Practices can be effective in reducing errors, yet can often be cost-prohibitive, or impractical, to implement



Best Practices

MICRO MOTION CORIOLIS OIL & GAS METERING RECOMMENDED PRACTICES FOR UPSTREAM ALLOCATION

Entrained Gas Error Mitigation Software

- Many manufacturers have developed software algorithms designed to minimize the impact of entrained gas
- Software error mitigation algorithms typically monitor Coriolis diagnostics, calculate and report “remediated” values
- Remediated values effectively substitute historical values for actual measured values when diagnostics indicative of entrained gases exceed threshold values
  - Remediated values often improve the accuracy of the intended measurement, however can also often mask true meter response
  - Error mitigation algorithms are typically based on specific scenarios that may, or may not, match any given application
- Software algorithms can also provide gas void fraction (GVF) estimates based on measured density and “historical” liquid density
  - Accuracy of GVF estimate is dependent on specifics of each application
- There are, however, currently limited options to **accurately *quantify gas void fraction*** and ***accurately correct for errors*** in ***mass flow, density, and volumetric*** flow due to bubbly liquids

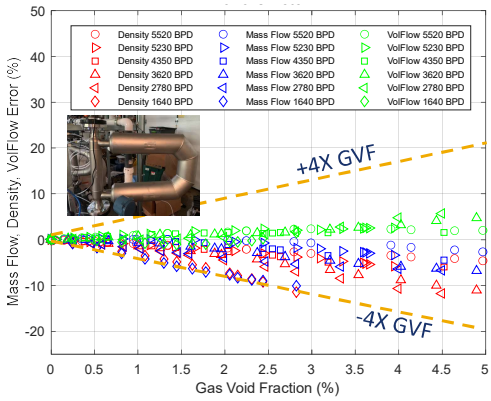
Quantifying Errors in Coriolis Meters Operating on Bubbly Liquids

- Errors in Coriolis meters operating on bubbly liquids is a well-known issue
- Vast majority of Coriolis meters utilize single phase calibrations that become increasing inaccurate on bubbly liquids with increasing gas void fraction
- As operability on bubbly liquids has improved, inaccuracies due to entrained gas are often now the limiting factor in many applications
- Operators typically have limited information to quantify errors in Coriolis meters due to bubbly flows
  - Limited data is available quantifying Coriolis errors in bubbly flows
  - Gas void fraction levels typically are often unknown, variable, and not readily quantifiable
  - Sources of errors due to entrained gas are often complex

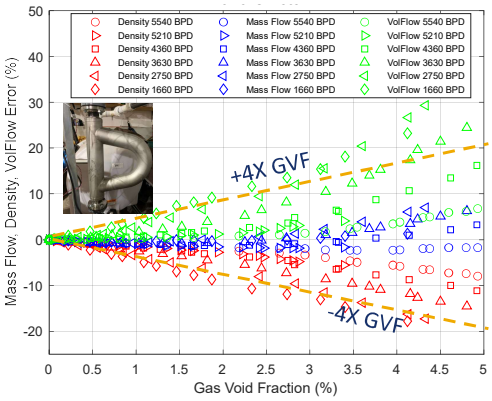
Coriolis Meter Errors on Bubbly Liquids

Webinars

Coriolis Meter A – 2 inch



Coriolis Meter B – 2 inch



- *In general, all Coriolis meters report errors in mass flow and density that typically scale with GVF*
- *Errors due to Bubbly Liquids are typically meter-design and fluid-property specific*

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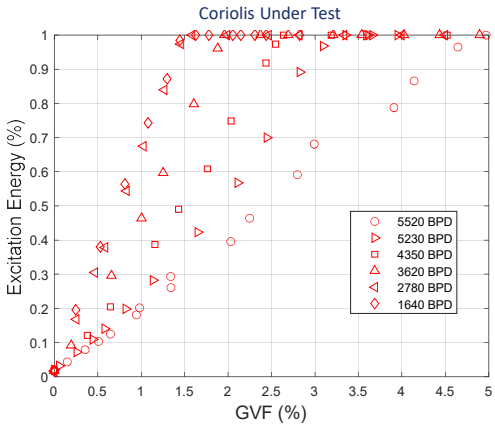
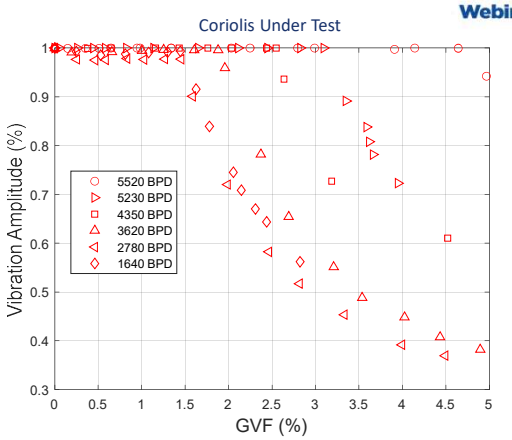
Coriolis Diagnostics





- *Excitation Energy metric increases with increasing gas void fraction until saturation*
- *Vibration Amplitude remains at 100% until EE saturates*
- *After EE saturates, VA decreases with increasing Gas Void Fraction*

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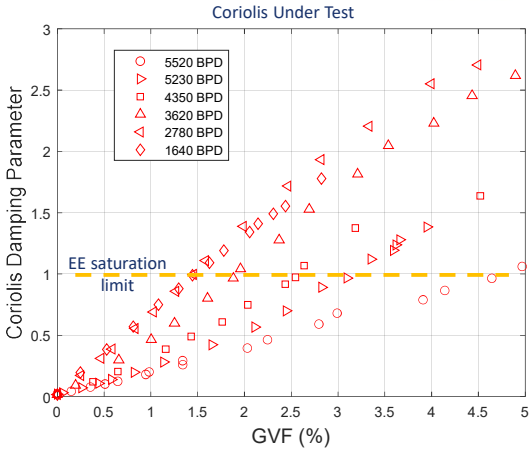
Coriolis Diagnostics – CMFD Parameter

