NORTH SEA FLOW MEASUREMENT WORKSHOP
measuring for the energy transition

Multiphase Flow Metering Using Coriolis Meters

aramco

Sakethraman Mahalingam
Aramco Overseas Company

Outline

I. Introduction

II. Flow Loop Test Setup

III. Test Results

   i. Statistics

   ii. Physics Based Error Modelling

   iii. Neural Network Modelling

IV. Conclusions

Introduction

- Coriolis meters increasingly used in upstream conditions
- Gas tolerance key to their performance
- Coriolis meters + water-cut meter may be able to measure multiphase flow[1]
- Key is to understand error in measurements and model them

Can we move from gas entrainment handling to multiphase metering?

1- Henry, M., Tombs, M., Zamora, M., and Zhou, F., "Coriolis mass flow metering for three-phase flow : A case study", Flow Measurement and Instrumentation, 2013, Vol. 30, pp. 112–122

Meter Under Test - Rotamass TI

- Rotamass RCUS38S, 3”
- Dual Tubes, U-Shape, Stainless Steel 316L
- Flow Range: up to 50 ton/hr
- Advanced DSP and oscillation drive control
- Uninterrupted functionality in presence of entrained gas

RC*N20K	no limit
RC*S34S	no limit
RC*S34H	no limit
RC*S36S	50 %
RC*S36H	50 %
RC*S38S	30 %
RC*S38H	30 %
RC*S39S	7 %

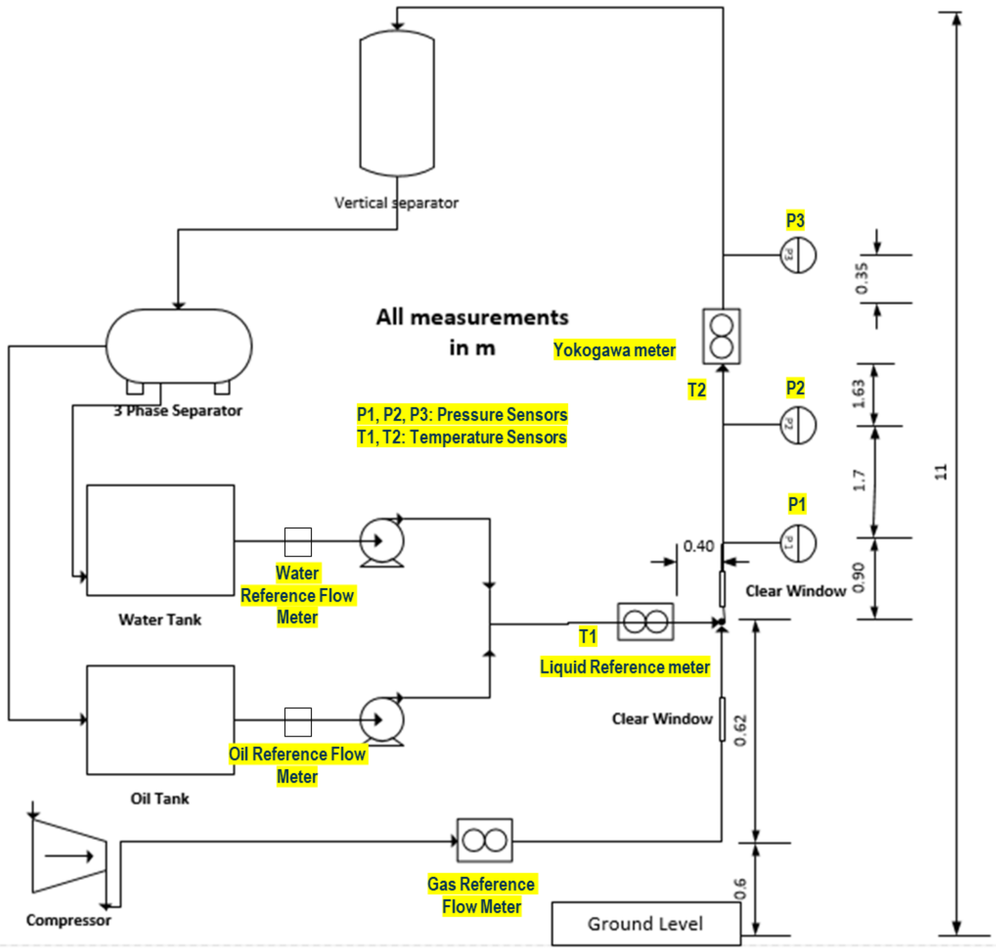
Entrained gas limits - values serve as guide only primarily for service

Test Protocol

- Conducted at Cranfield University multiphase flow loop
  - Four water-cuts - 0, 30, 70 and 100%
  - Gas volume fraction (GVF) from 0 to 50%
  - Liquid flow rates of up to 5 to 30m^3/hr (750 to 4500 barrels per day)
  - Repeated validation runs on different days
  - Total of 175 test points
  - Stabilized data logged every second for 3 minutes at each test point

Test Setup

- Meter installed on 2-inch riser
- Coriolis meter nominally 3-inch diameter
- Short adaptors used up & down stream
- Liquid Coriolis reference meters
- Uncertainty on liquid flow rate <1%
- Thermal anemometer air flow meter
- Uncertainty of 2% on air flow rate
- Fully automated control of flow loop



Cranfield University Flow Loop

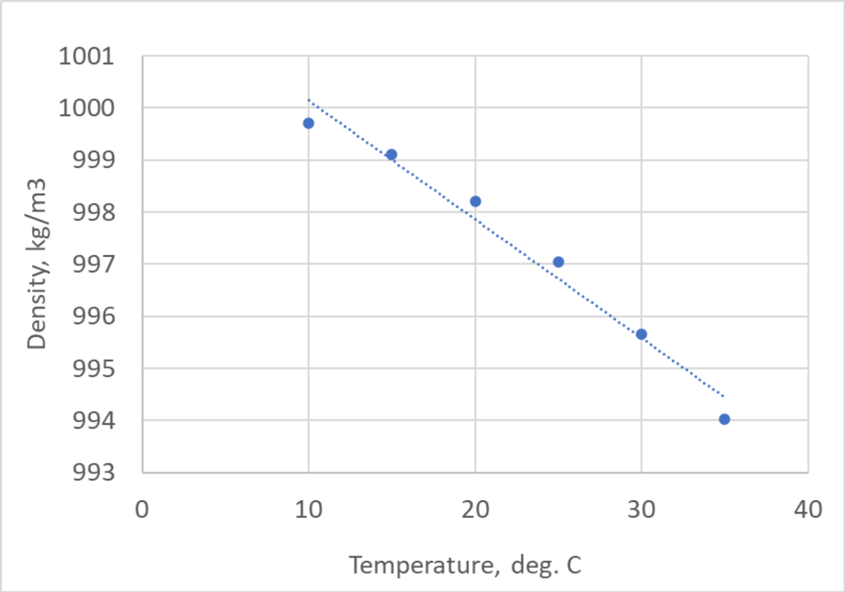
Cranfield University Process Engineering Lab

Coriolis Meter Under Test

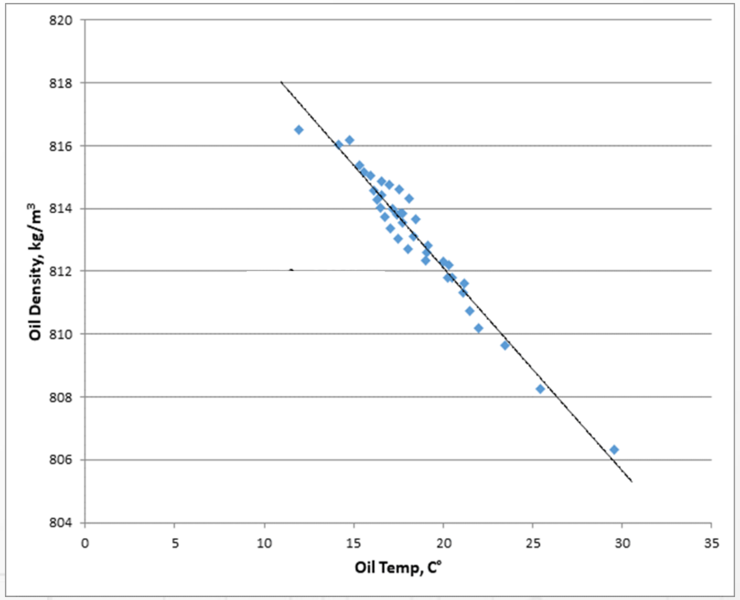
Fluid Properties

- Liquid properties based on internal testing
- Air density taken as 1.225kg/m3 at 15C and 101.325kPa[1]
- Air considered an ideal gas

