Welcome!

The program will begin soon.

You will not hear audio until we begin.

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Webinars

Multiphase Flow Measurement Sensing Domains, Part 2: Mechanical Phenomena and Fluid Regimes

Robert Adams, Aramco Americas: Aramco Research Center – Houston

October 30, 2023

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Webinars

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Agenda

Webinars

1. Multiphase Flow Meters (MPFMs) for the Oil & Gas Industry
2. Sensing Domains Overview
3. Mechanical Sensing Domains
   i. Oil/Water/Gas Measurement Phenomena
   ii. Phase Fraction Measurement Techniques
   iii. Flow Rate Measurement Techniques
   iv. Flow Regime Dependence
4. Conclusions & Acknowledgments

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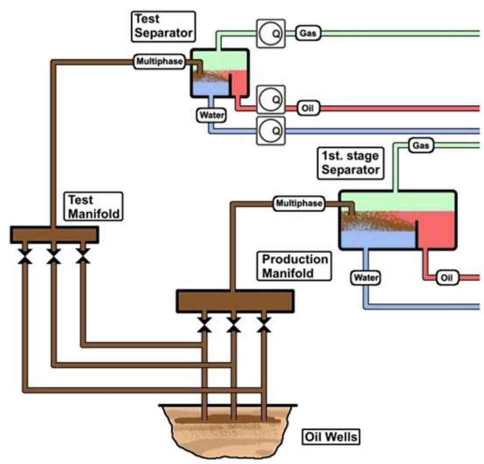
Multiphase Flow Background

Webinars

- Multiphase Flow Meters (MPFMs)
  - Continuous measurements of oil/water/gas flow rates
  - Augment or Replace test separators
  - Enhance production optimization & allocation
  - Decrease OPEX & HSE risk



"Handbook of Multiphase Metering, NFOGM"
https://nfogm.no/wp-content/uploads/2014/02/MPFM_Handbook_Revision2_2005_ISBN-82-91341-89-3.pdf

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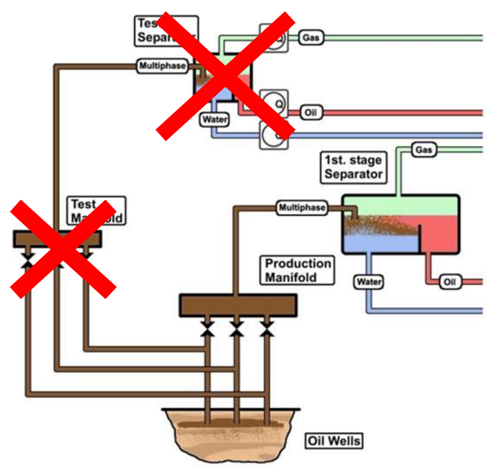

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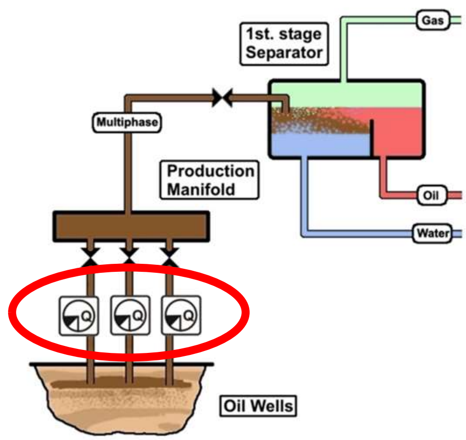

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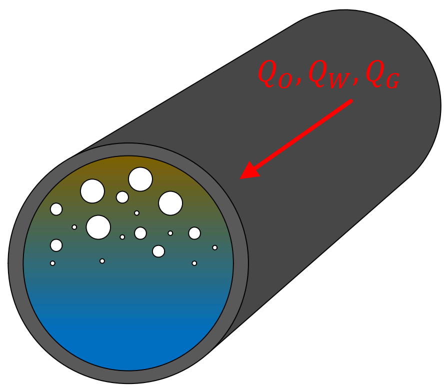
Multiphase Flow Background