- Coriolis Mass Flowmeter Damping (CMFD) parameter defined is the ratio of normalized Excitation Energy Metric to the normalized Vibration Amplitude

$$CMFD \equiv \frac{EE}{VA}$$

- CMFD is highly correlated to gas void fraction for a given fluid within a given Coriolis meter at given operating conditions
- Applicable for operation well-beyond EE saturation
- Quantitative relationship changes with parameters such as bubbly size, pressure, etc

- $CMFD$ is a useful metric to assess relative prevalence of entrained gas



Summary of Impact of Entrained Gas on Coriolis meter

- ***Accuracy*** of Coriolis mass flow, density, and volumetric flow ***degrades with onset of entrained gas***
  - Errors typically scale with the gas void fraction and are typically within +/- several times the gas void fraction
  - Gas Void Fraction is typically unknown
- Coriolis errors depend on Coriolis Design parameters and operating parameters
  - Coriolis meters can over-read or under-read due to entrained gases
- Coriolis diagnostics provide qualitative information on bubbly flow
  - CMFD Parameter correlates well with gas void fraction
  - There is no effective "Excitation Energy threshold" below which gas void fraction does not impact accuracy
- Coriolis meters typically remain "operable" well-beyond excitation energy saturation
- Robust tolerance of entrained gases of modern Coriolis meters results in significant, yet often unrecognized, errors in ***mass flow, density and volumetric flow*** on bubbly liquids
- ***Speed of Sound augmented Coriolis*** technology provides an empirically-informed, first-principles approach to ***quantify gas void fraction*** and ***correct for errors*** in Coriolis meters applicable to a wide range bubbly liquid applications

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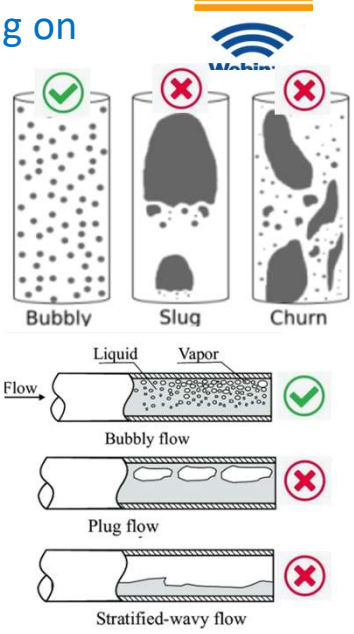
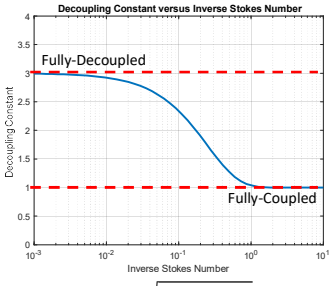
Sources of Errors in Coriolis meters Operating on Bubbly Liquids

- Multiphase mixtures are inherently more complex than single phase fluids
- Bubbly liquids are a subset of multiphase flows and are defined as liquids containing gas bubbles in which the bubbles are well-dispersed
  - Small bubbles, low GVF, high flow rates
  - Bubbly liquids are common in upstream oil and gas application
  - Gas carry-under from separators and gas break-out of dissolved gases often result in bubbly liquids
- Bubbly liquids are inhomogeneous and significantly more compressible than single-phase liquids
- For Coriolis meters operating on bubbly flows, errors in Coriolis meter are often primarily associated with two physical mechanisms: ***Decoupling*** and ***Compressibility***



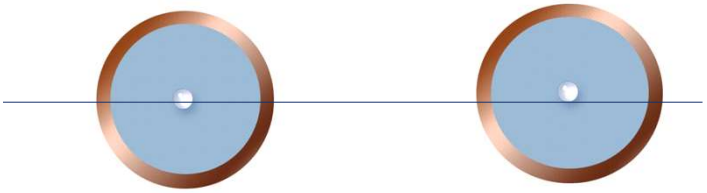
Errors due to *Decoupling*

- Decoupling of bubbly liquids occurs when the motion of the bubbles "decouple" from that of the liquid phase and flow tube itself
- ***Decoupling*** causes Coriolis meters to ***under-report***
- Decoupling ratio, K, is defined as the ratio between the motion of the bubbles and that of flow tube with 1< K < 3
- Decoupling ratio is determined primarily by the inverse Stokes number
- Data indicates that Oil and Gas applications can exhibit a full-range of decoupling behavior from fully-coupled to fully-decoupled



$$\delta \equiv \sqrt{\frac{2\nu_f}{2\pi f_{cor} R_{bubble}^2}}$$

Fully-Coupled bubble motion matches that of flow tube
k_d ,k_m ➔1



Fully-Decoupled bubble motion exceeds that of flow tube by 3x
k_d ,k_m ➔3

High Viscosity Limit

Low Viscosity Limit

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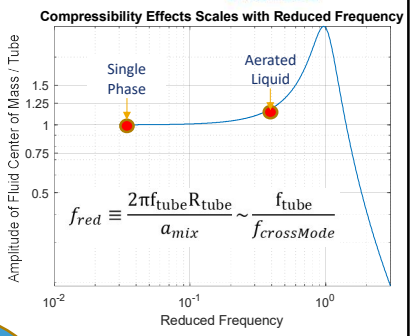
Errors due to *Compressibility*

- Compressibility effects occur when the Coriolis vibrational frequency approaches the frequency of the first acoustic cross mode of the tube
- Reduced frequency is defined as the ratio of vibrational frequency to the first acoustic cross mode
- Entrained gas significantly reduces process fluid sound speed, and increases the reduced frequency
- ***Compressibility*** causes Coriolis meters to ***over-report*** mass flow

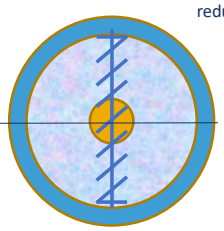


W/O air
Stiff Spring

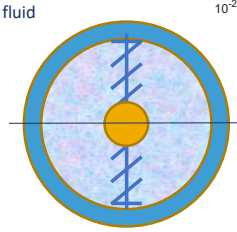
Aeration reduces "stiffness" of spring, reduces natural frequency of fluid resonator