Water Density



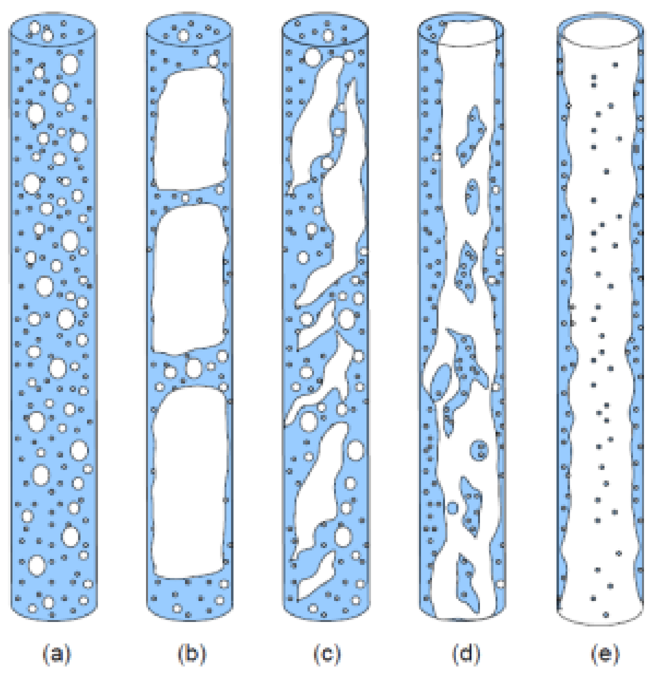
Oil Density



1- "Performance of the Jet Transport Airplane: Analysis Methods, Flight Operations, and Regulations", First Edition, Trevor M. Young, 2018, pp.583, John Wiley & Sons Ltd.

Flow Regime Visualization

- Most points fall between bubbly and churn flows
- Flow not fully developed at the meter



(a) Bubbly Flow

(b) Slug Flow

(c) Churn Flow

(d) Annular Flow

(e) Annular Mist Flow

K. W. McQuillan and P. B. Whalley, "Flow patterns in vertical two-phase flow," Int. J. Multiph. Flow, vol. 11, no. 2, pp. 161–175, 1985.

Water-cut: 30%,
Gas flow rate: 10Sm^3/hour
Liquid flow rate: 6m^3/hour

Test Results – General Observations

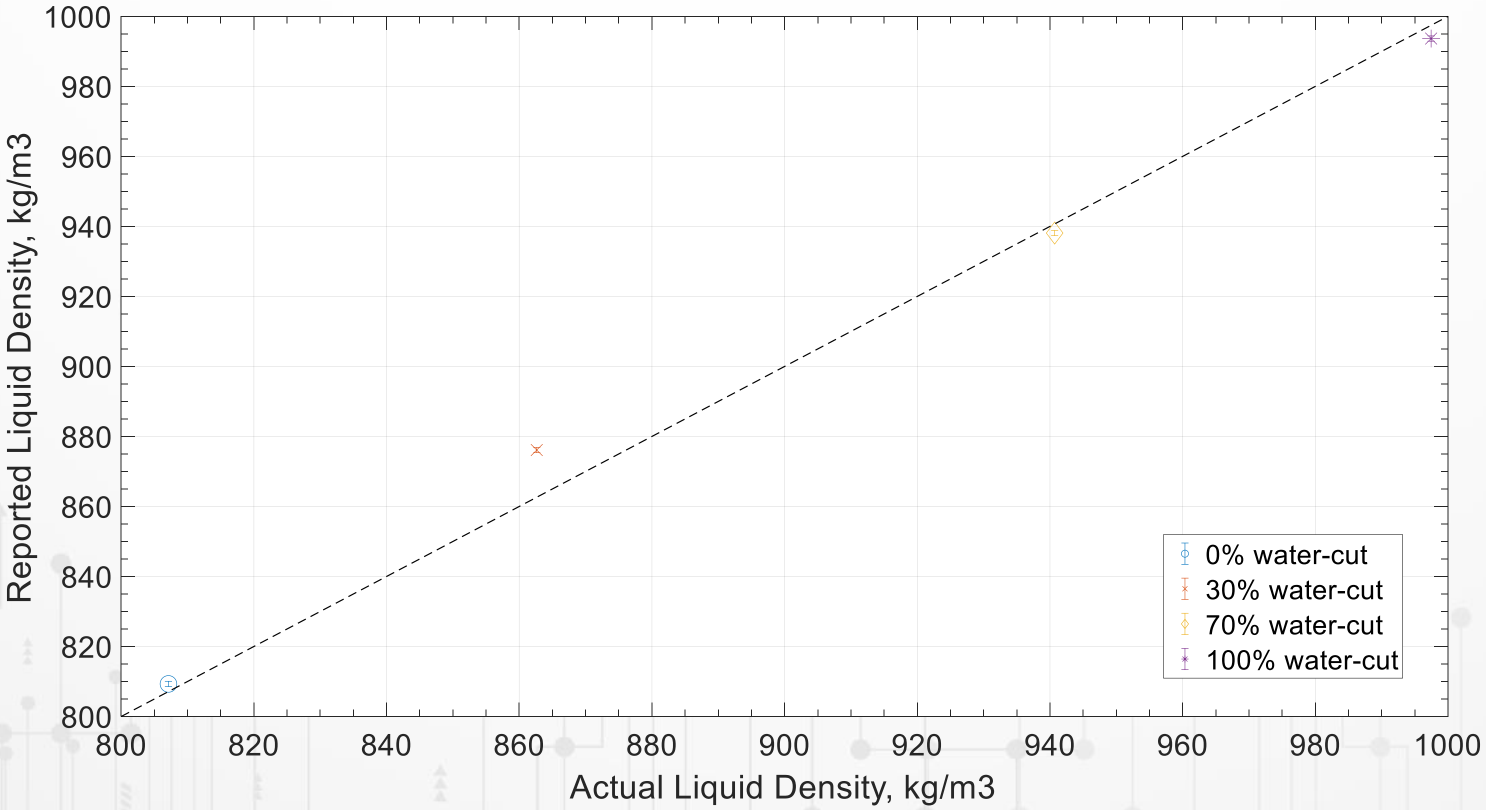
- Meter handled up to 50% GVF, produced density and mass flow measurements
- Increased scatter in measurements above 40% GVF
- Density and Mass flow rate errors generally within ±35% across the test

- Meter unable to handle above 50% GVF
- Meter slightly oversized for the 2-inch line

- Flow loop may have higher uncertainty at higher GVF
  - Reference liquid flow meter uncertainty higher at low liquid flow
  - Reference gas flow rate measurement uncertainty

