Monitoring Multiphase Flow via Earth's Field Nuclear Magnetic Resonance

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Fluid Science & Resources

www.fsr.ecm.uwa.edu.au/

Motivation for research

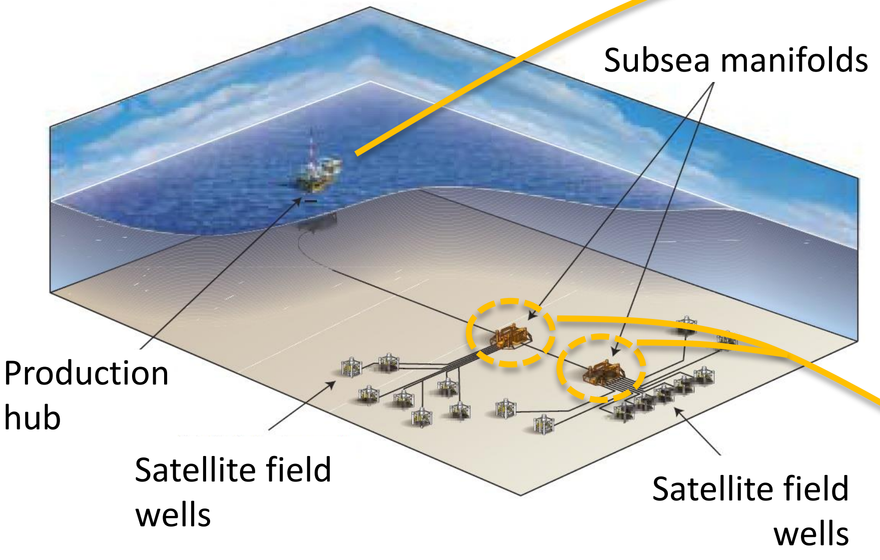
The future of oil and gas production

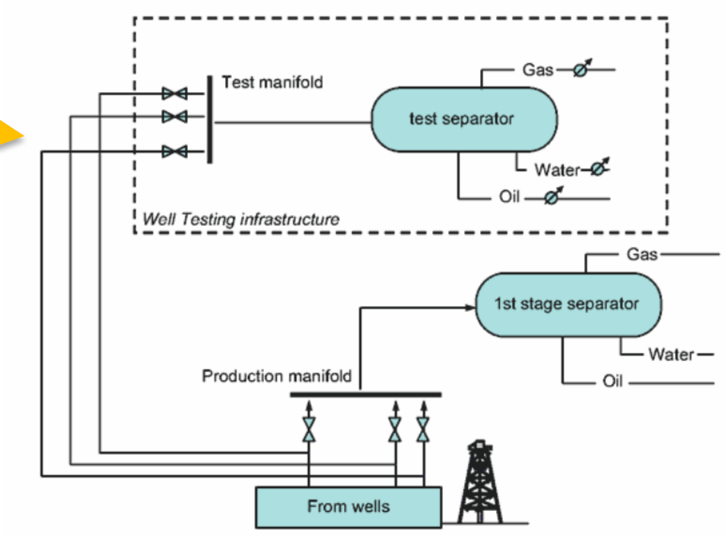
- Development of deeper offshore fields and marginal fields
- Increased produced water
- Increased subsea processing

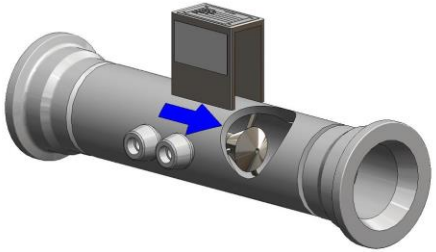
Objectives of flow metering

- Measurement of phase fractions
- Measurement of phase velocities
- Flow regime identification