W/ Air
Soft Spring

f_{red}^2 ➔0
incompressible motion of center of mass of fluid is locked to that of flow tube



Center of mass of process fluid is suspended in center of tube by "stiffness" of the fluid



f_{red}^2 >0
Compressibility causes the motion of center of mass of fluid to exceed that of flow tube

Single Phase Liquid

Aerated Liquid

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Theory of Errors due to Decoupling and Compressibility for Coriolis Meters operating on Bubbly Liquids

- Hemp, 2006, developed a reduced order model to quantify errors in Coriolis meters operating on aerated liquids, isolating errors in the mass and density reported by Coriolis meters operating on bubbly flows due to decoupling and compressibility:

$$\dot{m}_{meas} = \dot{m}_{liq}\left(1 - \underbrace{\frac{(k_m-1)}{1-\alpha}\alpha}_{\text{Decoupling}} + \underbrace{G_m f_{red}^2}_{\text{Compressibility}}\right) \quad \text{and} \quad \rho_{meas} = \rho_{liq}\left(1 - \underbrace{k_d\alpha}_{\text{Decoupling}} + \underbrace{G_d f_{red}^2}_{\text{Compressibility}}\right)$$

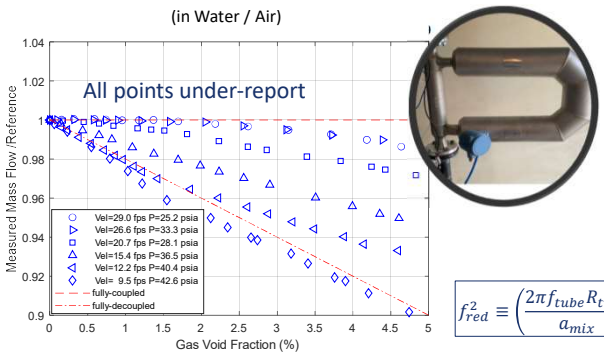
- Decoupling causes under-readings and errors scale with the decoupling ratio ($1 < k_{m,d} < 3$) and gas void fraction, α
- Compressibility causes over-readings and errors scale with the compressibility constant ($G_{m,d}$) and the square of the reduced frequency, f_{red}^2

$$f_{red} \equiv \frac{2\pi f_{tube} R_{tube}}{a_{mix}} \sim \frac{f_{tube}}{f_{crossMode}}$$

Role of Compressibility increases in Large Bore Coriolis Meters

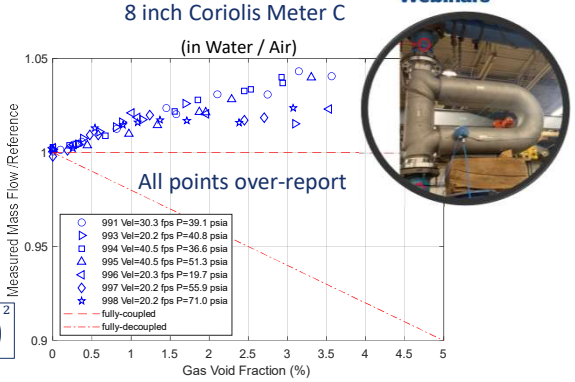
Webinars

2 inch Coriolis Meter A
(in Water / Air)



$$f_{red}^2 \equiv \left(\frac{2\pi f_{tube} R_{tube}}{a_{mix}}\right)^2$$

8 inch Coriolis Meter C
(in Water / Air)



- Each meter exhibits errors due to decoupling and compressibility
- Primary difference attributed to compressibility effects being ~16X larger in 8-inch compared to 2-inch meter
- For highly viscous fluids, K_m, K_d ➔ 1, theory indicates entrained gases may will result in systematic over-report of mass flow, which may, or may not, be indicated by a change in measured density

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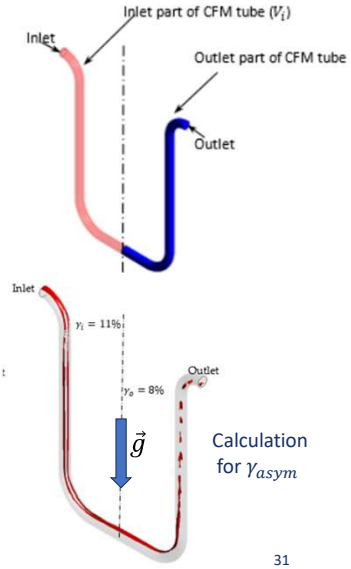
Errors due to Inlet-to-Outlet GVF Asymmetry

- Inlet-to-Outlet Gas Void Fraction asymmetry (γ_{asym}) is defined as the difference in GVF between the inward flowing flow tube and the outward flowing flow tube
- Shavrina (2022) showed calculated γ_{asym}correlated with observed mass flow errors
- Flow tube orientation with respect to gravity drives asymmetry, with downward flow orientations increasing gas void fraction, and upward flowing orientations decreasing gas void fraction
  - γ_{asym} increases with increasing gas void fraction and decreasing flow velocity
- Flag mounting flow tubes and maintaining high flow velocities can be effective at reducing Inlet-to-Outlet GVF Asymmetry



sensors MDPI

Article

The Investigation of Gas Distribution Asymmetry Effect on Coriolis Flowmeter Accuracy at Multiphase Metering

Evgeniia Shavrina [1,*], Yan Zeng [2], Boo Cheong Khoo [1] and Vinh-Tan Nguyen [3]