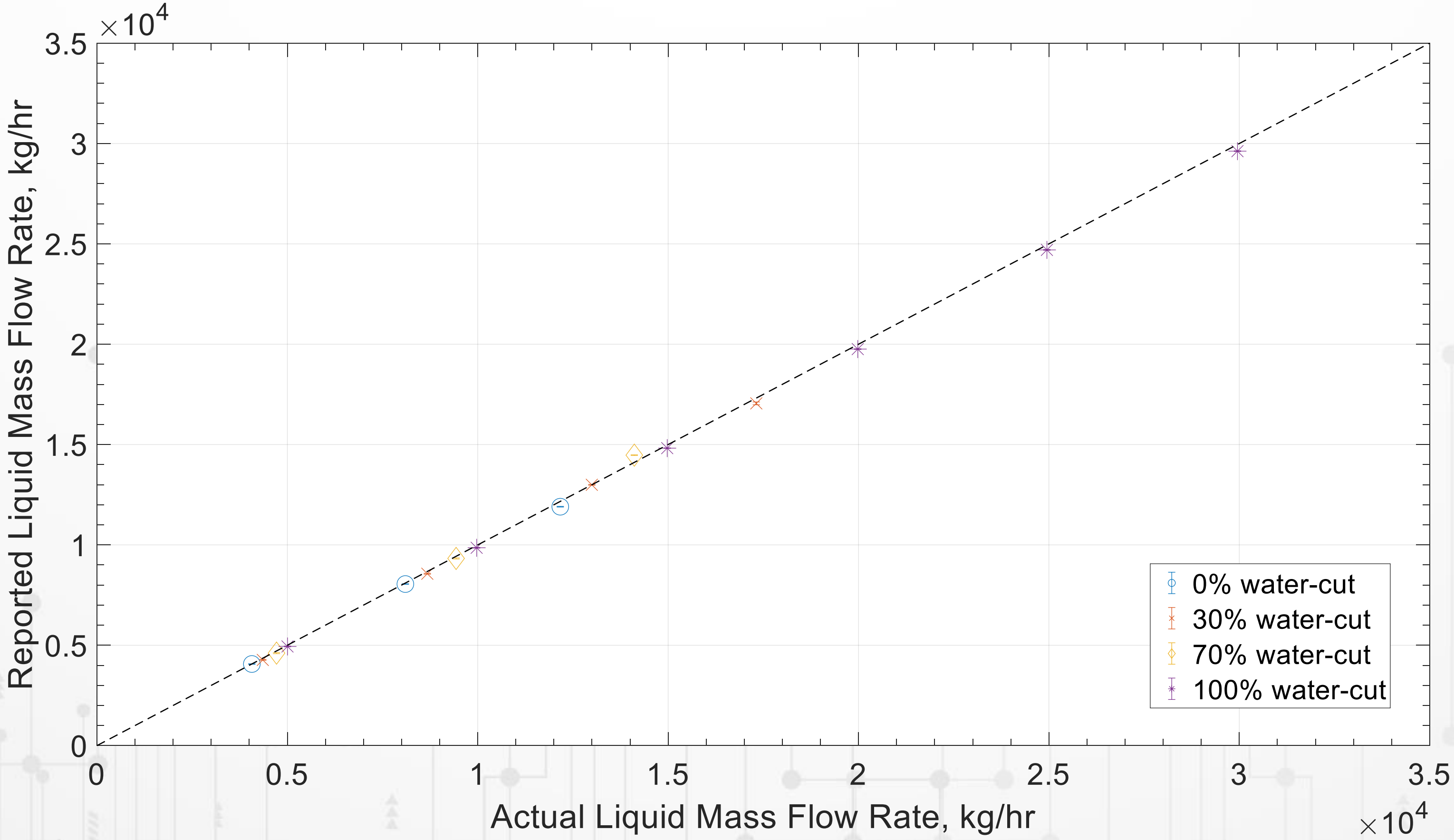
Liquid Density Measurement Under 0% GVF

- Density at 30% water-cut slightly higher than expected
- Otherwise, meter mostly within 0.5% reading



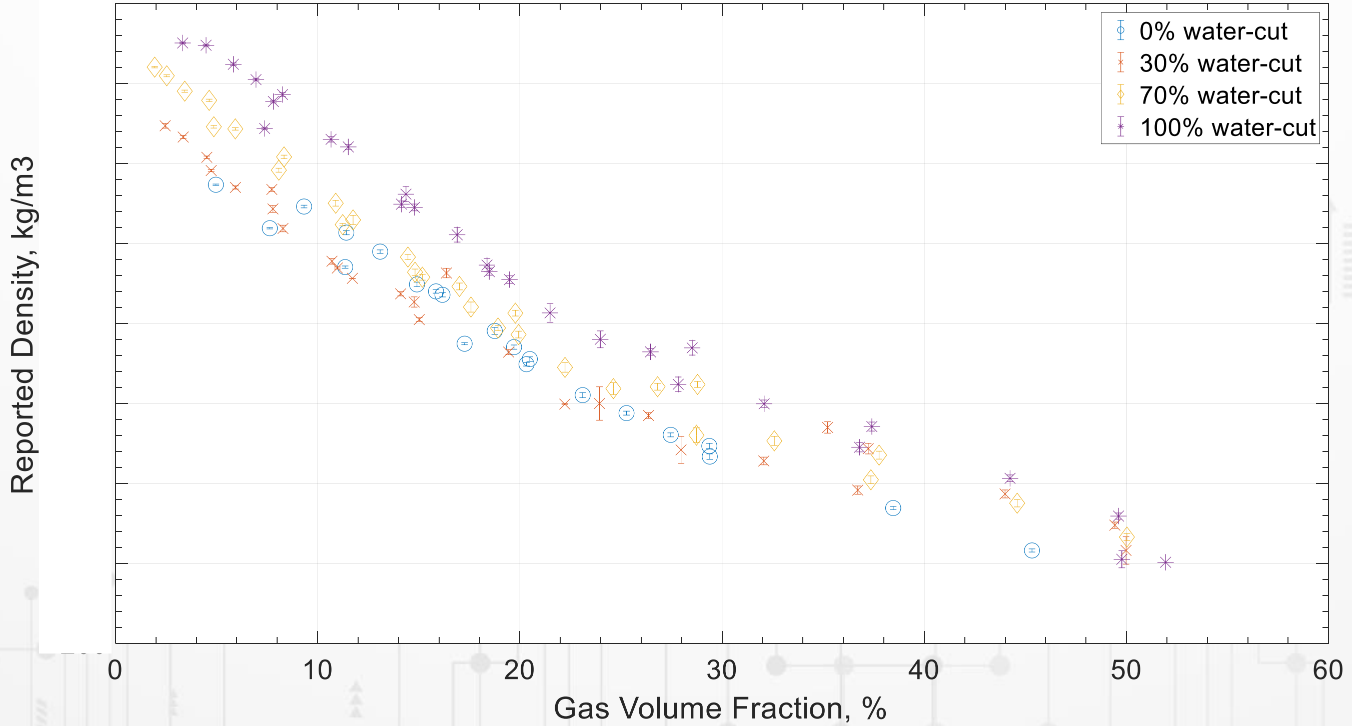
Liquid Mass Flow Measurement Under 0% GVF

- All measurements within 0.5% of expected readings



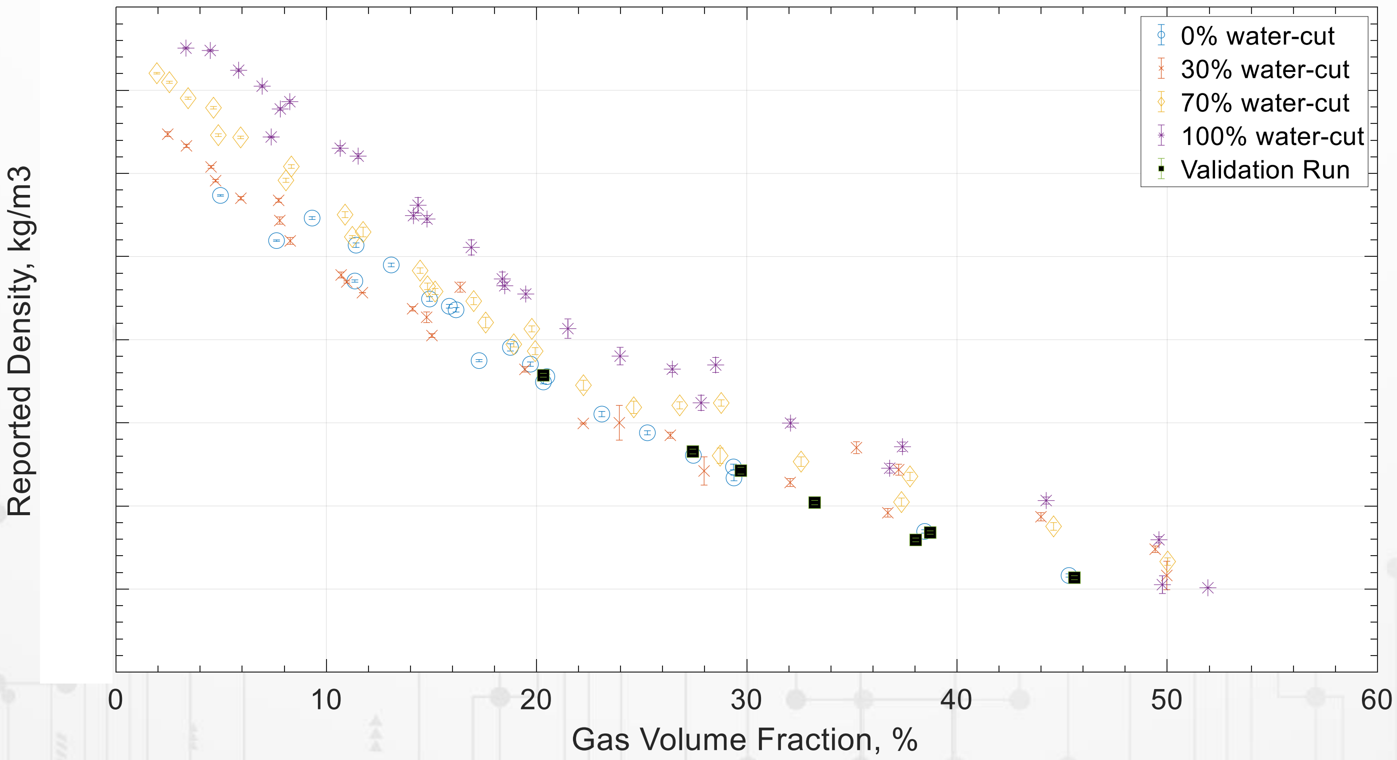
Reproducibility of Density Measurements – in GVF