- Flow rates of oil/water/gas
  - Three equations and three unknowns

$$Q_{TOT} = Q_O + Q_W + Q_G$$
$$S_1 = f_1(Q_O, Q_W, Q_G)$$
$$S_2 = f_2(Q_O, Q_W, Q_G)$$



Multiphase Flow Background

Webinars

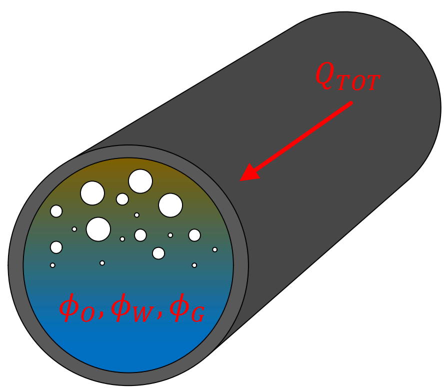
- Phase fractions of oil/water/gas and total flow rate
  - Four equations and four unknowns
  - Assumes no slip between phases

$$1 = \phi_O + \phi_W + \phi_G$$

$$S_1 = f_1(\phi_O, \phi_W, \phi_G)$$

$$S_2 = f_2(\phi_O, \phi_W, \phi_G)$$

$$Q_{TOT} = Q_{TOT} \cdot \phi_O + Q_{TOT} \cdot \phi_W + Q_{TOT} \cdot \phi_G$$



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Multiphase Flow Background

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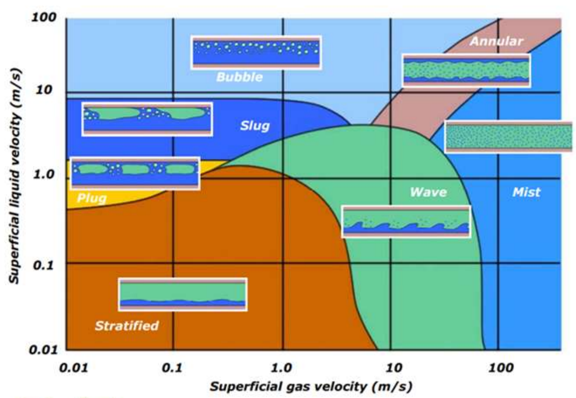
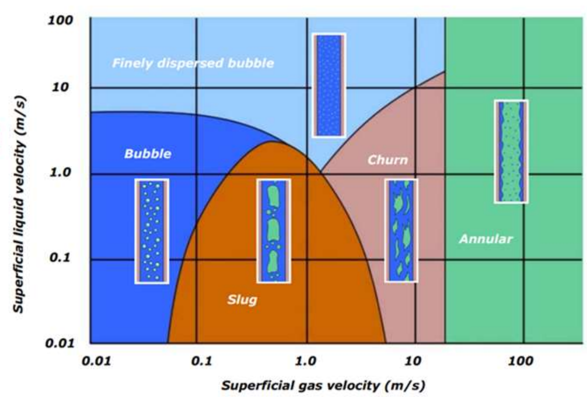
Horizontal Flow Regimes



Vertical Flow Regimes



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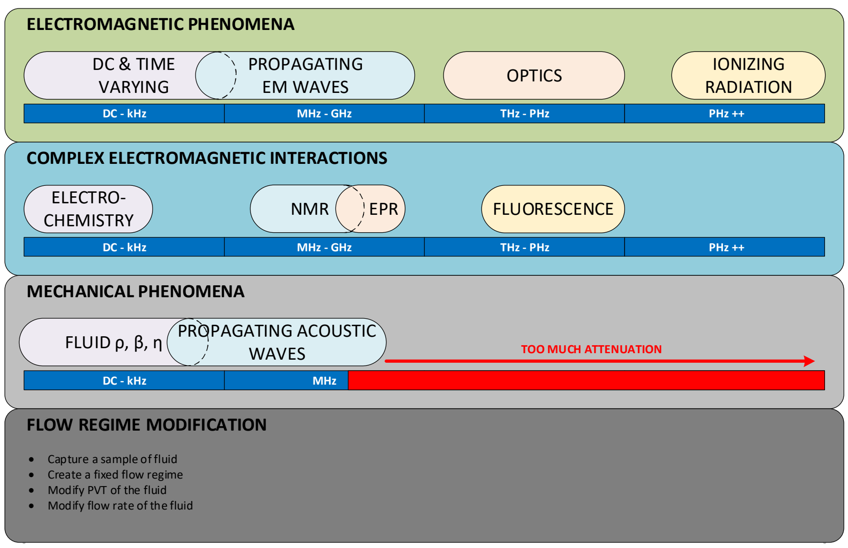
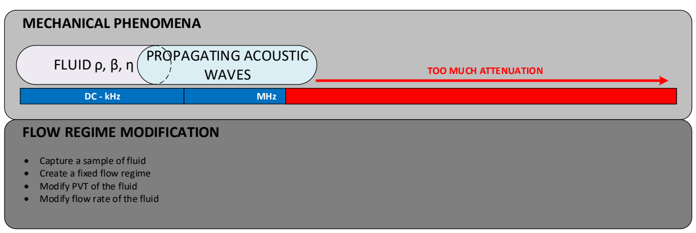
Multiphase Flow Sensing Domains