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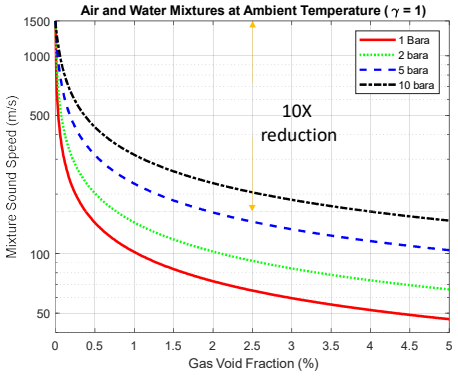
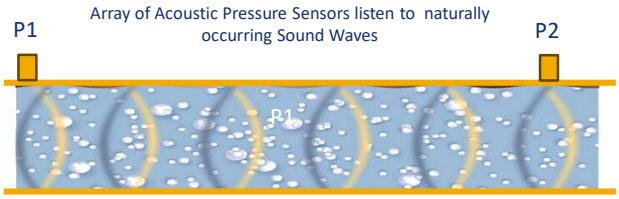
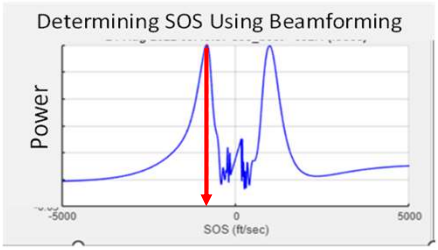
Role of Sound Speed in Coriolis Errors in Bubbly Liquids

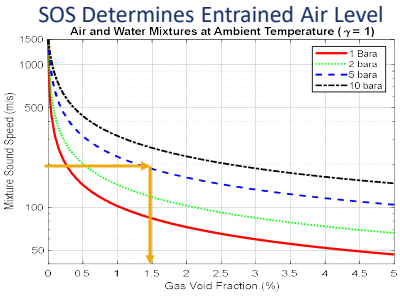
- ***Speed of Sound*** (SOS) of low-frequency, long-wavelength sound waves within a bubbly mixture is a thermophysical property that ***directly influences*** the interaction of the process fluid and vibrating flow tubes within ***Coriolis meters***
- SOS is essentially the ratio of the bulk modulus to the density of mixtures
- Since gases are typically orders of magnitude more compressibility than liquids, small amounts of entrained gas result in large changes to the mixture sound speed
- Process fluid sound speed, a_{mix}, determines gas void fraction, α, and reduced frequency, f_{red}:
  - $\alpha \approx \frac{\gamma P}{\rho_{liq}\, a_{mix}^2}$ and $f_{red}^2 \equiv \frac{(2\pi\ _{tube} R_{tube})^2}{a_{mix}^2}$
- ***Measuring sound speed*** of the process fluid enables quantification of gas void fraction and reduced frequency and ***provides basis for improving accuracy of Coriolis meters*** operating on bubbly liquids



SONAR Based Speed of Sound and Gas Void Fraction







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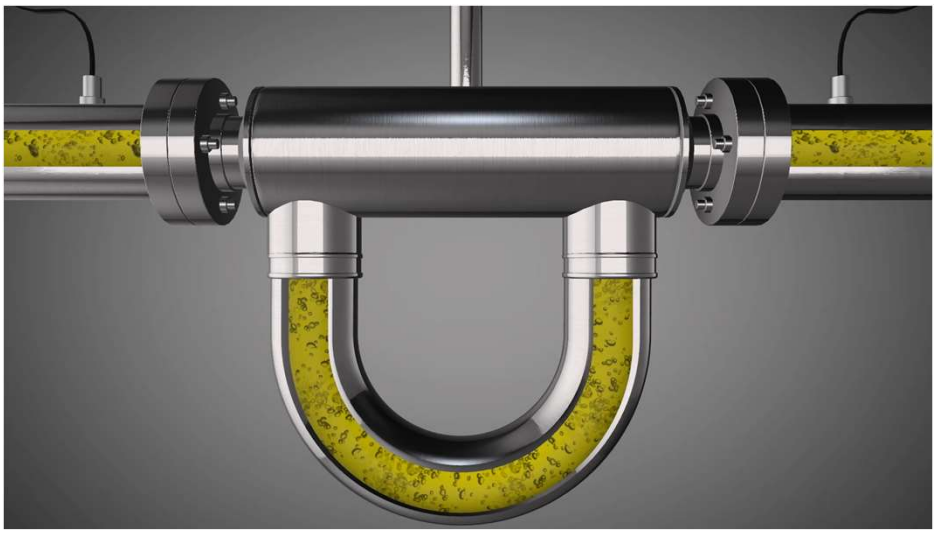

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History of Speed of Sound Augmented Coriolis Technology

Webinars

World's First Downhole Fiber Optic Multiphase Flowmeter Deployed on Deepwater GoM Platform

2000

Clamp-on Multiphase Flow Meter for Industrial Processes

2002

Quantifying Gas Carry-Under to improve Coriolis-based Net Oil

2005

Technology Demonstration of SOS Augmented Coriolis Meters

2020

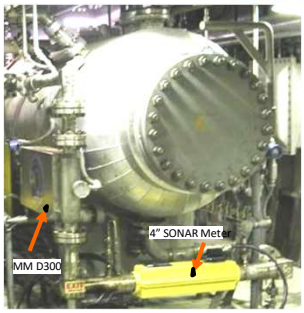
Integrated, Retrofittable, Speed of Sound Augmented Coriolis meter

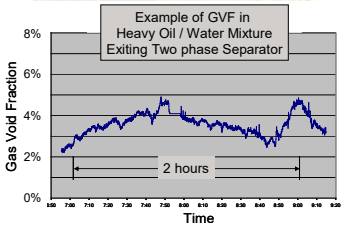
2023

SONAR Augmented Coriolis Meter Technology leverages >25 years of SONAR Flow measurement experience

Early SONAR Coriolis Net Oil on 2ϕ for Heavy Oil Separator

- Two-phase test separators designed to provide Coriolis-density-based Net Oil
  - Approach met accuracy requirement for light-oil for many years
  - Large errors encountered when applied heavy-oil
- SONAR-based GVF meters were installed on liquid outflow of separator
  - Confirmed 0%-8% GVF in liquid leg under normal conditions
  - Measured GVF used to interpret Coriolis measured density in terms liquid-phase density
- GVF-corrected density-based Watercut measurements confirmed by portable well-test separators to be accurate for Heavy Oil / Water mixtures with Gas Carry-under
- GVF measurements indicated entrained gas was present, to varying degrees, in all test separator liquid out-flow lines





*" The addition of GVF capability is the last piece of the puzzle to ensure accurate (density-based) well testing" **

– Eric Ward, Production Allocation Engineer

*Reference: Ward, E., " New Class of Meter Solves Old Problem Impacting Well Test Accuracy", SPE Paper 100893, to be presented at the 2006 SPE Western Regional Meeting, Anchorage, AK, 8-10 May 2006.