- Reported density stable within a given test setting even under significant GVF
- Reported density – almost insensitive to liquid volumetric flow rate



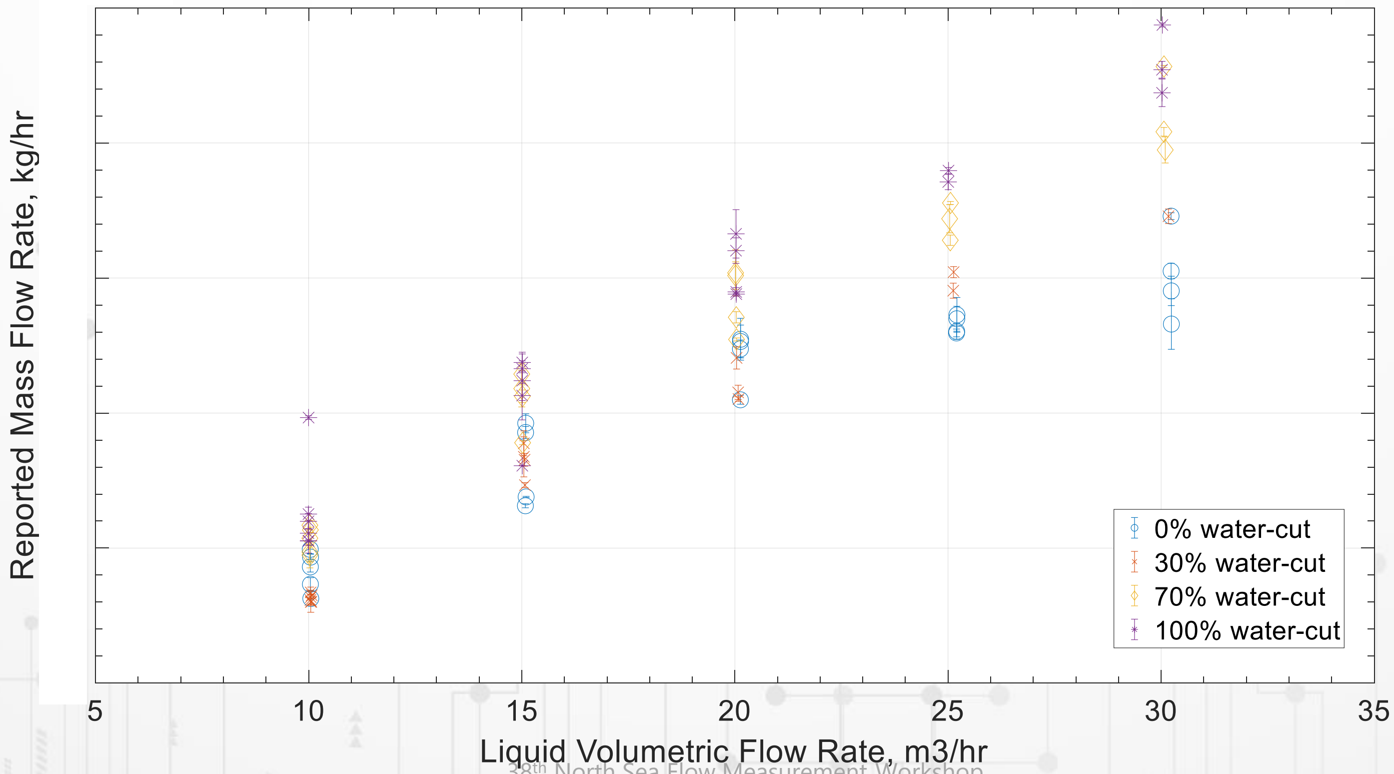
Repeatability of Density Measurements – in GVF

- Reported density stable in validation runs
- Similar behaviour of density decrease with respect to GVF
- Typical scatter of about 1-2% within a test



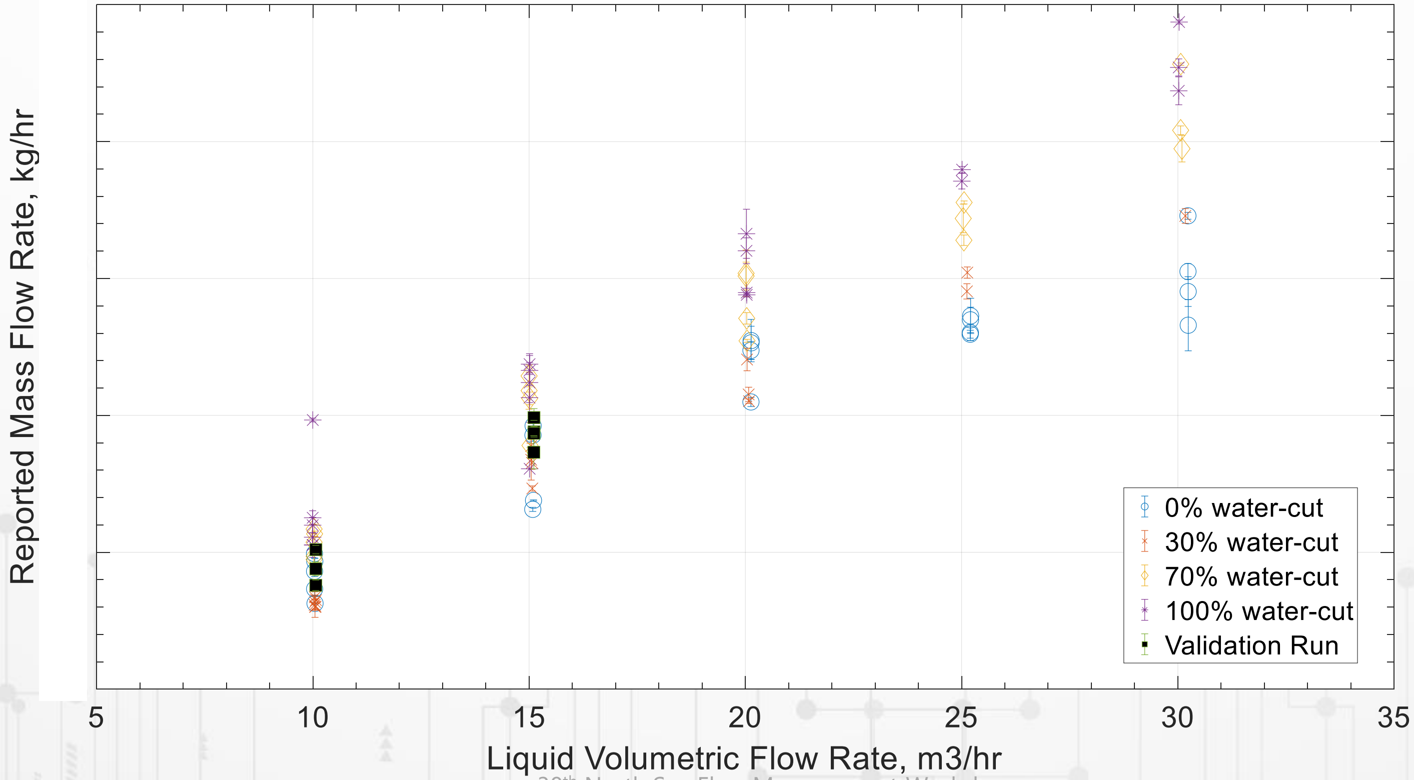
Reproducibility of Mass Flow Measurements – in GVF

