CorVera™

Accurate Coriolis Mass Flow and Density of Bubbly Liquids

Measurement Focus Group Meeting

December 7th 2022

Agenda

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- Introduction
- Coriolis Meters Operating in Bubbly Flows
- Speed of Sound Augmented Coriolis Meters
- Experimental Data on Coriolis Meters Operating in Bubbly Flows
- Correcting Errors in Mass Flow, Density, and Volumetric Flow
- Applications in Energy Industry
- Summary

Introduction

- Coriolis meters are the meter of choice for many applications due to their accuracy, reliability, safety advantages and low operational costs
  - Introduced in 1978, Coriolis meter now serve >20% of the $10 billion Industrial flow meter market
- Coriolis meters are calibrated to accurately measure a wide range of single-phase flows
  - Historically ***Entrained Gas is*** known to degrade both the ***operability*** and ***accuracy*** of Coriolis meters
  - Modern Coriolis meters have been designed to improve ***operability*** in bubbly flows
  - Modern Coriolis meters are not designed to, nor are they capable of, maintaining ***accuracy*** in generalized bubbly flows
- Augmenting Coriolis meters with a process fluid speed measurement enables Coriolis meters to maintain near-single phase ***accuracy*** in bubbly flow
- CorVera has developed proprietary technology to correct Coriolis measurement errors in presence of entrained gas, available through its CORx™ product platform

Theory of Errors of Coriolis Meters in Bubbly Flows

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- Bubbly fluids exhibit more complex behavior than single phase fluids within vibrating Coriolis flow tubes causing Coriolis meter to report errors in mass flow and density
- Errors in Coriolis meters due to bubbly flows can be attributed to decoupling and compressibility

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

- Decoupling errors scale gas void fraction, α
- Compressibility errors scale with reduced frequency, $f_{red} = fR/a_{mix}$
- Gas void fraction and reduced frequency each scale with the ***Speed of Sound*** of the process fluid

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, Small Bubbles

Low Viscosity, Large Bubbles

Speed of Sound Augmented Coriolis Meters

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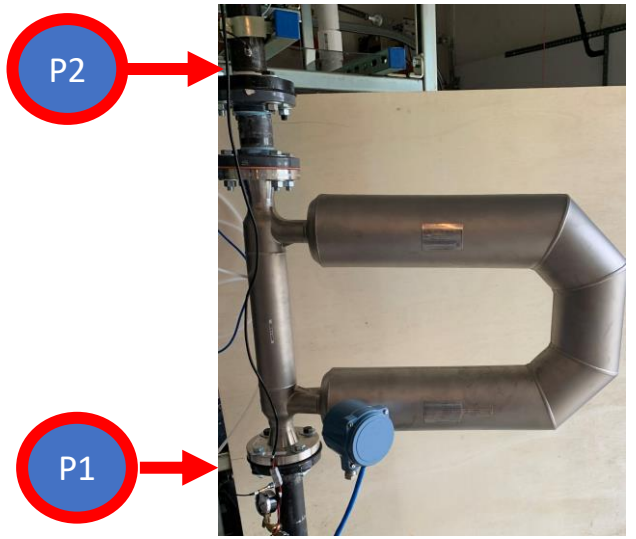
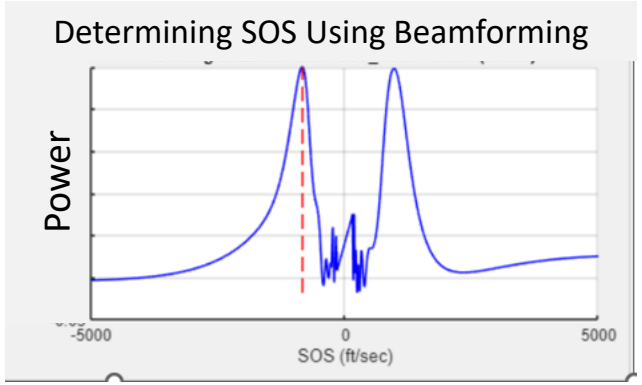
- ***Speed of sound*** is a thermophysical property of bubbly mixtures which quantifies both ***gas void fraction*** and the ***reduced frequency*** of bubbly flows within a Coriolis meter
- Measuring **speed of sound** provides a first-principles basis to mitigate errors associated with bubbly flows on a real-time basis
- CORx™ utilizes ***beam-forming*** techniques to determine the ***speed of sound*** of the process fluid by interpreting the output of an array of pressure transducers mounted externally to, and spanning the length of, the flow tubes of the Coriolis meter
- CORx™ does not affect/alter output from existing Coriolis meter, existing outputs used as input to correction



Minimally intrusive pressure sensors (P1,P2) installed in piping adjacent to Coriolis meter