Subsea production arrangement

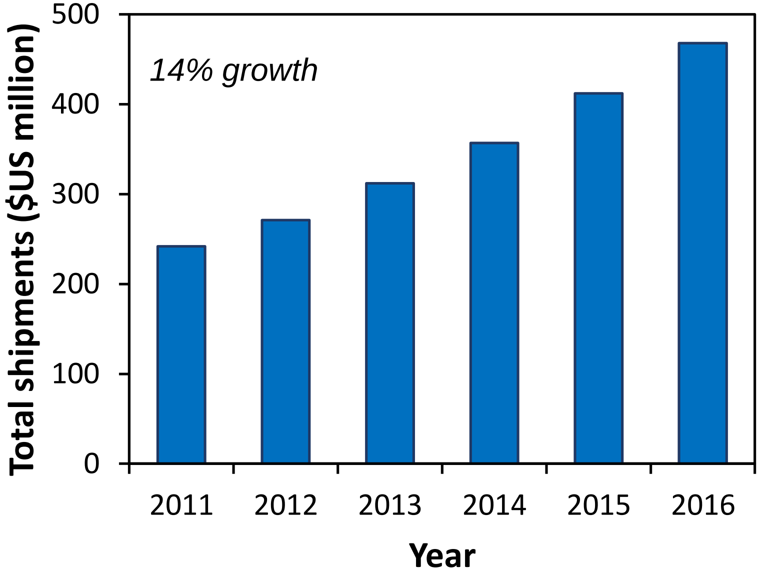






Atkinson, I., et al., A New Horizon in Multiphase Flow Measurement. Oilfield Review, 2004. 16(4): p. 52-63

World Multiphase flow meter market

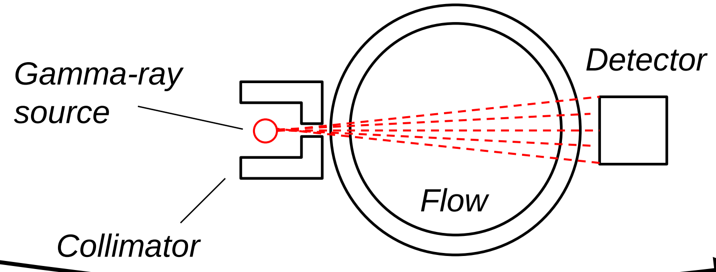


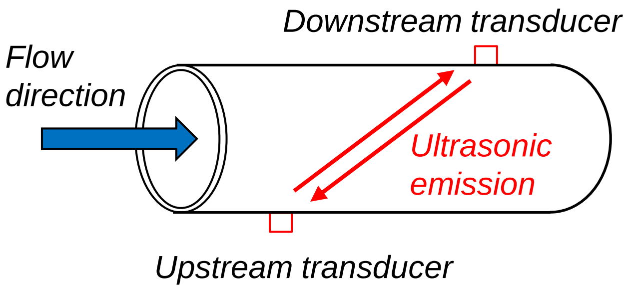
J. Yoder, The many phases of multiphase flowmeters, Pipeline & Gas Journal, 240 (2013) 40-41

Multiphase flow meter technologies

Common measurement principles

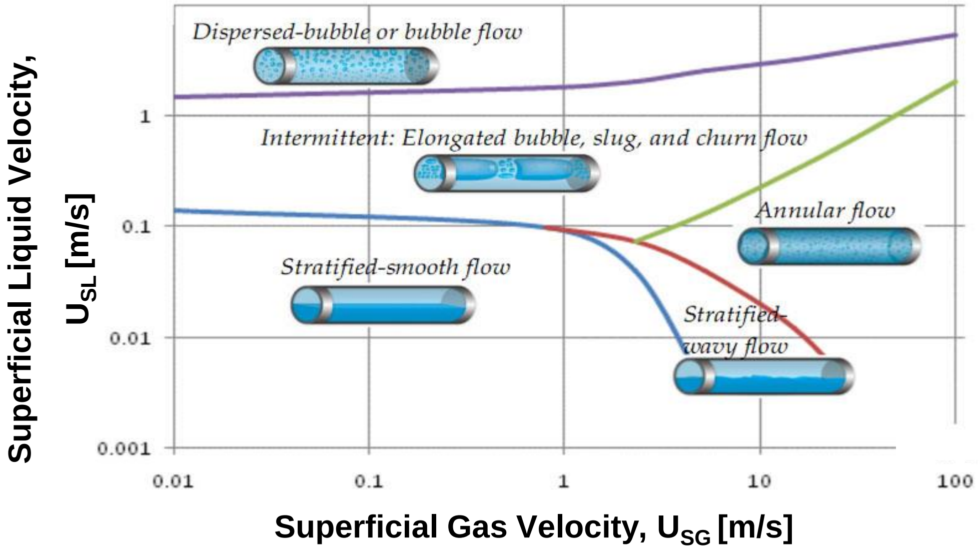
- Gamma ray attenuation
- Electrical impedance measurement
- Ultrasonic measurement systems