- Reported mass flow less stable than density under GVF
- Reported mass flow – dependant volumetric flow rate, water-cut & GVF



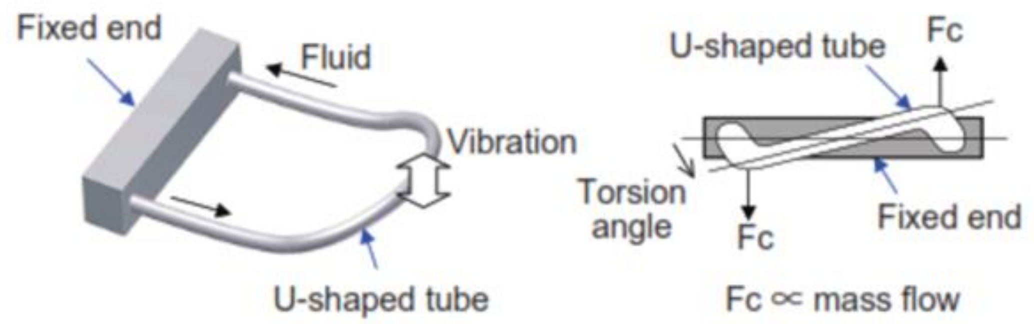
Repeatability of Mass Flow Measurements – in GVF

- Reported mass flow similar under validation runs
- Scatter higher at higher GVF as output is much more unstable



Coriolis Meter Under Multiphase Flow

- Gas entrainment causes issues
  - Control of vibration
  - Measurement of vibration



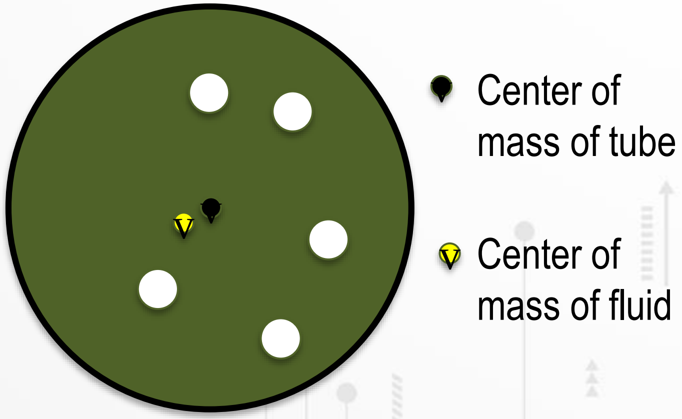
- Control issues
  - Increasing gas $\Rightarrow$ increased damping
  - Increased damping $\Rightarrow$ increased power to maintain vibration
  - Safe operation $\Rightarrow$ limited energy

- Measurement cannot be achieved when there is no control
- Measurement needs to be corrected once control issues are resolved

Effect of Gas Entrainment

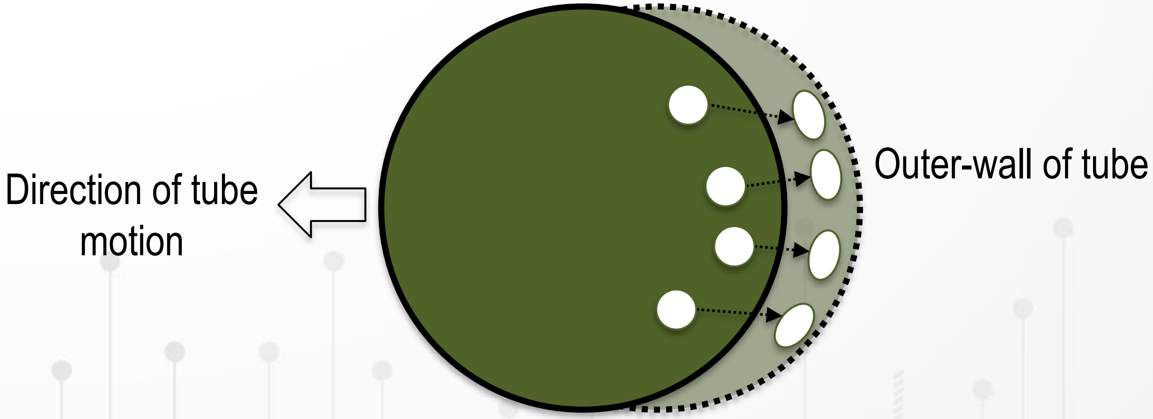
Gas entrainment issues[1,2,3]

- Phase decoupling $\Rightarrow$ gas phase and liquid vibration response decoupled
- Gas compressibility $\Rightarrow$ larger reaction caused by compressed fluid being pushed toward outside wall



Phase Decoupling

Always causes a negative error[1,3]



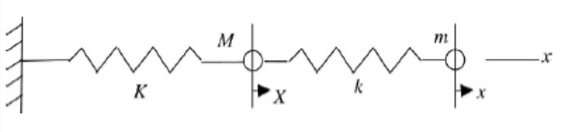
Gas Compressibility

Always causes a positive error[1,3]

1 - Basse, N., "A review of the theory of Coriolis flowmeter measurement errors due to entrained particles", Flow Measurement and Instrumentation, 2014, Vol. 37, pp.107–118
2 - Weinstein, J., "Multiphase Flow in Coriolis Mass Flow Meters – Error Sources and Best Practices", Proceedings of the North Sea Flow Measurement Workshop, 2010
3 - Hemp, J., and Kutin, J., "Theory of errors in Coriolis flowmeter readings due to compressibility of the fluid being metered", Flow Measurement and Instrumentation, 2006, Vol. 17, pp. 359-369

Physics Based Error Modelling

- Hemp and Kutin[1] (2006) developed a theoretical framework
- *K = tube stiffness* *M = tube mass*
- *k = fluid stiffness* *m = fluid mass*



- Error in density
- $E_d = -3\alpha + \frac{1}{4}\left[\frac{w_1 b}{c}\right]^2$
- Error in mass flow rate
- $E_{\dot{m}} = \frac{-2\alpha}{1-\alpha} + \frac{1}{2}\left[\frac{w_1 b}{c}\right]^2$

Phase decoupling error

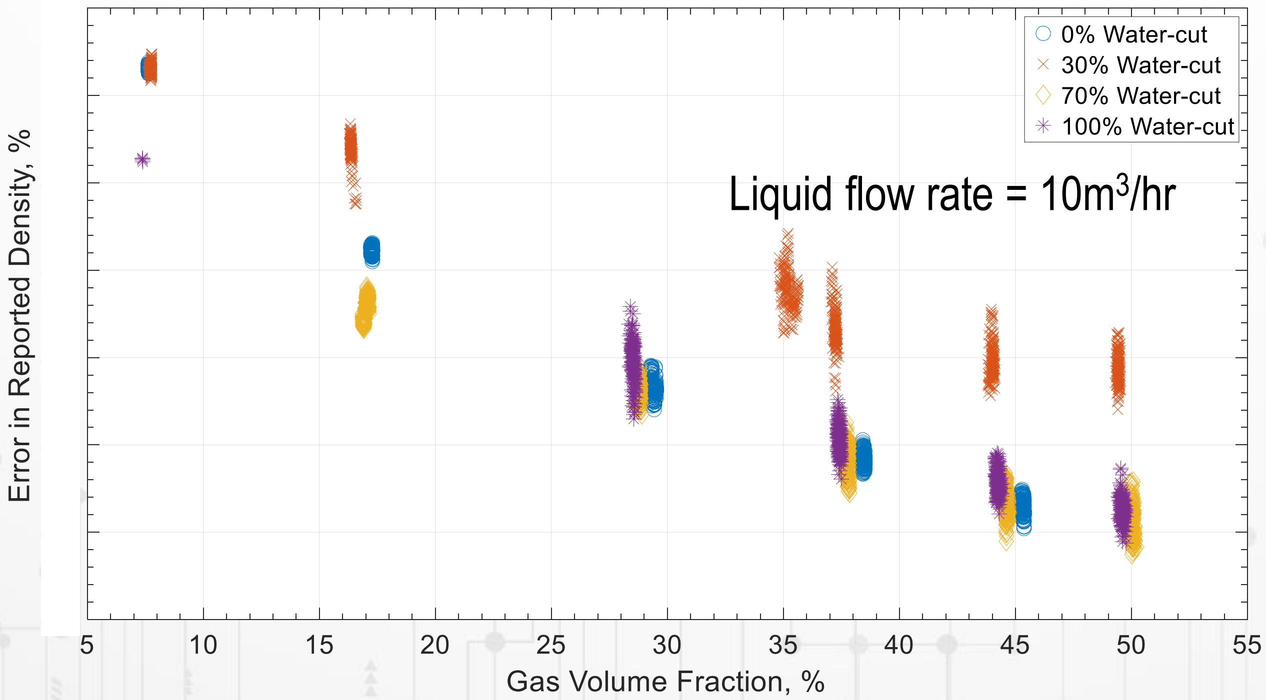
Compressibility error

E_d = Error in density
α = gas volume fraction
w_1 = actual resonance frequency of vibration for two-phase fluid
b = inner diameter of flow tube
c = speed of sound in two phase fluid