Overview of Mechanical Phenomena

- Part 2 will focus on Mechanical phenomena and Fluid Regimes
- Progress thru the mechanical sensing spectrum from low frequency to high frequency
- Measurement examples from each domain that can be used in MPFM systems to discriminate phase fractions and flow rates



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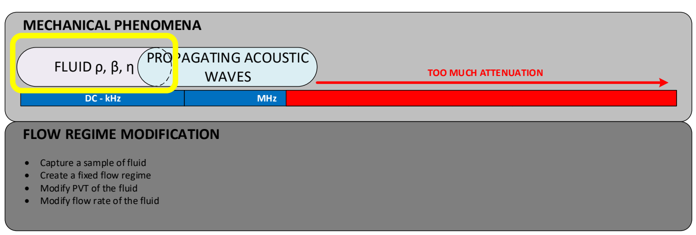

Mechanical Properties of Fluid Phases

- Primary mechanical phenomena to discriminate oil/water/gas
  - Density (ρ), viscosity (η), compressibility (β)

Mechanical Properties of Fluid Phases

Webinars

- Primary mechanical phenomena to discriminate oil/water/gas
  - Density (ρ), viscosity (η), compressibility (β)
  - Oil density varies with API
  - Water density varies with salinity

ρ_G ρ_O ρ_W

≈ 0 $[0.7 - 1.0]$ $[1.0 - 1.2] g/cc$

$$\boxed{\rho_M = \phi_O \cdot \rho_O + \phi_W \cdot \rho_W + \phi_G \cdot \rho_G}$$

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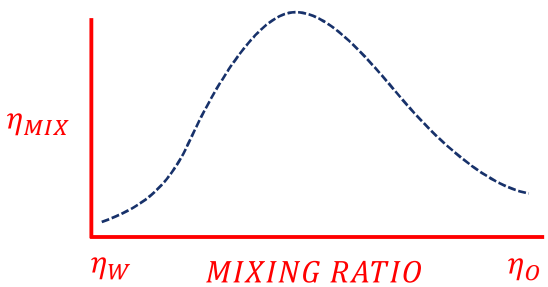
Mechanical Properties of Fluid Phases

- Primary mechanical phenomena to discriminate oil/water/gas
  - Density (ρ), viscosity (η), compressibility (β)
  - Oil viscosities vary wildly
  - Emulsifications, foams, temperature



Mechanical Properties of Fluid Phases

Webinars

- Primary mechanical phenomena to discriminate oil/water/gas
  - Density (ρ), viscosity (η), compressibility (β)
  - Differentiate gas from liquids

β_O, β_W $\qquad\qquad\qquad$ β_G

$\leq 5 \times 10^{-10}$ $\qquad\qquad\qquad$ $\sim 10^{-5}\, m^2/N$

$$\boxed{\beta_M = \frac{V_M}{\left(\frac{V_O}{\beta_O} + \frac{V_W}{\beta_W} + \frac{V_G}{\beta_G}\right)}}$$

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Mechanical Properties of Fluid Phases

- Primary mechanical phenomena to discriminate oil/water/gas
  - Density (ρ), viscosity (η), compressibility (β)

$$1 = \boxed{\phi_G} + \phi_{W+O}$$

$$\rho_M = f(\phi_G, \phi_{W+O})$$

$$\beta_M = f(\phi_G, \phi_{W+O})$$

$$\eta_M = ???$$

ρ_G ≈ 0 — ρ_O $[0.7 - 1.0]$ — ρ_W $[1.0 - 1.2]\,g/cc$

β_O, β_W $\leq 5 \times 10^{-10}$ — β_G $\sim 10^{-5}\, m^2/N$

$$\boxed{\rho_M \not\perp \beta_M}$$

Equivalent System Model

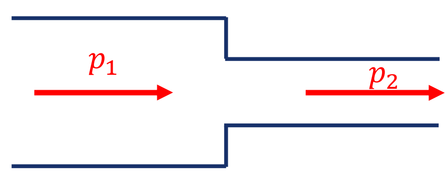
- Deeper understanding of mechanical phenomena of fluids with equivalent system model

Equivalent System Model

Webinars

- Deeper understanding of mechanical phenomena of fluids with equivalent system model
  - Hydraulic resistance (R)

$$\boxed{R = \frac{p_1 - p_2}{Q}} \Rightarrow \boxed{Q = \frac{p_1 - p_2}{R}}$$



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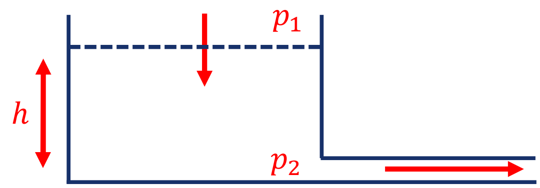
Equivalent System Model