Advantages of nuclear magnetic resonance

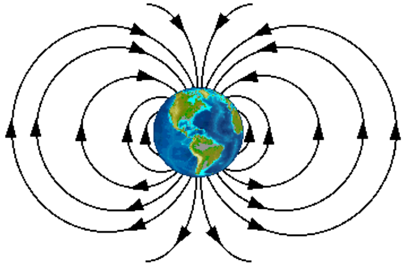
- Non-invasive measurement
- Non-radioactive technology
- Flow regime independent



Commercial magnetic resonance flowmeter: M-Phase 5000

Nuclear magnetic resonance

Summary of nuclear magnetic resonance (NMR) magnetic field strengths

Earth's field NMR	Well-logging tool	Magnetic resonance imaging	Chemical spectroscopy
			

Ultra-low field — *Low field* — *High field*

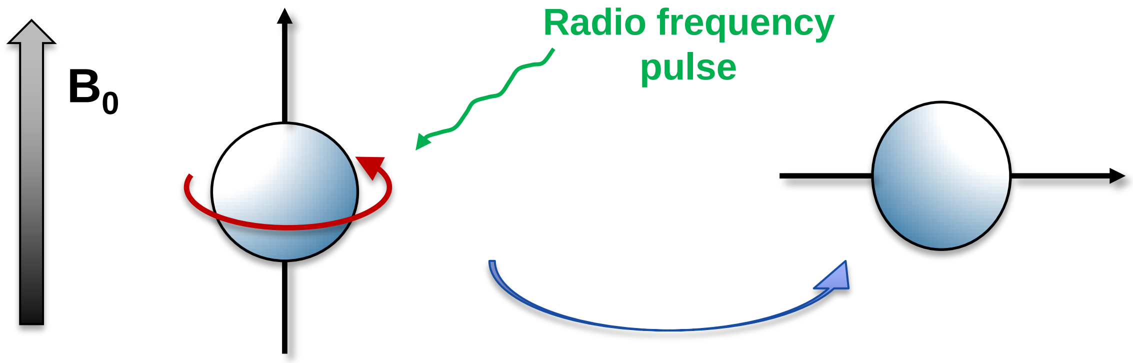
50 µT — 50 mT — 7 T

Nuclear magnetic resonance