Measured and Corrected Liquid Density

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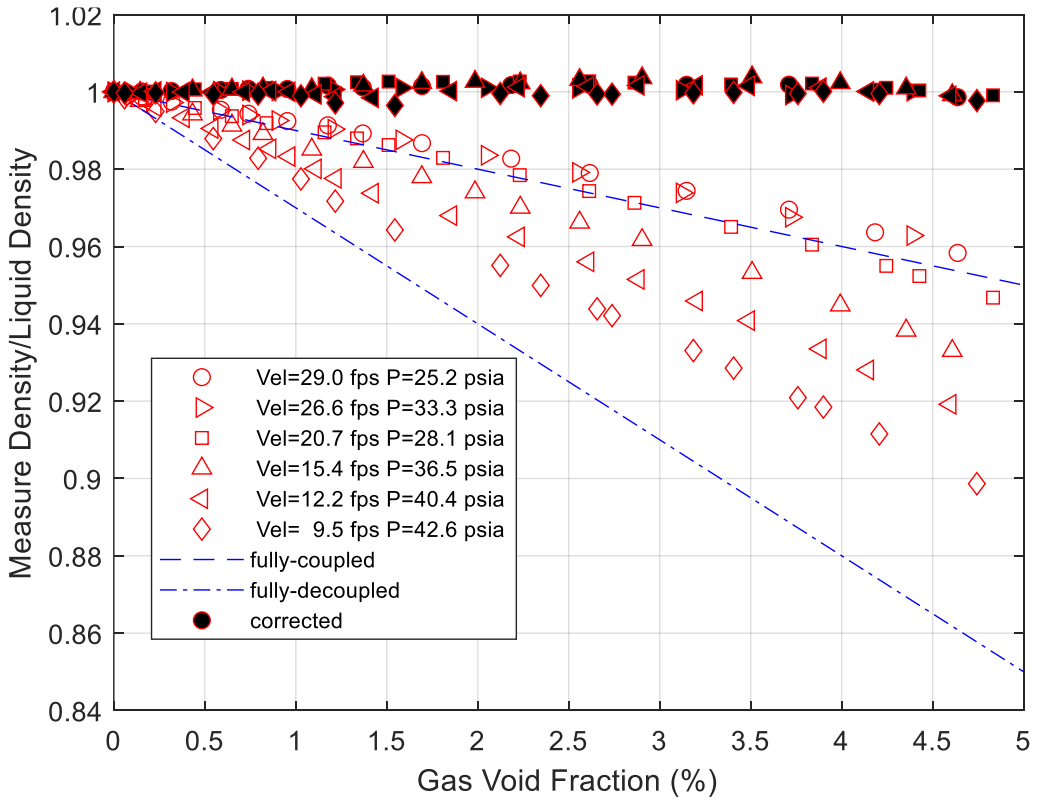
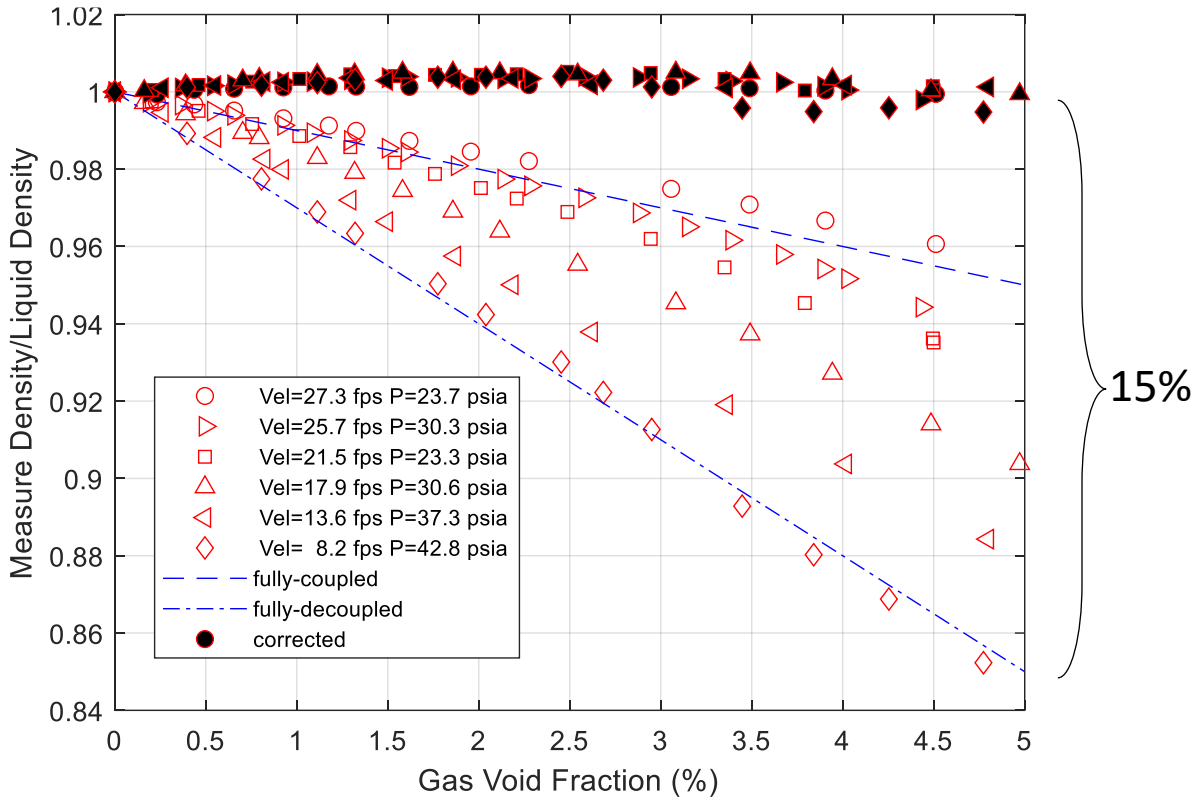
Coriolis Meter A