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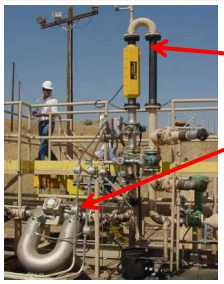
Early SONAR Coriolis based Net Oil on Compact 2ϕ Separator

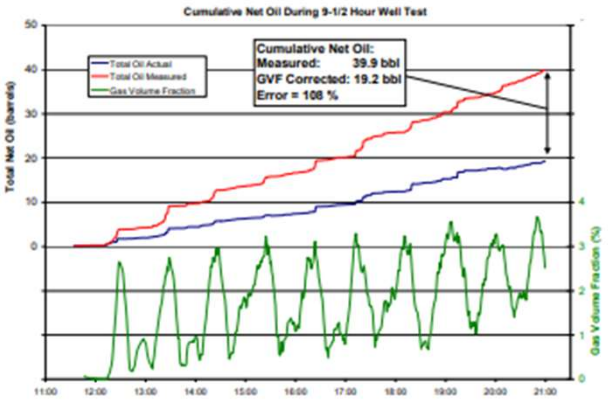
SONAR Meter

Coriolis Meter



SONAR Meter

Coriolis meter

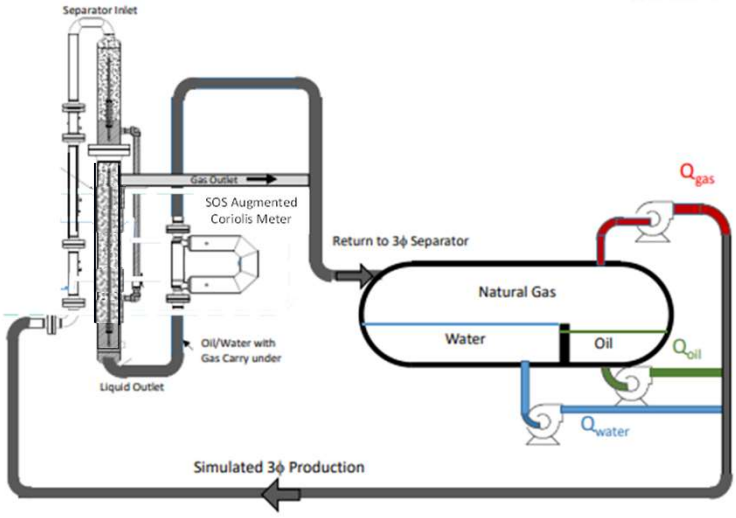


0-4% GVF results in 108% Over-report of Net-Oil during 9 ½ hour Well Test

Source: Gysling and Loose, Using SONAR-based Gas Volume Fraction Meter for Improved Net Oil Rate Measurement, 2005 Canadian School of Hydrocarbon Measurement

Watercut of Liquid Outlet of 2ϕ Separator with Gas Carry-Under

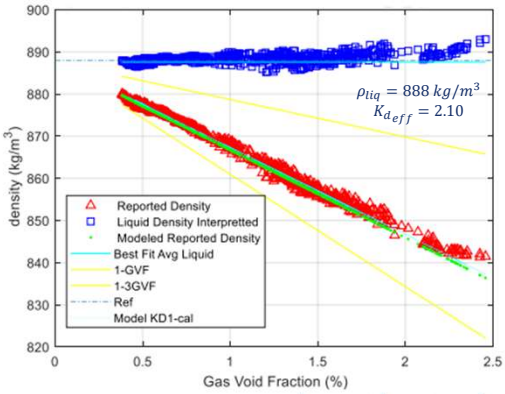
- SOS Augmented Coriolis meter on liquid outlet of a compact 2ϕ separator
- Flow loop holds rate and composition of high GVF oil/water/gas mixture
- Gas carry-under varied by varying liquid level in separator
- Coriolis density and Speed of Sound measurements used to determine density of liquid phase and watercut in presence of varying gas void fraction



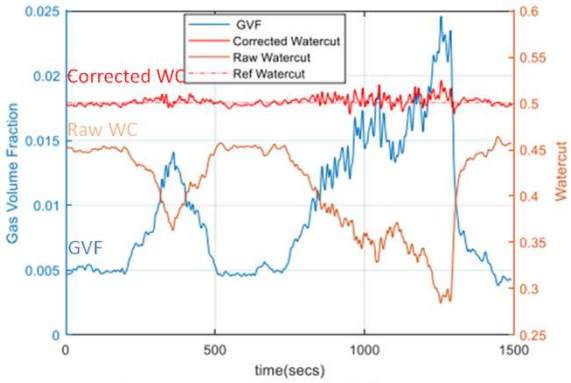
Accurate Density-Based Watercut w/ Gas Carry-Under

Webinars

Reported and Corrected Density vs Gas Void Fraction as Liquid Level in Separator is varied



Raw and Corrected Water and Gas Void Fraction



Measured Gas Void Fraction of 0.4 to 2.5%, Measured density ranges from 840 kg/m^3 to 880, Raw Watercut ranges from 30% to 45% Corrected watercut aligns with reference watercut (50%), independent of gas void fraction

Source: Gysling and Dragnea, 2020 NorthSea Flow Measurement Workshop Paper

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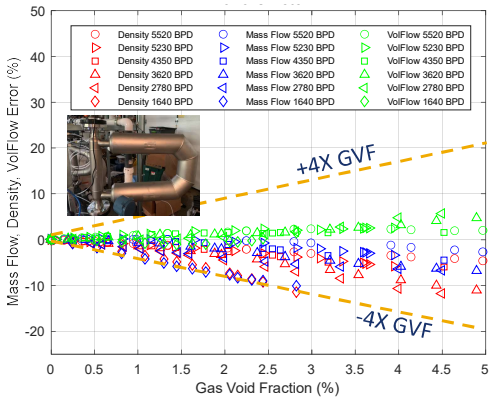
- Summary