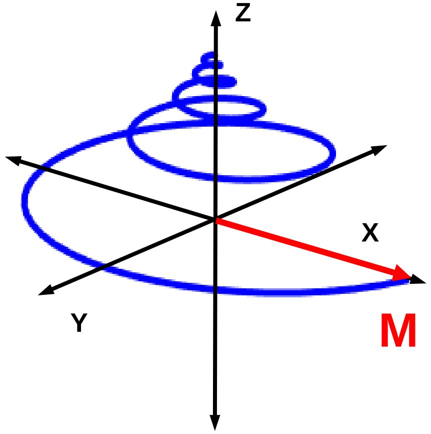
Basic classical mechanics description

1. Align nuclei ([1]H atoms) with magnetic field (polarisation)

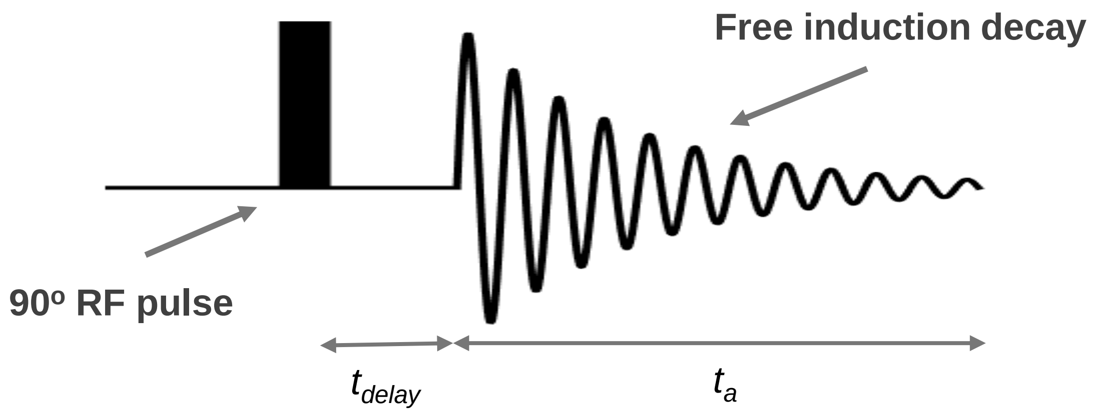
2. Apply radio frequency pulse



3. Observe the magnetisation relax



Pulse and Collect Experiment

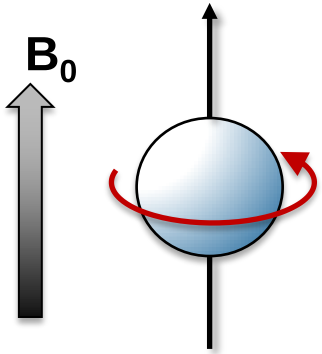


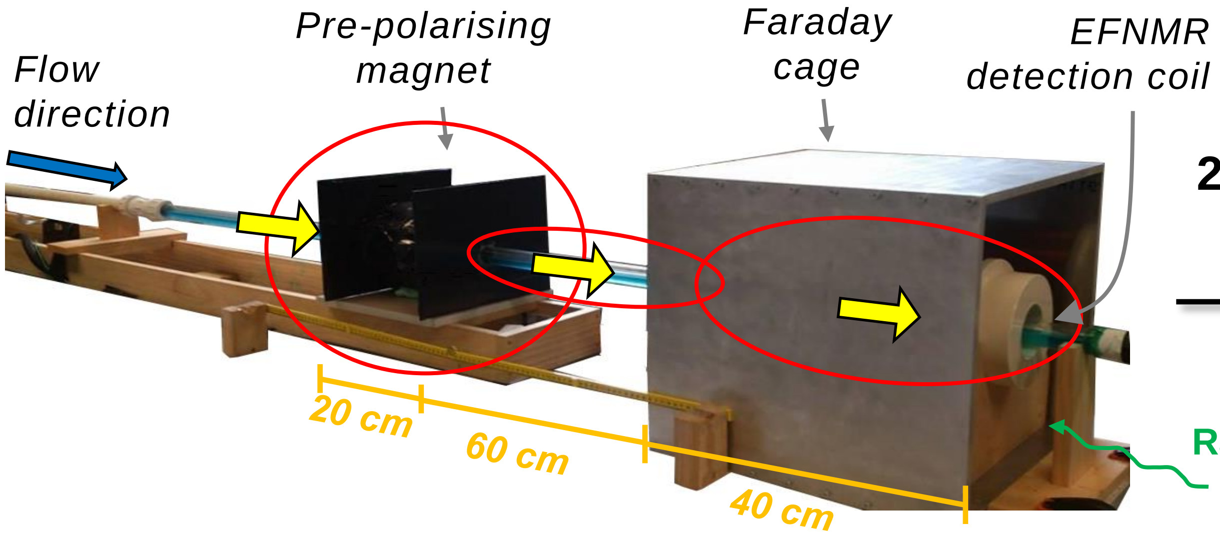
The Earth's field NMR flow meter

Key system features

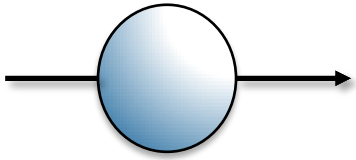
- Detected in the Earth's magnetic field
- Time of flight measurement
- Remote detection system