Coriolis Meter B



Corrected liquid density determined utilizing measured density and gas void fraction to quantify compressibility / decoupling characteristics for each data set

Measured and Corrected Liquid Mass Flow

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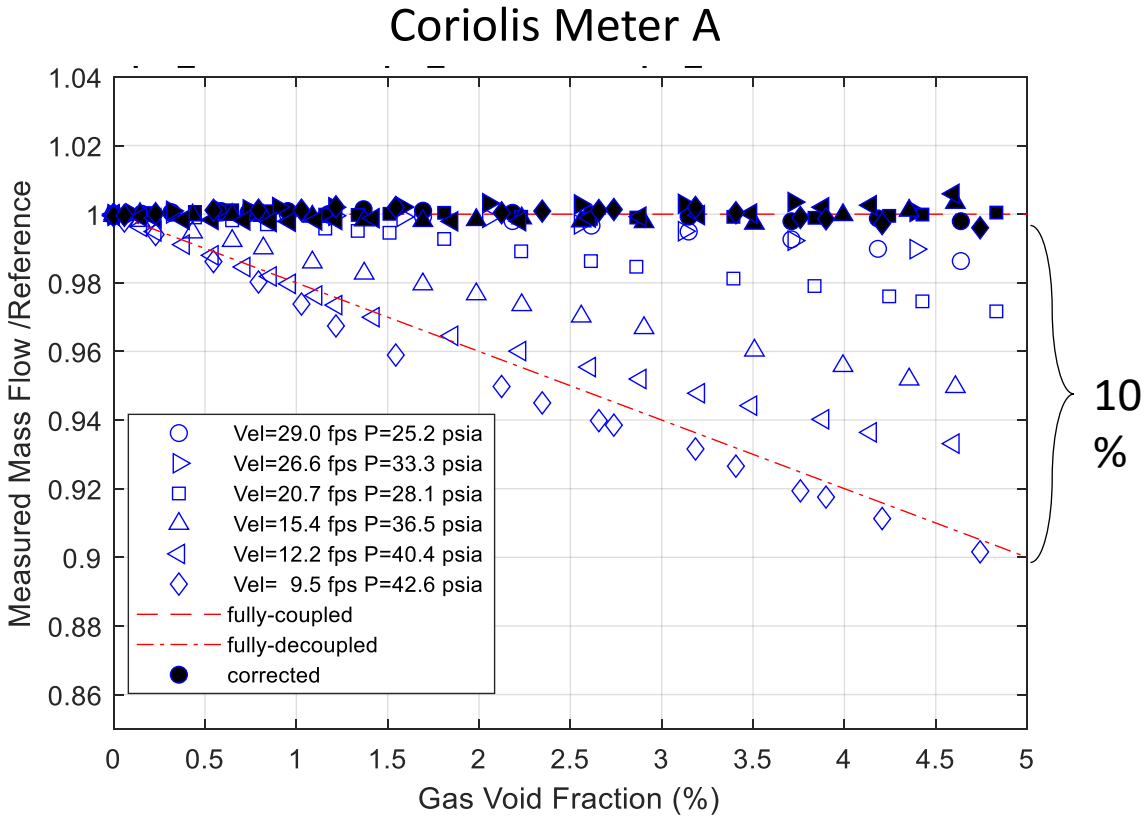