1 - Hemp, J., and Kutin, J., "Theory of errors in Coriolis flowmeter readings due to compressibility of the fluid being metered", Flow Measurement and Instrumentation, 2006, Vol. 17, pp. 359-369

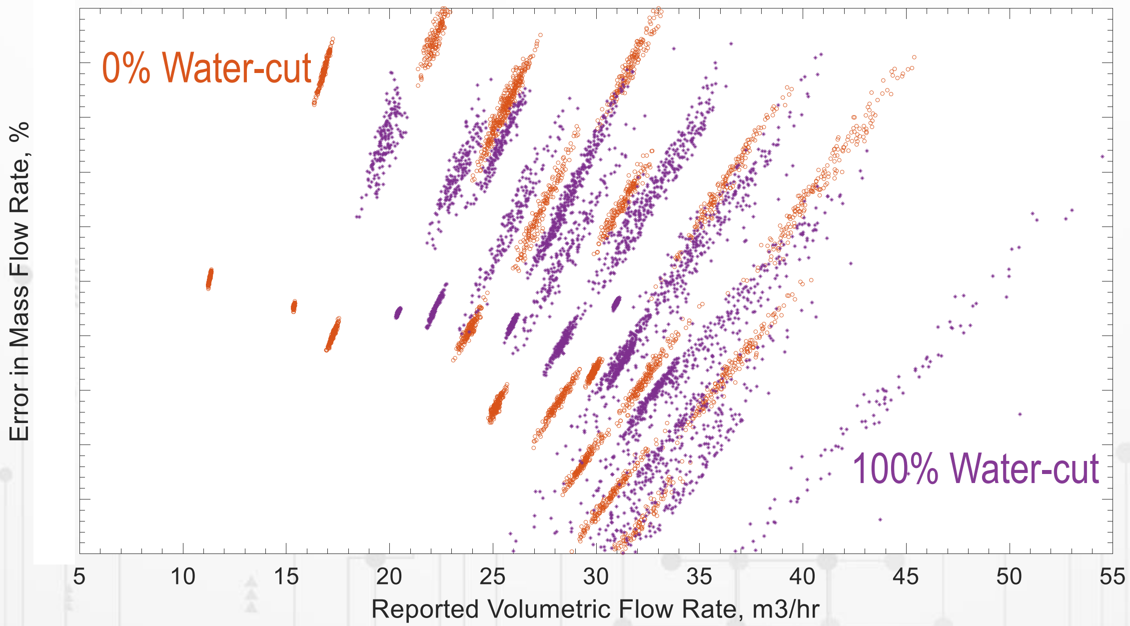
Error in Reported Density

- Error always negative and almost linearly increases with gas volume fraction
- Drop in reported density for 30% water-cut data slightly lower than other water-cuts



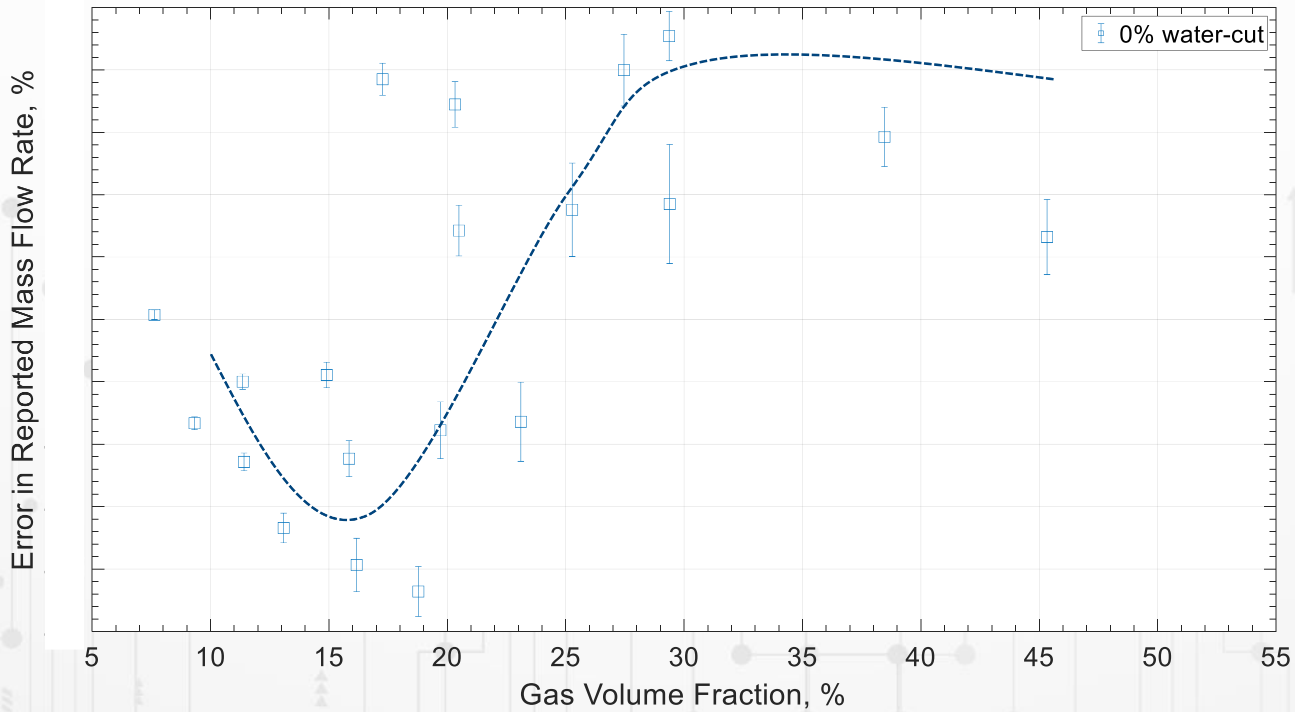
Error in Mass Flow – Effect of Volumetric Flow

- Mass flow rate error – both positive and negative errors
- Error – a function of volumetric flow rate, GVF and water-cut
- Reported volumetric flow rate calculated from mass flow rate and density
- Larger scatter in error in lower viscosity fluid – 100% water-cut



Error in Mass Flow – Effect of GVF

- Mass flow rate – function of volumetric flow rate, GVF and water-cut
- Clear effect of compressibility errors causing change in error direction