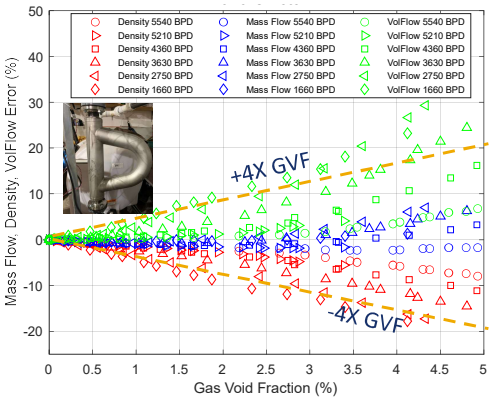
Coriolis Meter Errors on Bubbly Liquids

Webinars

Coriolis Meter A – 2 inch



Coriolis Meter B – 2 inch



- *In general, Coriolis meters report errors in mass flow and density that typically scale with GVF*
- *Errors due to Bubbly Liquids are typically meter-design, fluid-property, and operationally specific*

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A Method for Correlating Mass Flow Errors

- Liquid density, ρ_{liq}, is determined utilizing regression of time-varying measured density, ρ_{meas}, and gas void fraction, α
- Measured density and liquid density define a density error parameter,

$$\Psi \equiv 1 - \frac{\rho_{meas}}{\rho_{liq}}$$

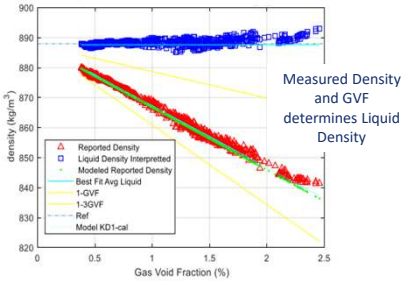
- Mass flow error parameter defined as:

$$\Phi \equiv 1 - \frac{\dot{m}_{meas}}{\dot{m}_{liq}}$$

- Mass flow correction is based on correlating Φ as a function of the density error parameter, Ψ, the gas void fraction, α, and the reduced frequency, f_{red}

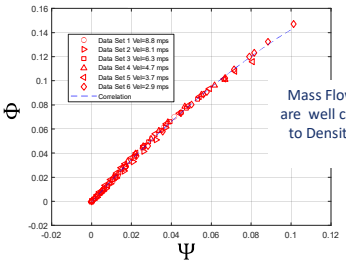
$$\Phi \equiv F(\Psi, \alpha, f_{red}^2)$$

- Correlations are Coriolis model number, flow tube orientation, and flow condition specific



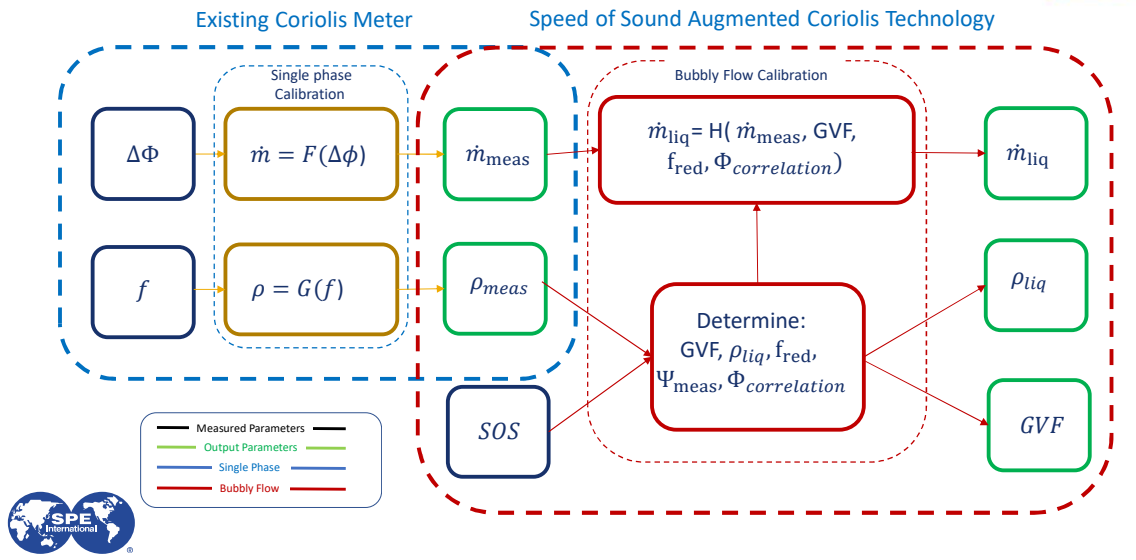
Measured Density and GVF determines Liquid Density

Mass Flow Error Parameter Correlation



Mass Flow Errors are well correlated to Density Errors

Schematic of SOS augmented Coriolis Measurement



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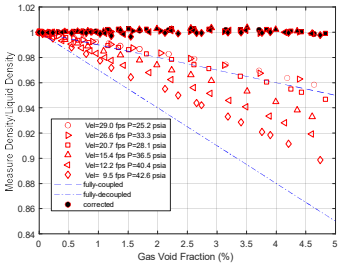
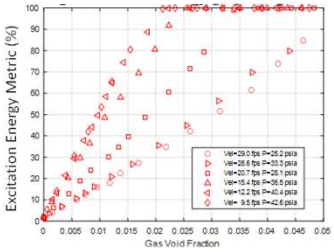
Correction applied to 2-inch Coriolis Meter (A) on Air/Water