Webinars

- Deeper understanding of mechanical phenomena of fluids with equivalent system model
  - Hydraulic resistance (R)
  - Hydraulic capacitance (C)

$$\boxed{C = \frac{A}{\rho g}} \Rightarrow \boxed{Q = \frac{C \cdot d(p_1 - p_2)}{dt}}$$



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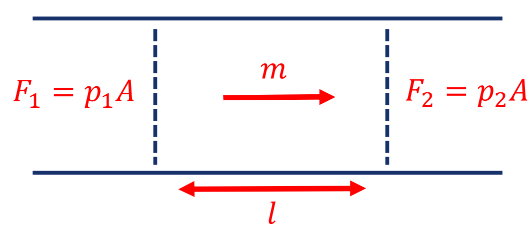
Equivalent System Model

- Deeper understanding of mechanical phenomena of fluids with equivalent system model
  - Hydraulic resistance (R)
  - Hydraulic capacitance (C)
  - Hydraulic inertance (L)

$$\boxed{L = \frac{l \cdot \rho}{A}} \Rightarrow \boxed{Q = \frac{L}{l} \int (p_1 - p_2) dt}$$



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Equivalent System Model

Webinars

- Deeper understanding of mechanical phenomena of fluids with equivalent system model
  - Hydraulic resistance (R)
  - Hydraulic capacitance (C)
  - Hydraulic inertance (L)
  - Density, compressibility, and viscosity

$$\boxed{Q = \frac{p_1 - p_2}{R}}$$

$$\boxed{Q = \frac{C \cdot d(p_1 - p_2)}{dt}}$$

$$\boxed{Q = \frac{L}{l} \int (p_1 - p_2) dt}$$

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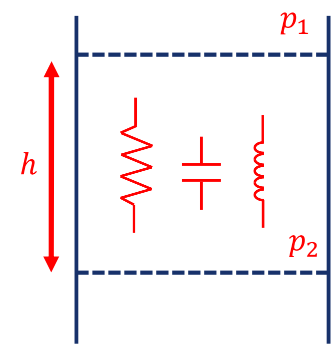
Phase Sensing, Density

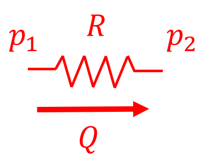
- Density is the most straightforward measurement
  - Pressure gradient, known cross-section
- Complications when fluid is flowing
  - Frictional losses (R)
  - Fluid reactance (C,L)
  - Flow regime

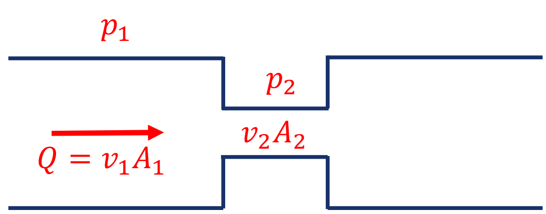
$$\boxed{\rho_M = f(p_1 - p_2)}$$



Flow Sensing, Pressure Drop

- Venturi meters, orifice meters, etc. operate off the same principle
  - Pressure drop is a function of fluid flow rate, density
  - Range of measurement, minimize disturbance in PVT





Flow Sensing, Pressure Drop

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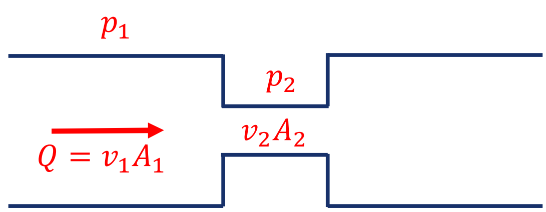
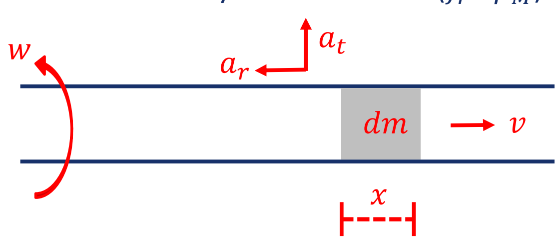
$$\boxed{Q = A_1 \sqrt{\frac{2}{\rho_M} \cdot \frac{p_1 - p_2}{\left(\frac{A_1}{A_2}\right)^2 - 1}}}$$