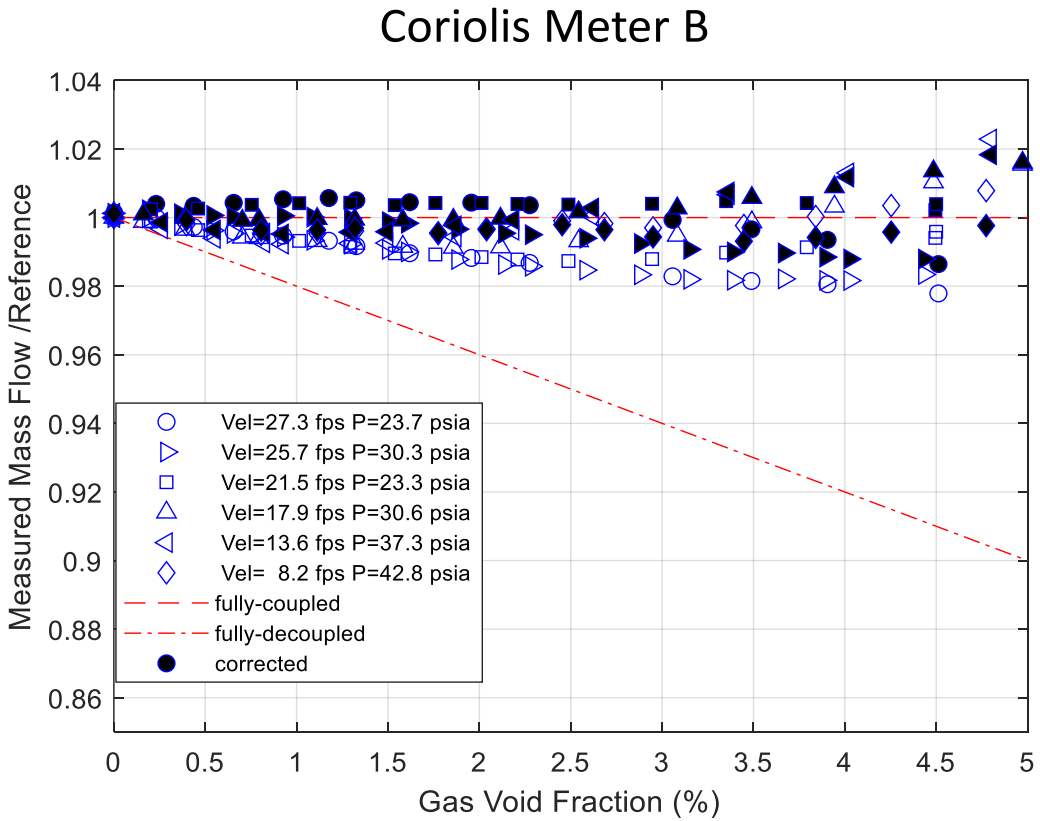

Corrected liquid mass flow determined utilizing measured mass flow, gas void fraction, reduced frequency and mass flow error function for each meter