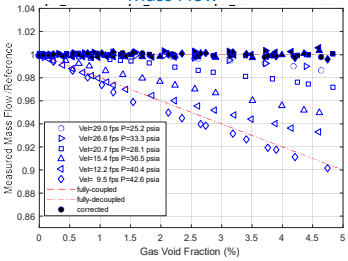
Density



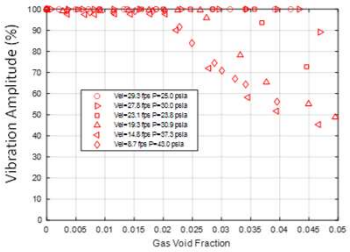
Drive Gain



Mass Flow



Vibration Amplitude



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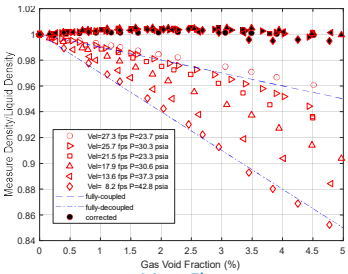
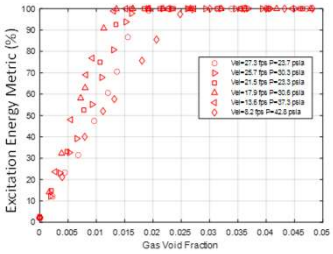
Correction applied to 2-inch Coriolis Meter (B) on Air/Water

Coriolis Meter B has ~4X compressibility effects of Coriolis Meter A

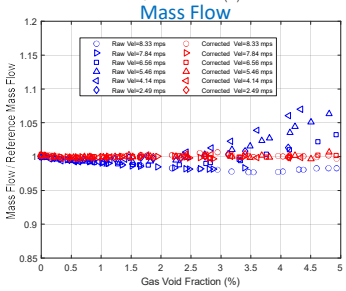
Density



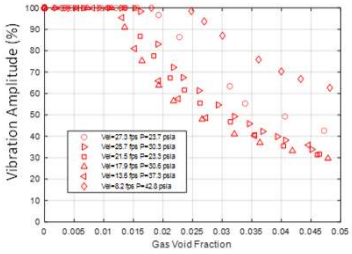
Drive Gain



Mass Flow



Vibration Amplitude



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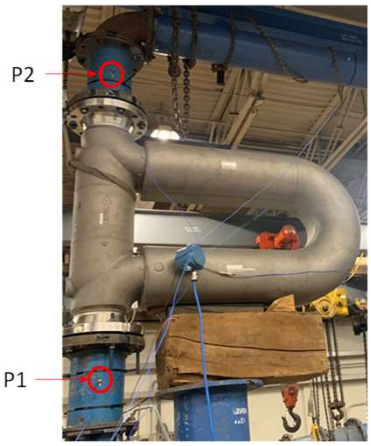
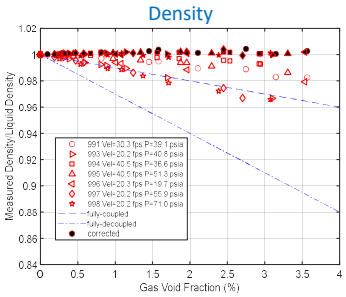
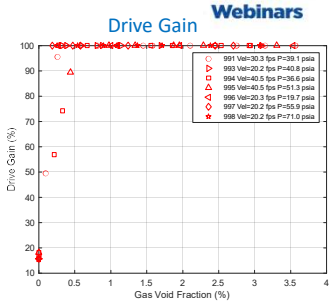
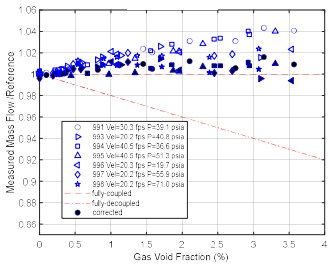
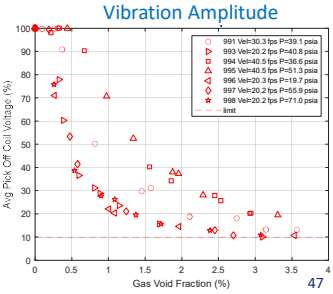
Correction applied to 8-inch Coriolis Meter (C) on Air/Water











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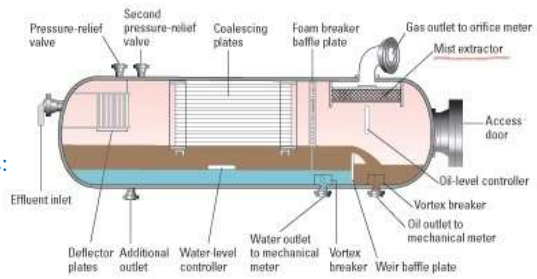
Separator-Based Measurements in Oil and Gas

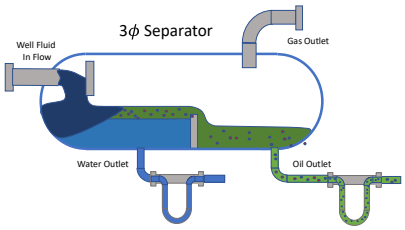
- Production from oil and gas reservoirs is inherently multiphase when arriving at the wellhead from subsurface
- Separators are designed with objectives to completely separate the gas and liquid phases
- Pre-treatments are often used to enhance separation, including heating the well stream or adding chemicals to break foams and emulsions
- Vessels are often fitted with internals to optimize separation such as: coalescing plates, mist breakers, baffles, level controllers
- Accurate separator-based measurements are critical for
  - Understanding subsurface reservoir performance,
  - Production optimization
  - Production allocation
  - Regulatory oversight

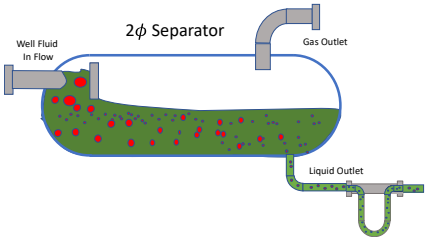


- Liquids exiting the separator are assumed to be single phase liquids when metered to determine production rates
- However, bubbly liquids often occur in liquid outlet due to gas carry-under and break out