Flow and Phase Sensing, Coriolis Meter

Webinars

- Coriolis effect
  - Induce rotation in a pipe, deflecting force generated by Coriolis effect
    - Function of mass flow rate of fluid ($\dot{m}$)
  - Resonant frequency of tube due to pipe geometry and fluid loading
    - Function of density of fluid in tube ($f_r \sim \rho_M$)



$$\boxed{F_c = 2wv(dm)}$$

$$\boxed{\dot{m} = F_c/(2wx)}$$

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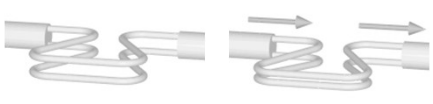
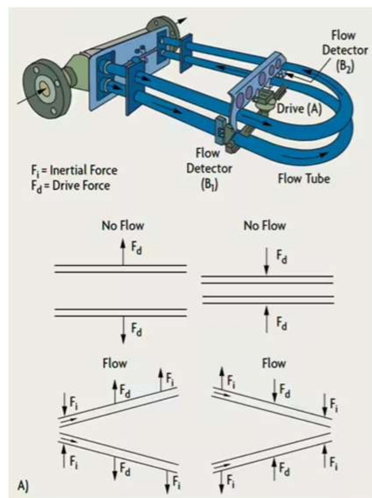
Flow Sensing, Coriolis Meter

- Typical Coriolis design:
  - Vibrate two parallel flow tubes
  - Measure dynamic strain at tube bends
    - Resonant frequency => ρ_M
    - Phase difference => $\dot{m}$
- Gas effect, unconstrained solution



https://en.m.wikipedia.org/wiki/Mass_flow_meter



https://www.omega.com/en-us/resources/what-is-a-coriolis-flow-meter

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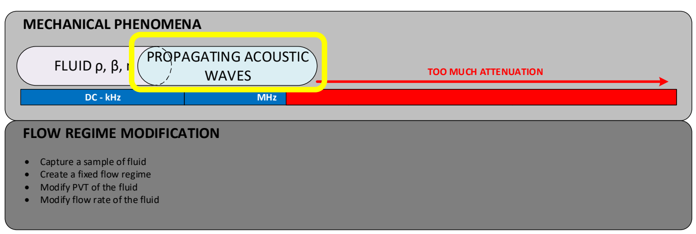
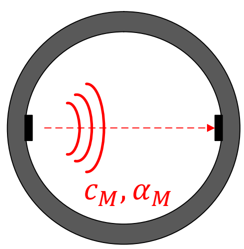
Overview of Mechanical Phenomena

- Propagating acoustic waves
  - Classical fluid properties (low freq.) to propagating waves (ultrasonics, etc.)
  - Frequency range spans $\sim 1kHz$ to $\sim 10MHz$



Propagating Acoustic Wave Phenomena

- In this frequency range, acoustic waves propagate through the fluid
  - Take advantage of different physics to measure fluid properties
  - Phase fractions are quantified by acoustic wave properties, e.g. media velocity and attenuation
  - Issues with phase fractions, e.g. non-unique solutions for mixture properties



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Acoustic Wave Properties

- Acoustic waves propagate through media with some sound speed (c)
  - Sound speed varies with different fluids and mixtures
- The amplitude rolls off exponentially with some attenuation coefficient (α)
  - Attenuation varies with different fluids and mixtures
  - Scales with frequency squared

$$\boxed{P \approx P_0 e^{-\alpha \cdot x} e^{j\left(\omega t - \frac{\omega}{c} \cdot x\right)}}$$

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$$\boxed{P \approx P_0 e^{-\alpha \cdot x} e^{j\left(\omega t - \frac{\omega}{c} \cdot x\right)}}$$

$$\boxed{c = \sqrt{1/\beta\rho}}$$

$$\boxed{c_M \approx \frac{\phi_G}{c_G} + \frac{\phi_O}{c_O} + \frac{\phi_W}{c_W}}$$

c_G c_O c_W

≈ 343 $[1200 - 1500]$ $[1480 - 1600] m/s$

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Acoustic Wave Properties

Webinars

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  - Scales with frequency squared

$$\boxed{P \approx P_0 e^{-\alpha \cdot x} e^{j\left(\omega t - \frac{\omega}{c} \cdot x\right)}}$$

$$\boxed{\alpha = f(f^2, \rho, \beta, \eta)}$$

$$\boxed{\alpha_M = ???}$$

α_W / f^2 $\approx 10^{-14}$

α_O / f^2 $\approx 10^{-13}$

α_G / f^2 $\approx 10^{-11}\ Np \cdot s^2/m$

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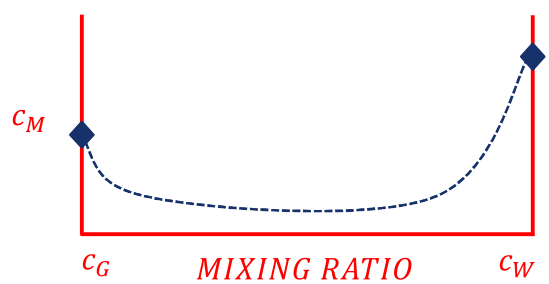
Acoustic Wave Properties