Measured and Corrected Liquid Volumetric Flow

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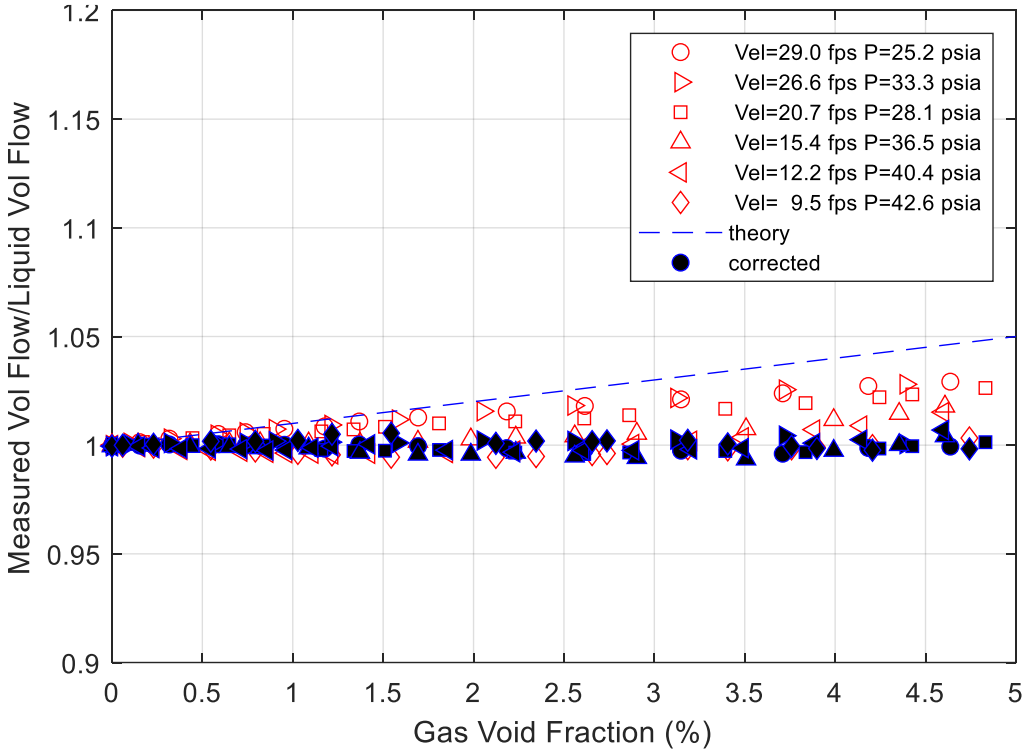
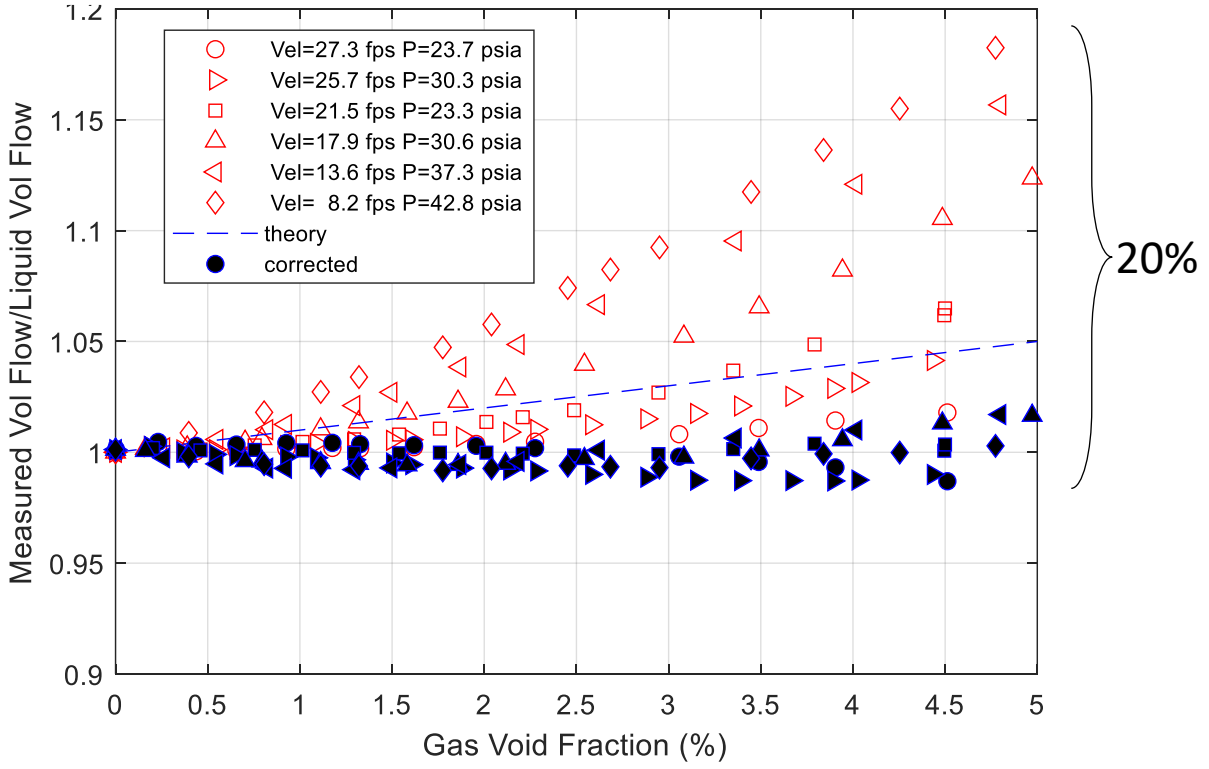
Coriolis Meter A



Coriolis Meter B



Corrected liquid volumetric flow determined using corrected liquid mass flow and the determined liquid density at each point