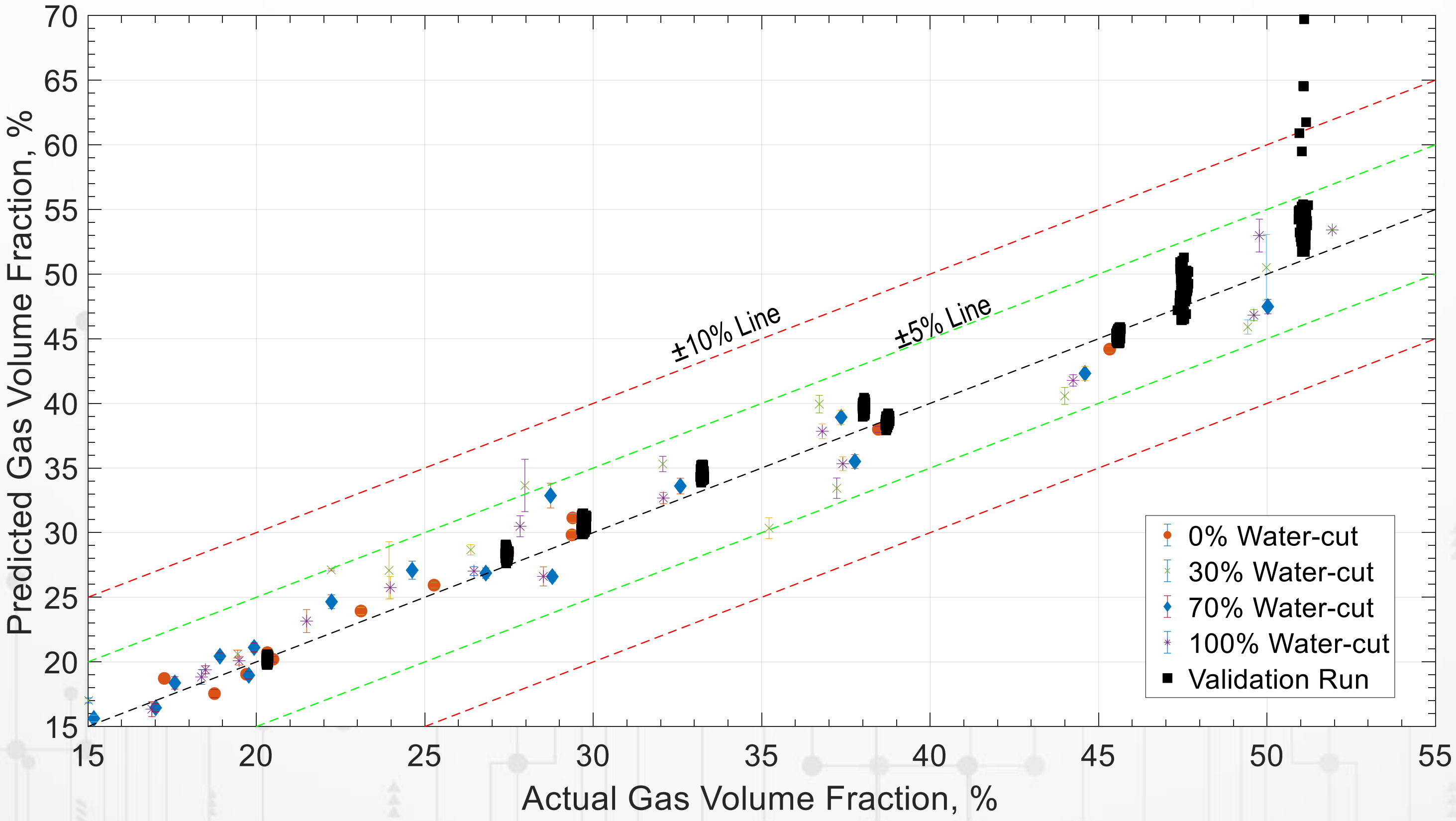


Modelling Approach

- Use Hemp's theoretical framework as a guide
- Assume water-cut is known from an additional sensor
- Fit error equations with experimental data for density and mass flow rate
- Iterate loops where needed for convergence where applicable
- Validate against repeated experiments

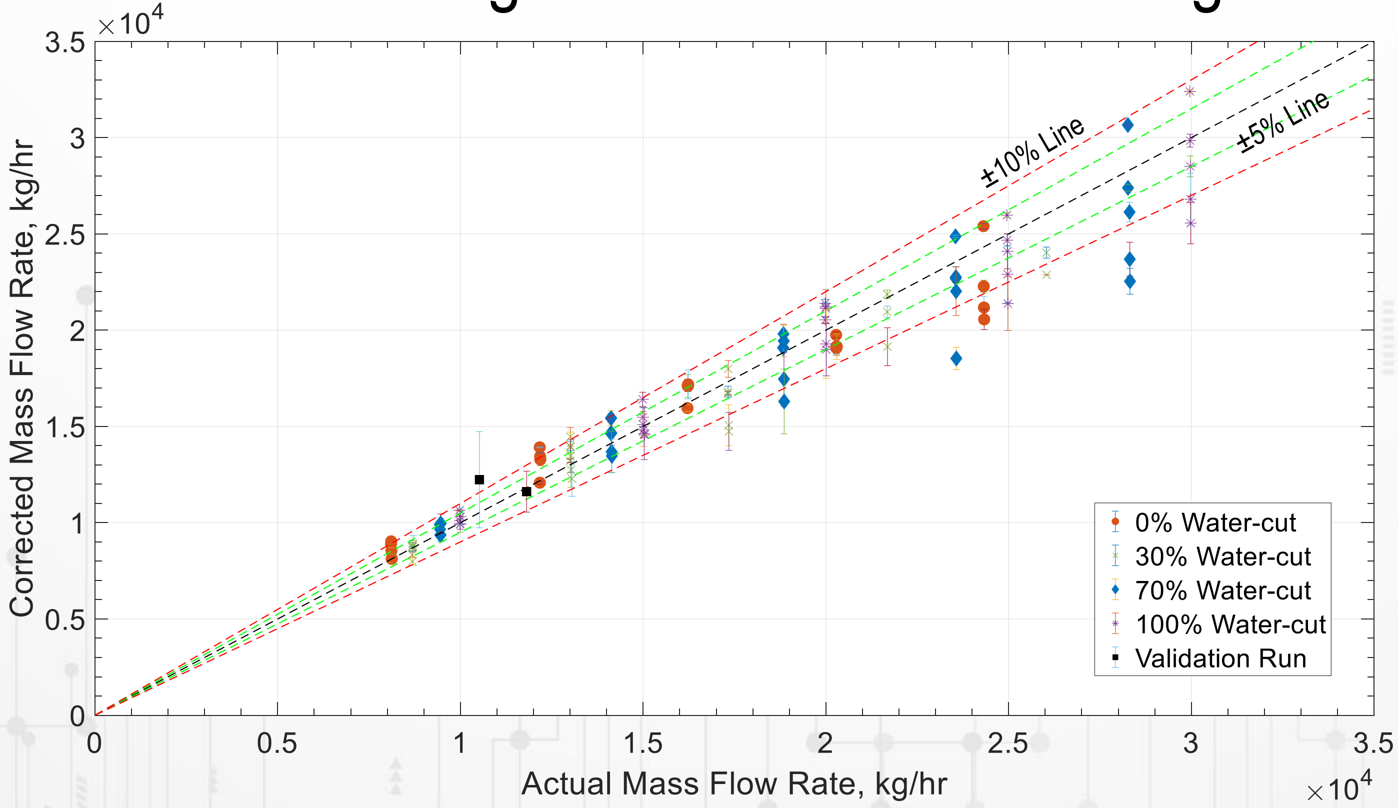
Error Modelling Results – GVF from Density

- Most points well within 5% GVF error
- Scatter in density measurement and flow loop uncertainty (2%) evident



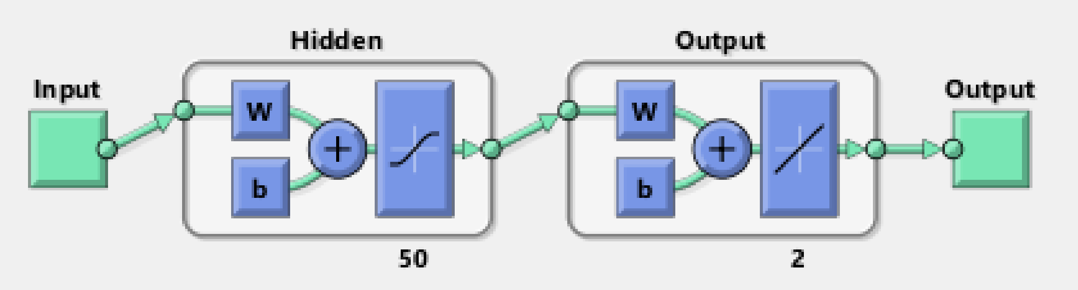
Error Modelling Results – Mass Flow Rate

- Significant reduction in original error possible
- Many points outside 10% range – effect of scatter in original flow rate & flow loop