- Less than ideal properties:
  - Gas + liquid sound speed mixtures have non-unique solutions
  - Acoustic impedance, bubble resonance, gas scattering



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Acoustic Wave Properties

Webinars

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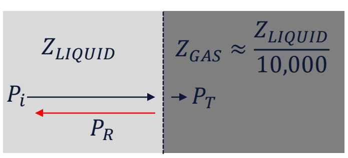
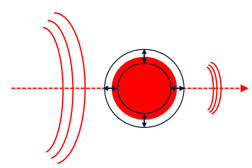
Acoustic Impedance



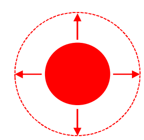
$$\frac{P_T}{P_i} = \frac{2 \cdot Z_{GAS}}{Z_{GAS} + Z_{LIQUID}} \approx 5 \times 10^{-4}$$

Bubble resonance



$$[100, 1000]kHz \approx [30, 3]\mu m$$

Scattering cross-section



$$\sigma_s \sim 4\pi r^2$$

4x larger than geometric cross-section!

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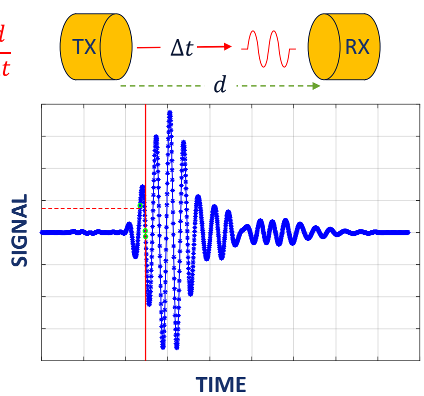
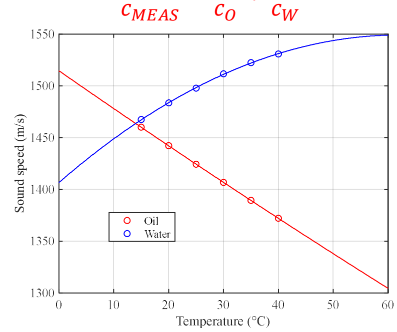
Flow and Phase Sensing, Ultrasonics

- Transmit ultrasonic wave, receive at some distance away
- Infer sound speed from travel time

$$c_{MEAS} = \frac{d}{\Delta t}$$

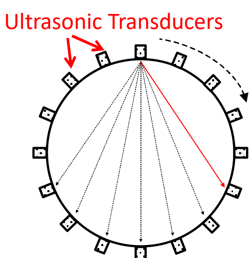


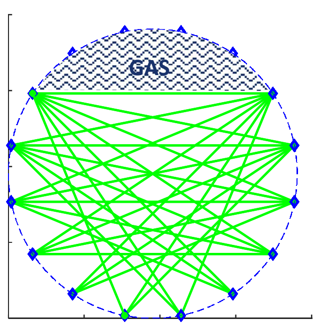
$$\frac{1}{c_{MEAS}} = \frac{\emptyset_O}{c_O} + \frac{\emptyset_W}{c_W}$$

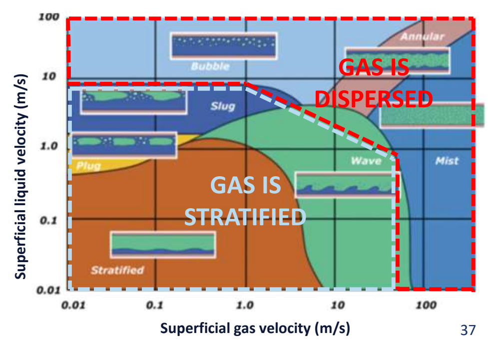


Flow and Phase Sensing, Ultrasonics

- Tomographic imaging as another independent measurement
  - Image bubbles based on reflections or lack of path response
  - Flow regime dependence