Excitation Energy Metric & Vibration Amplitude

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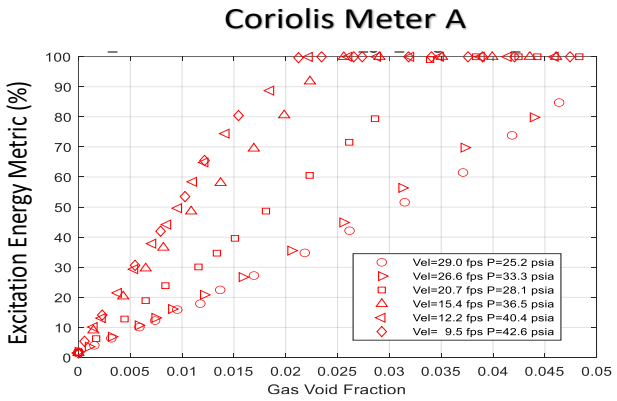
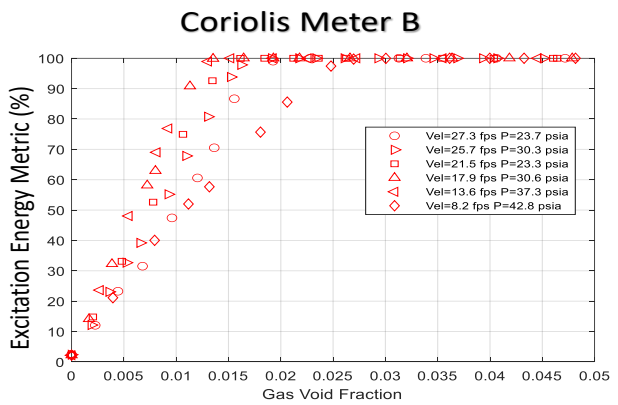
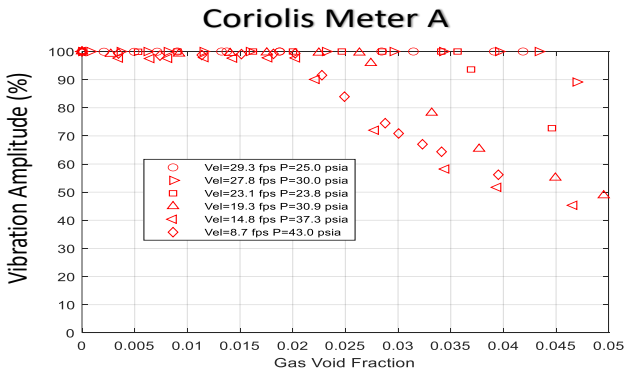
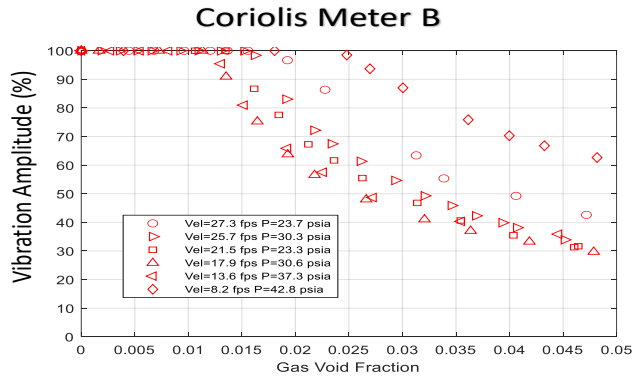




Excitation energy metric saturates at relatively low percentage of gas void fraction





Corresponding vibration amplitude decreases after excitation energy metric saturates

Each Coriolis meter remains **operable** and continues to report **correctable** mass flow and density, with reduced vibration amplitudes and saturated excitation energy