1. Polarisation



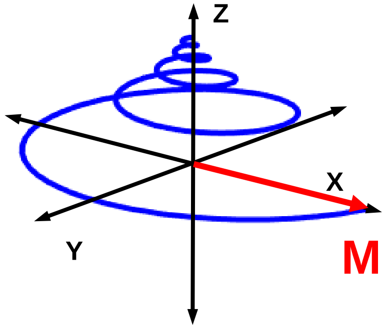


2. Excitation

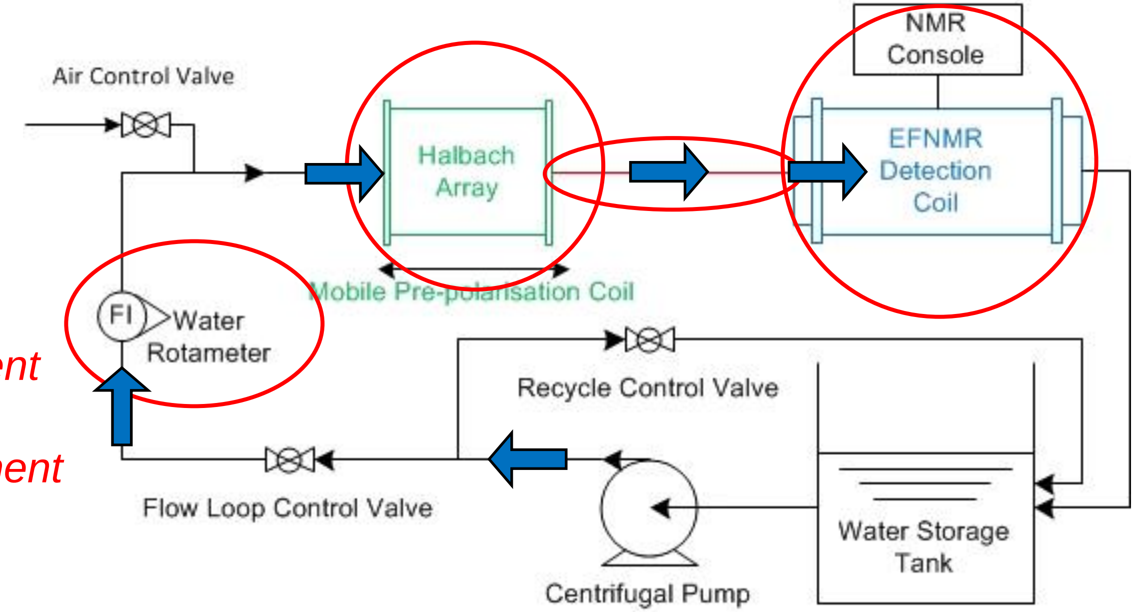


Radio frequency pulse

3. Detection



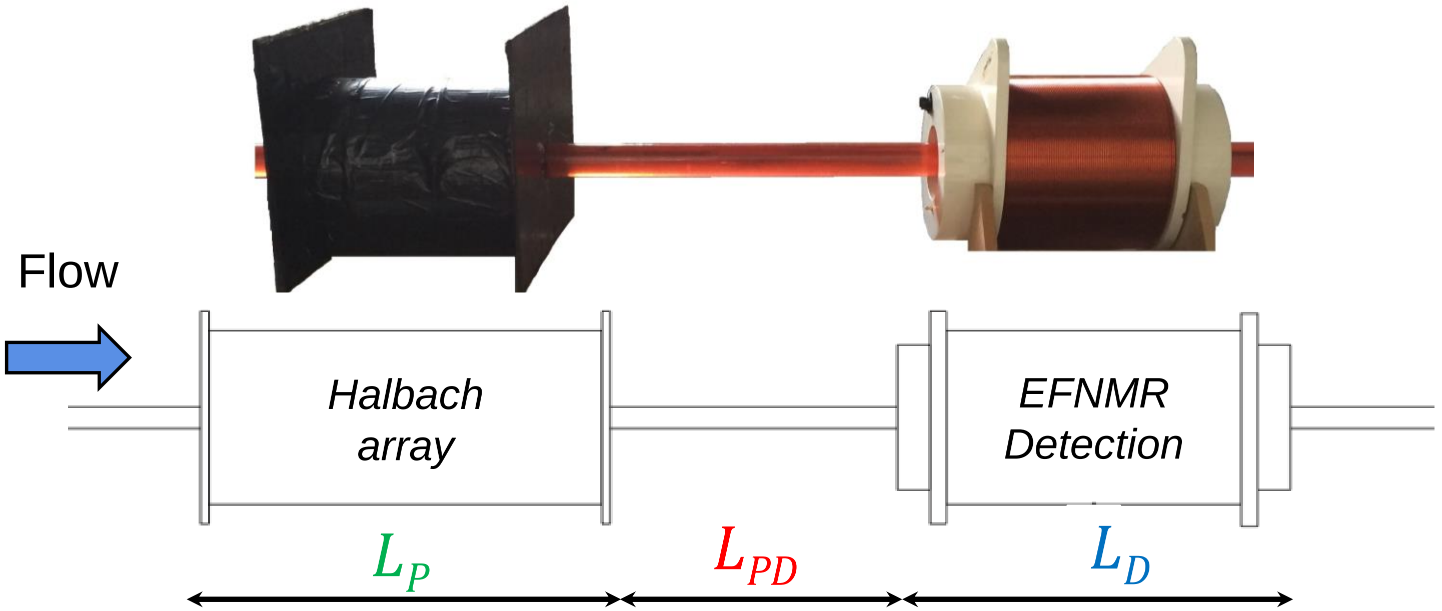
Independent flowrate measurement



EFNMR: Earth's field nuclear magnetic resonance

Model for NMR signal

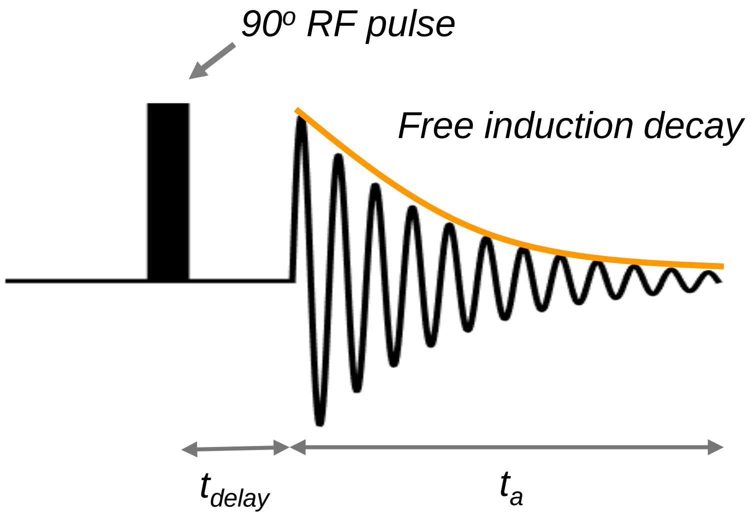
Polarisation **Intermediate decay** **Detection**



$$\tau_{PD} = \frac{L_{PD}}{v} \qquad \tau_{PD} = \frac{L_{PD}}{v} \qquad \tau_D = \frac{L_D}{v}$$

$$\mathbf{S}(v, t_a) = S_0\left(1 - e^{-\frac{\tau_P}{T_1}}\right) e^{-\frac{\tau_{PD}}{T_1}} \left(1 - \frac{t_{delay} + t_a}{\tau_D}\right) e^{-\frac{t_{delay}+t_a}{T_2^*}}$$

Pulse and Collect Sequence



Parameters

L: length
τ: residence time
v: velocity
S_0: initial magnetization
T_1: spin-lattice relaxation
T_2^*: observed spin-spin relaxation