Neural Network Modelling - Approach

Three inputs
1. Reported density
2. Reported mass flow rate
3. Water-cut



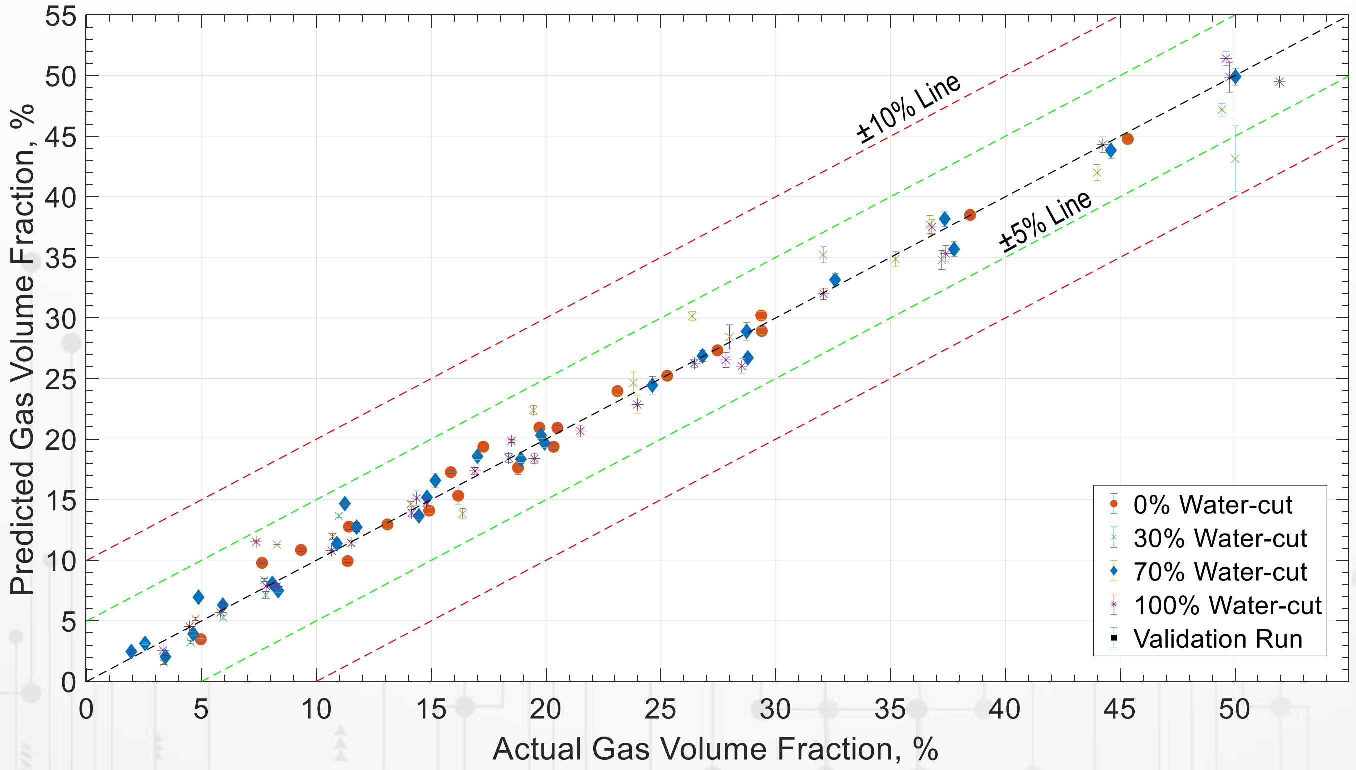
Two outputs
1. Gas volume fraction
2. Total mass flow rate

50 hidden layers
Bayesian regularization method

- Neural network setup identified by trial and error
- Bayesian regularization better for complex problems but takes time
- Levenberg-Marquardt faster but more suited for simpler problems

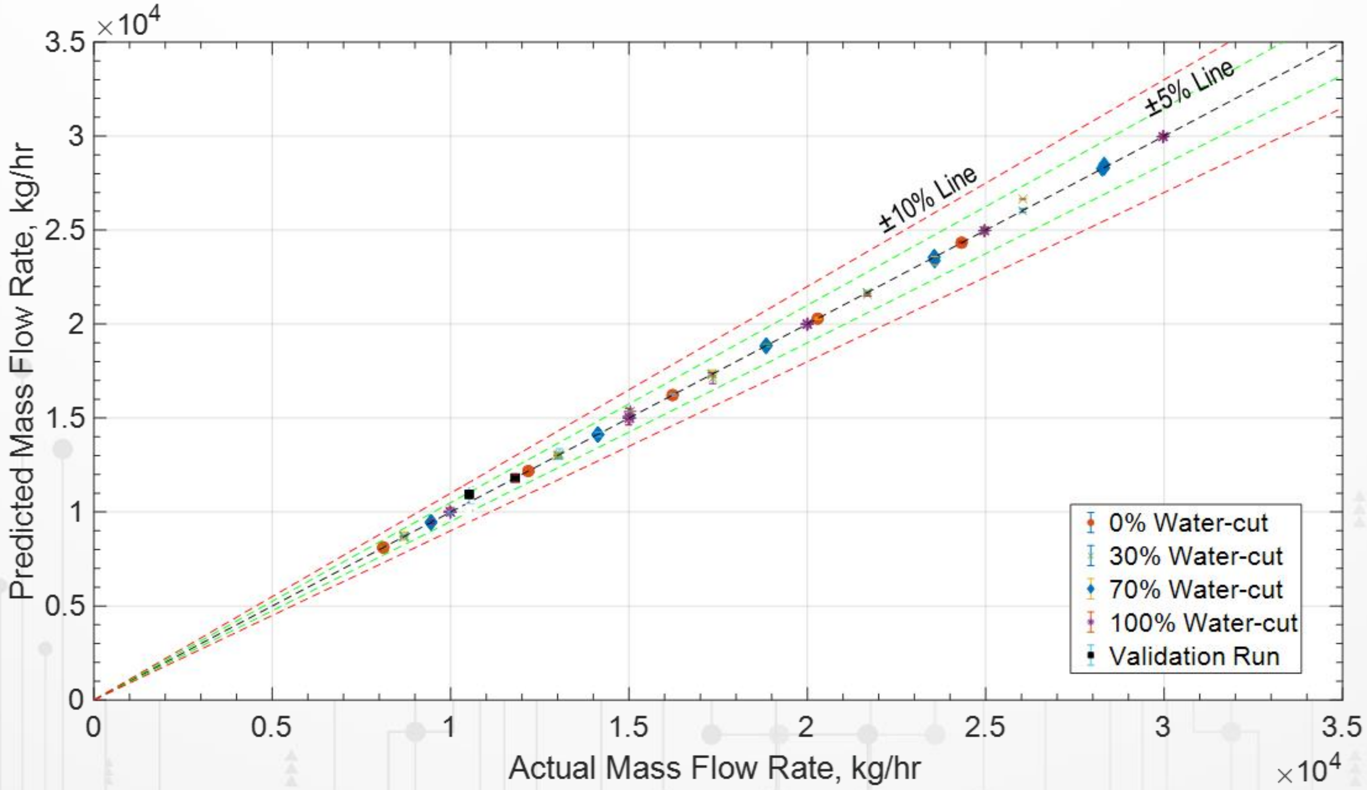
Neural Network Results – GVF

- Excellent model prediction – similar results to error modelling results
- Almost all predictions within 5% of actual GVF



Neural Network Results – Total Fluid Flow

- Excellent predictions from model –better than physics model
- Neural networks are data hungry – more data in training, better results



Conclusions

- Yokogawa Coriolis meter shows significant gas tolerance
- Meter density outputs are repeatable even under multiphase flow
- Higher scatter in mass flow rate under multiphase flow
- Physics based error models do help reduce error in measurements
- Neural network model performed better for mass flow rate corrections
- Machine learning methods are data hungry, need a large training set
- Potential to combine multiple methods to avoid pitfalls of each method

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Contact Us

Saketh Mahalingam

Aramco Overseas Company

Sakethraman.Mahalingam@aramcooverseas.com

Peter Weidemann

Yokogawa Rota GmBH

Peter.Weidemann@de.yokogawa.com

Dr. Lao Liyun

Cranfield University

L.Lao.@cranfield.ac.uk