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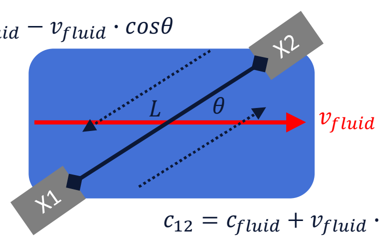
Flow and Phase Sensing, Ultrasonics

- Acoustic methods to directly measure flow:
  - Differential travel time
  - Backscatter/Doppler effect

$$c_{21} = c_{fluid} - v_{fluid} \cdot cos\theta$$



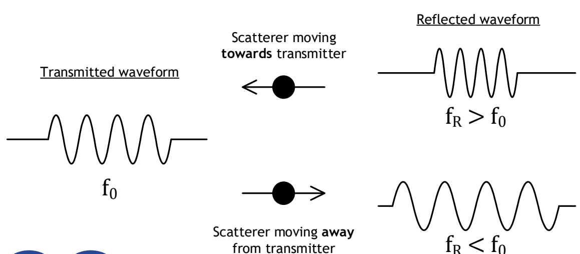
$$c_{12} = c_{fluid} + v_{fluid} \cdot cos\theta$$

$$\boxed{v_{fluid} = \left(\frac{L}{2cos\theta}\right)\left(\frac{t_{21} - t_{12}}{t_{12} \cdot t_{21}}\right)}$$

$$\boxed{c_{fluid} = \left(\frac{L}{2}\right)\left(\frac{t_{21} + t_{12}}{t_{12} \cdot t_{21}}\right)}$$

Flow and Phase Sensing, Ultrasonics

- Acoustic methods to directly measure flow:
  - Differential travel time
  - Backscatter/Doppler effect



$$v_{fluid} = -\frac{(f_R - f_0) \cdot c_{fluid}}{2 \cdot f_0 \cdot cos\theta}$$

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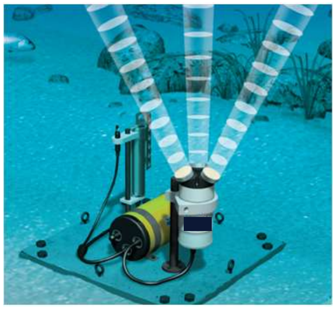
Flow and Phase Sensing, Ultrasonics

- Acoustic methods to directly measure flow:

System utilizing differential travel time to measure 3D flow profiles

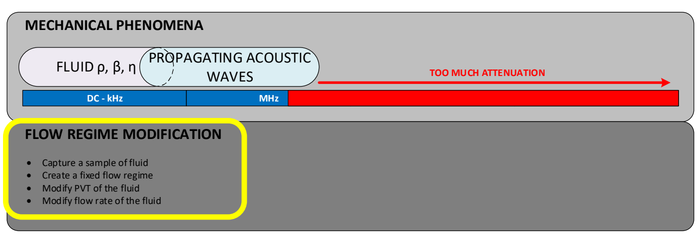
System utilizing acoustic backscatter to measure 3D flow profiles



https://www.sontek.com/media/pdfs/adp-brochure.pdf

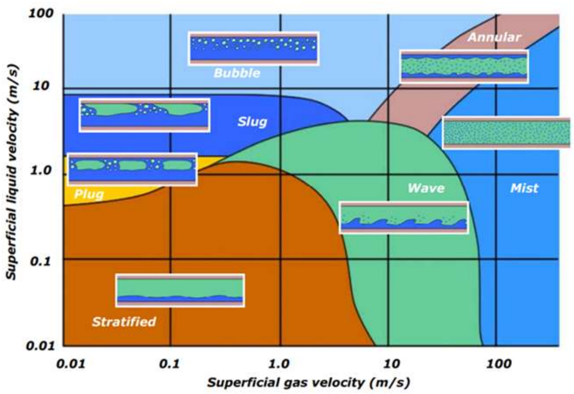
Overview of Mechanical Phenomena

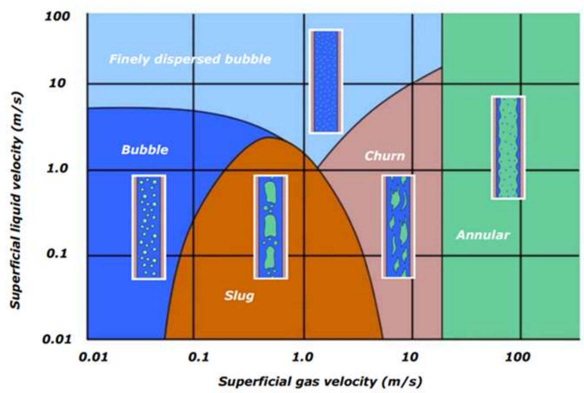
- Flow regime modification
  - Forcing a particular horizontal or vertical flow regime
  - Capturing fluid samples, modifying flow rates or PVT properties