Impact of GVF on Separator-Based Measurements

- Separator effectiveness is complex function of many variables include flow rates, fluid properties, control components and prevalence of foaming and/or emulsions
- Non-optimal separator performance typically results in often significant, but unquantified, levels of gas carry-under
- Mapping of Coriolis and/or turbine errors due to GVF is application specific, but 0-5% GVF could result in up to ~+/-10% error in mass flow or volumetric flow
- For each 1000 BPD of production, each 1% uncertainty in mass flow or volumetric flow can result in annualized uncertainty of production of 3650 bbl/year (~$250,000 @ $70/bbl)
- Real time GVF measurements can improve measurements by
  - providing feedback to optimize separator operation to reduce GVF
  - correcting for measurement errors due to GVF when present





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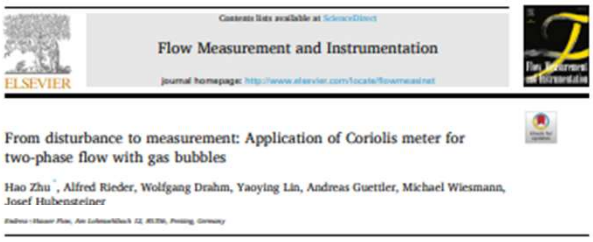
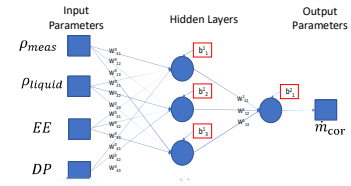
Emerging Coriolis Technologies

- Role of sound speed in improving accuracy of Coriolis meters is gaining recognition
- At least one manufacturer has introduced an approach that leverages dual Coriolis drive frequencies to improve accuracy on bubbly liquids
- Technology infers the sound speed (a_{mix}), and gas void fraction (α) by comparing measured densities at the two frequencies and utilizing an empirically-informed, first-principles model for the effect of compressibility.
- Literature indicates the approach is limited to "suspended" bubbles - i.e. fully-coupled flows
- Limited published data on accuracy or effectiveness of this approach on bubbly liquids

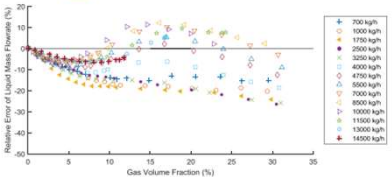


Neural Networks to Correct Coriolis meters

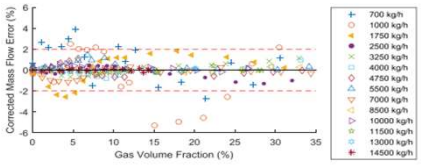
- Researchers have applied Neural Networks (NN) and other Artificial Intelligence (AI) to leverage readily available information to improve accuracy over a wide range multiphase flows from 0-100% GVF
- Errors in Coriolis meters in multiphase flows have been shown to correlate with many measured, operational, and design parameters
- NN typically utilize input parameters such as density of liquid phase, measured density, excitation energy, tube vibration amplitude, and pressure drop across meter to correlate mass flow errors based on training data sets
- Determining sufficiently-optimized input parameters and obtaining sufficiently-representative training data sets remains challenging
- The author is unaware of any commercial meters utilizing NN to correct for mass flow errors
- Currently an area of active research



Example of NN Structure



Mass Flow Errors



Corrected Mass Flow Errors

WANG *et al.*: GAS–LIQUID TWO-PHASE FLOW MEASUREMENT USING CORIOLIS FLOWMETERS
IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 66, NO. 5, MAY 2017

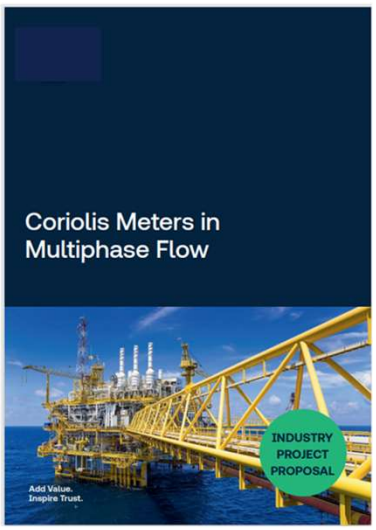
Third Party Testing - Joint Industry Project

Webinars

- As Coriolis meters are applied to more or more multiphase applications, there is a growing need for more third-party testing to evaluate accuracy and effectiveness of multiphase error mitigation approaches
- Joint Industry Projects are being formed to provide third party testing of Coriolis meter operating in multiphase flows
- Projects involve testing of specific Coriolis meters over a range of multiphase conditions with traceable single-phase references
- Projects offer engineering services to explore Neural Networks and other methods to interpret Coriolis diagnostics with goal of detecting and improving accuracy of Coriolis meters under multiphase conditions

"[This] project will provide large-scale, independent validation for the first time. This will enable operators to make informed decisions about the use of Coriolis technology in multiphase flows, saving them precious resource and money. We are looking for project partners to join us…to understand the accuracy of Coriolis technology when used in two and three phase flows"

-Dr Chris Mills, Sr. Engr. Consultant at a Multiphase Flow Testing Facility



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CorVera™ Webinars

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- **Summary**

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Summary

- Coriolis meters are being applied to more and more applications with continuous or intermittent multiphase condition
- Modern Coriolis meters can continue to report measurements to relatively high levels of gas void fractions (>20%)
- Coriolis meters operating on bubbly flows are exposed to errors in mass flow, density, and volumetric flow are typically bounded by +/- several times the gas void fraction
- Gas Void Fraction measurement has historically not been widely available to quantify entrained gases in most liquid flow measurement applications
- Coriolis diagnostics provide useful qualitative indications of entrained gas levels in liquids, well-beyond saturation of excitation energy metric
- Process fluid sound speed measurements can quantify gas void fraction levels within Coriolis and other meters to help quantify and mitigate measurement errors due to entrained gas
- Improving the accuracy of Coriolis meters operating on bubbly liquids is area of active research including approaches utilizing:
  - Bubbly liquid software mitigation algorithms using currently measured parameters
  - Advance errors correction methodology utilizing Neural networks
  - Augmenting Coriolis meters with fundamentally new measurement parameters

Webinars

Thank you
&
Discussion