SOS Augmented Coriolis meters enable Accurate Net Oil

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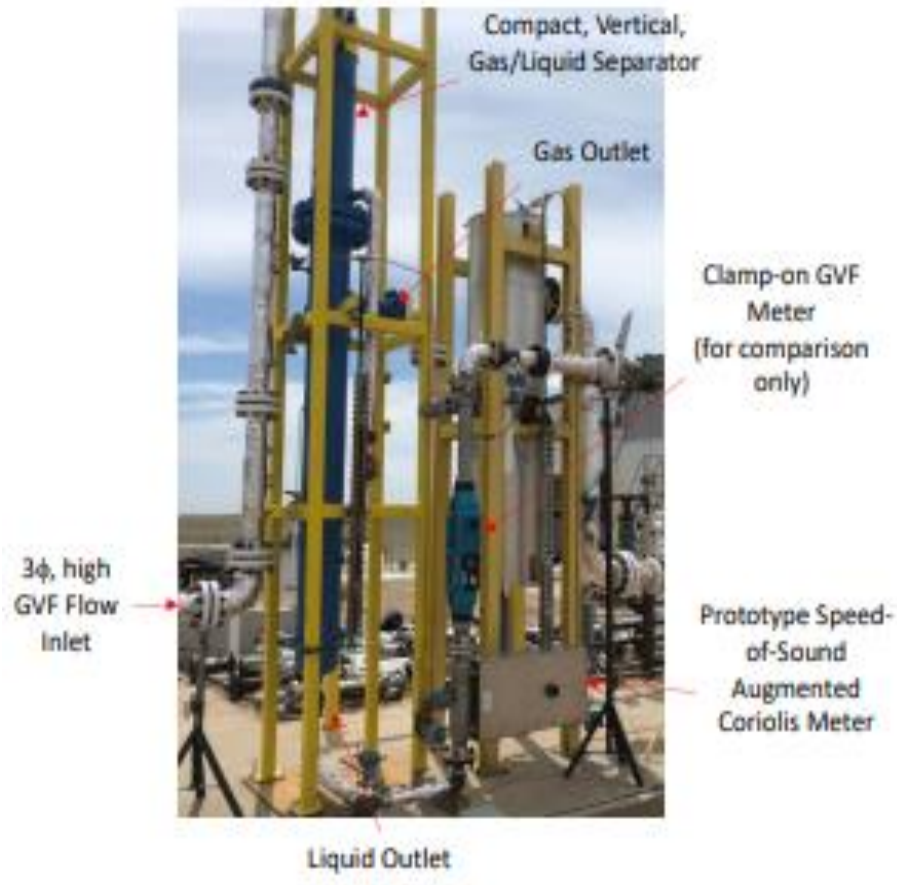
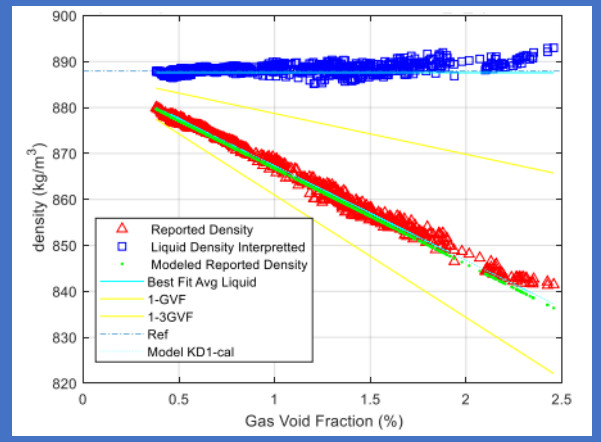
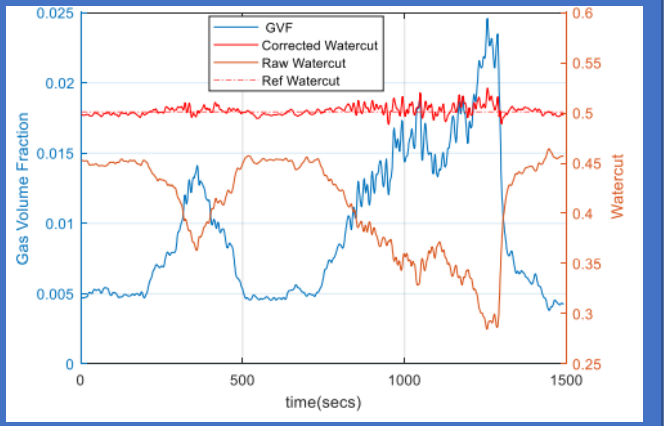
- Live fluids hydrocarbon gas and condensate on 3ϕ Flow Loop
- Coriolis Meter Installed on Liquid Leg of Separator
- GLCC Separator, Coriolis used for watercut
- Watercut held constant at 50% with gas carry-under varied by adjusting liquid level within Separator
- Raw watercut reported ranged from 30% to 45% for gas void fraction of 0.4 to 2.5%
- Corrected watercut matches reference watercut, independent of gas void fraction





Reported and Corrected Density vs Gas Void Fraction



Raw and Corrected Water and Gas Void Fraction

Source: 2020 Northea Flow Measurement Workshop Paper

Managed Pressure Drilling (MPD)