Fixed Flow Regime

- Measurement advantages with specific flow regimes





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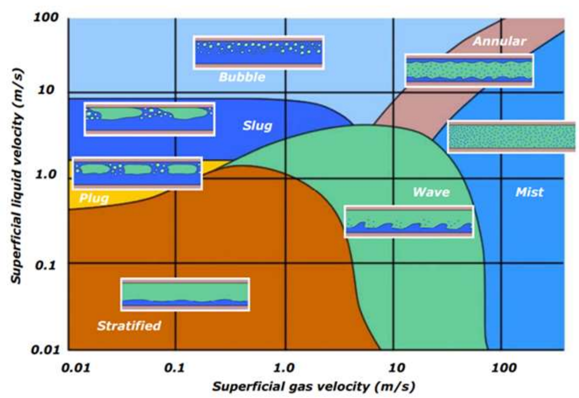
Fixed Flow Regime, Modify PVT

- Homogeneous mixing of fluid
  - No slip, fluids at same velocity
  - Mixing laws apply
- Gravity separation
- Slugs, plugs, stratification
  - Acoustic wave reflection off interfaces

Horizontal Flow Regimes



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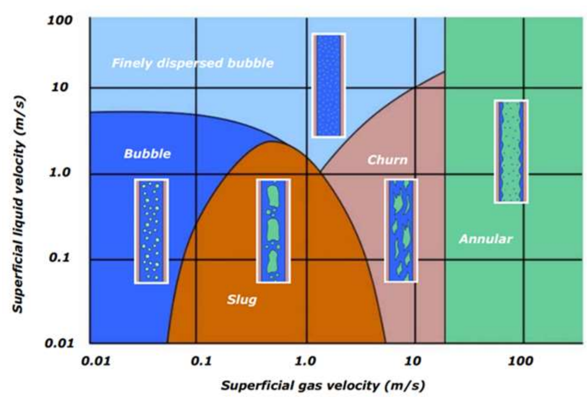
Fixed Flow Regime, Modify PVT

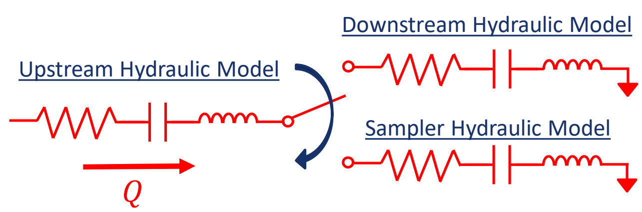
- Homogeneous mixing of fluid
  - No slip, fluids at same velocity
  - Mixing laws apply
- Bubbles -> slugs -> churn
  - Counting discrete bubbles
  - Stokes velocity
- Hydrostatic gradient

Vertical Flow Regimes

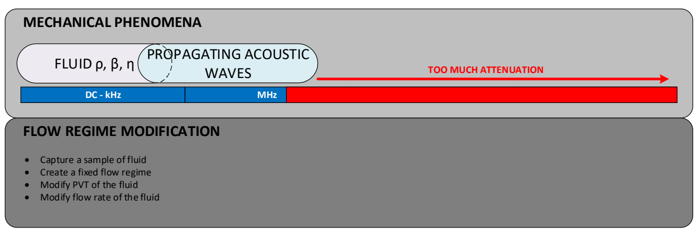


Capturing Fluid Samples

- Piston sampling meters: time to fill + fixed volume == flow rate
  - Errors come from:
    - Valve operating time, Static + dynamic friction of sampler
    - Multiphase flow – sampler can change equivalent impedance of fluid, distorts the dynamics of oil/water/gas flow

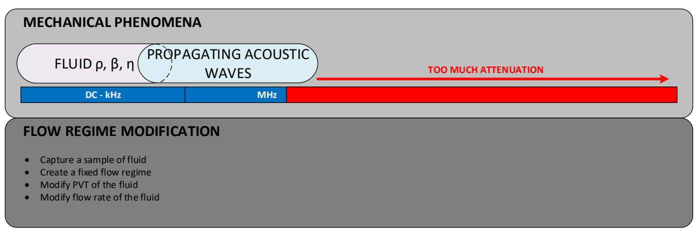


Conclusion & Acknowledgements



- Large variety of mechanical phenomena to measure phase fractions and flow rates
- Need other measurements of fluid that are orthogonal to mechanical properties to fully solve mixed multiphase flow
- This is not a complete list!

Conclusion & Acknowledgements



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  - SPE Flow Measurement Technical Section

Webinars

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