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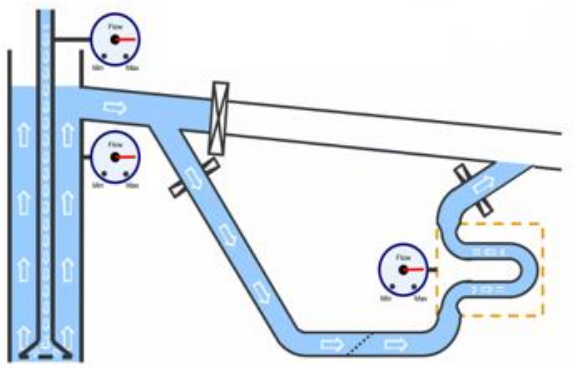
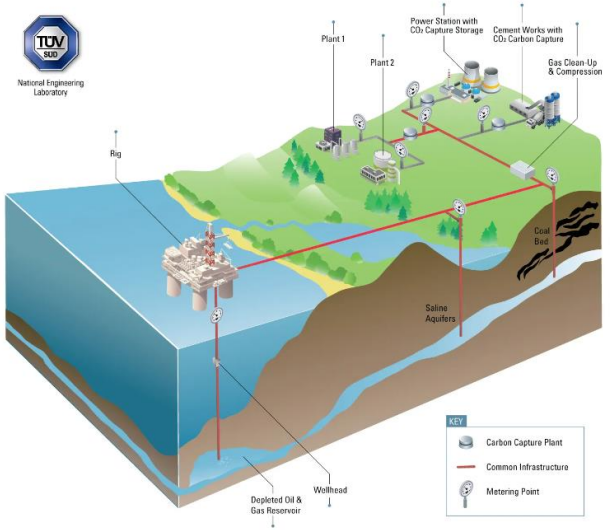
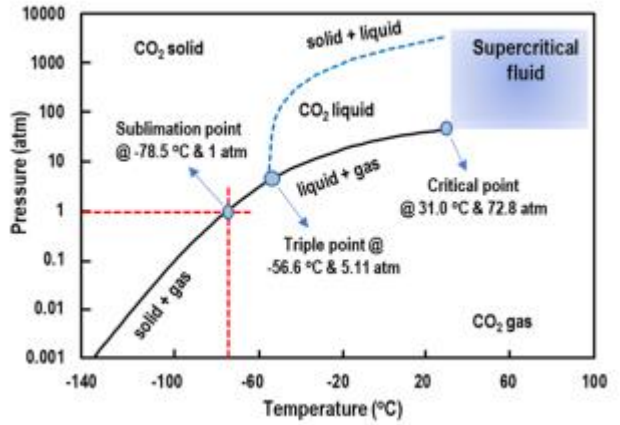
- MPD is a closed-loop drilling technique in which
  - Pore pressure, formation fracture pressure, and bottom hole pressure are balanced and managed at surface
  - Used extensively where there is a narrow pore-pressure to fracture-pressure window
  - Mandated on Deep Water exploration wells
- Drilling fluid pressure is supplemented by an applied surface back pressure
- Undetected fluid influx, or fluid loss, within well bore can lead to loss of well control
- Monitoring fluid losses and gains within the well-bore in real-time is critical measurement
  - Coriolis meters are installed to measured mass flow into and out of wellbore to detect fluid loss or gain in wellbore
  - Coriolis meters at inlet are at high pressure and do not experience entrained gas issues
  - Entrained gas within the mud return line decreases Coriolis meter accuracy and impairs ability to detect fluid loss or gain in the well bore
  - Mud return line is often diverted to create vertical flow upwards through flag-mounted Coriolis on mud return line to help Coriolis meter manage entrained gases
- COR_X™ Speed of Sound Augmented Coriolis Technology
  - Provides Surety of mass balance in closed drilling system by fundamentally improving accuracy of mass flow measurement on Mud Return Line when entrained gas is present
  - Improves early kick detection capability
  - Detects and quantifies free gas in drilling fluid
  - Improves accuracy of drilling fluid density measurements



CCUS - Carbon Capture, Utilization, and Storage

- CCUS is key to reducing carbon emissions
- Monetization and the associated financial transactions, environmental compliance, tax credits, will require accurate flow measurement data at each stage of the chain
- Compared to other substances transported by pipeline (oil, natural gas, water) the critical point of CO2 lies close to ambient
  - Small changes in P&T may lead to rapid changes in physical properties
  - Furthermore, the prevalence and variability of impurities add significant uncertainty regarding phase transition boundaries
- Speed of Sound Augmented Coriolis meters are well-suited for CCUS measurement
  - Improved compositional information under single-phase conditions by providing two thermophysical properties (density and sound speed) of the process fluid
  - Improved accuracy under multiphase conditions





CO2 Phase Diagram

Graphic adapted from: Mills, C., "Flow Measurement in Support of Carbon Capture, Utilization, and Storage", TUV-SUD NEL Report 2021_299

Summary

CorVera™

- Coriolis meters are calibrated to accurately measure a wide range of single-phase flows
  - Historically ***Entrained Gas is*** known to degrade both the ***operability*** and ***accuracy*** of Coriolis meters
  - Modern Coriolis meters have been designed to improve ***operability*** in bubbly flows
  - Modern Coriolis meters are not designed to, nor are they capable of, maintaining ***accuracy*** in generalized bubbly flows

- CORx™ = Speed of Sound Augmented Coriolis
- Cost-effective solution to improve the accuracy of Coriolis meters operating on bubbly liquids
  - Indication of the presence of entrained gas
  - Percentage volume of entrained gas (GVF <20%)
  - Density and Mass corrected to near single-phase accuracy
  - Agnostic to Coriolis manufacturer or type
  - No modification to existing Coriolis

- SoS Augmented Coriolis Meter, liken to ani-lock brakes
- Continued Surety of measurement under adverse process conditions
- Remove risk, human and or machine error

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Thank you
&
Questions

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