Tikhonov Regularisation

The inverse problem

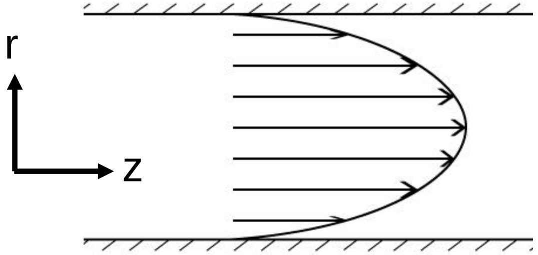
$$\mathrm{A} \times \mathrm{P}(v) = \mathrm{S} \quad \rightarrow \quad \mathrm{P}(v) = \mathrm{A}^{-1} \times \mathrm{S}$$

Model transfer matrix

Velocity probability distribution

NMR Signal

Pipe velocity distribution



Tikhonov regularisation

- Least squares fitting method
- Allows complex models to be fit to experimental data

Real image

Image with noise

Reconstructed image

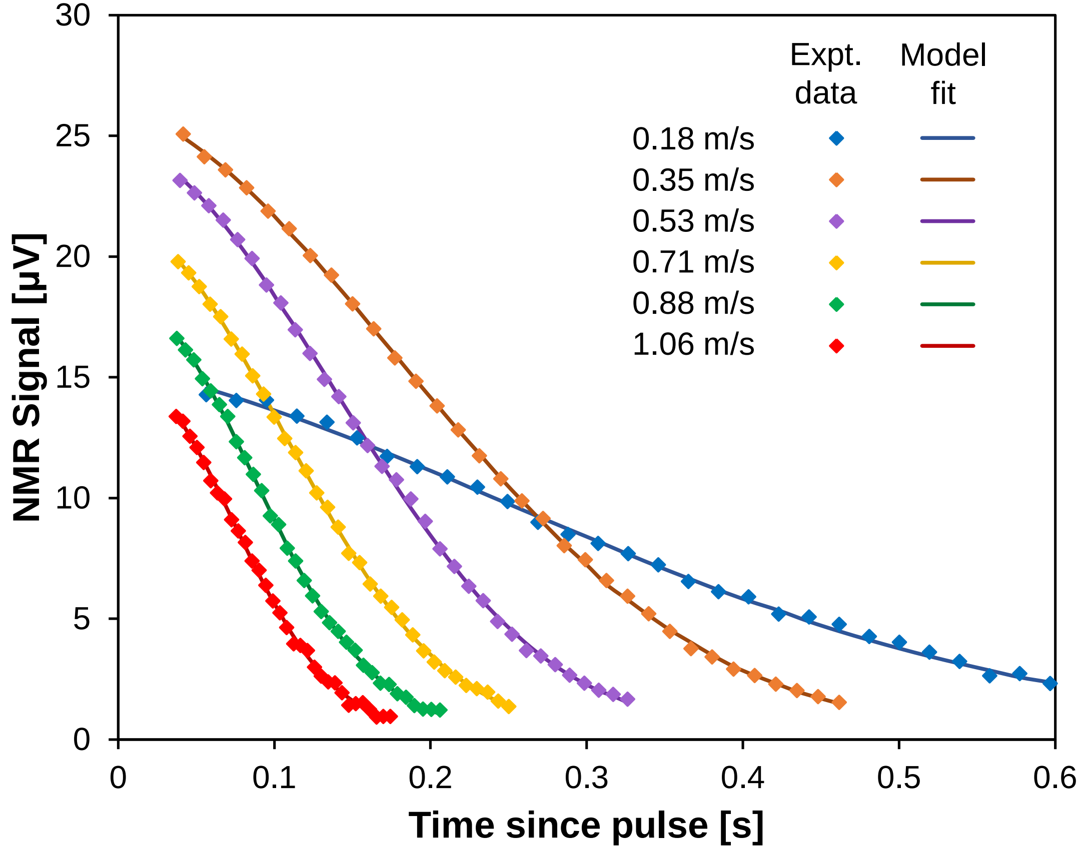
M. Bertero and P. Boccacci, Introduction to inverse problems in imaging. 1998, CRC Press.

Single phase velocity analysis

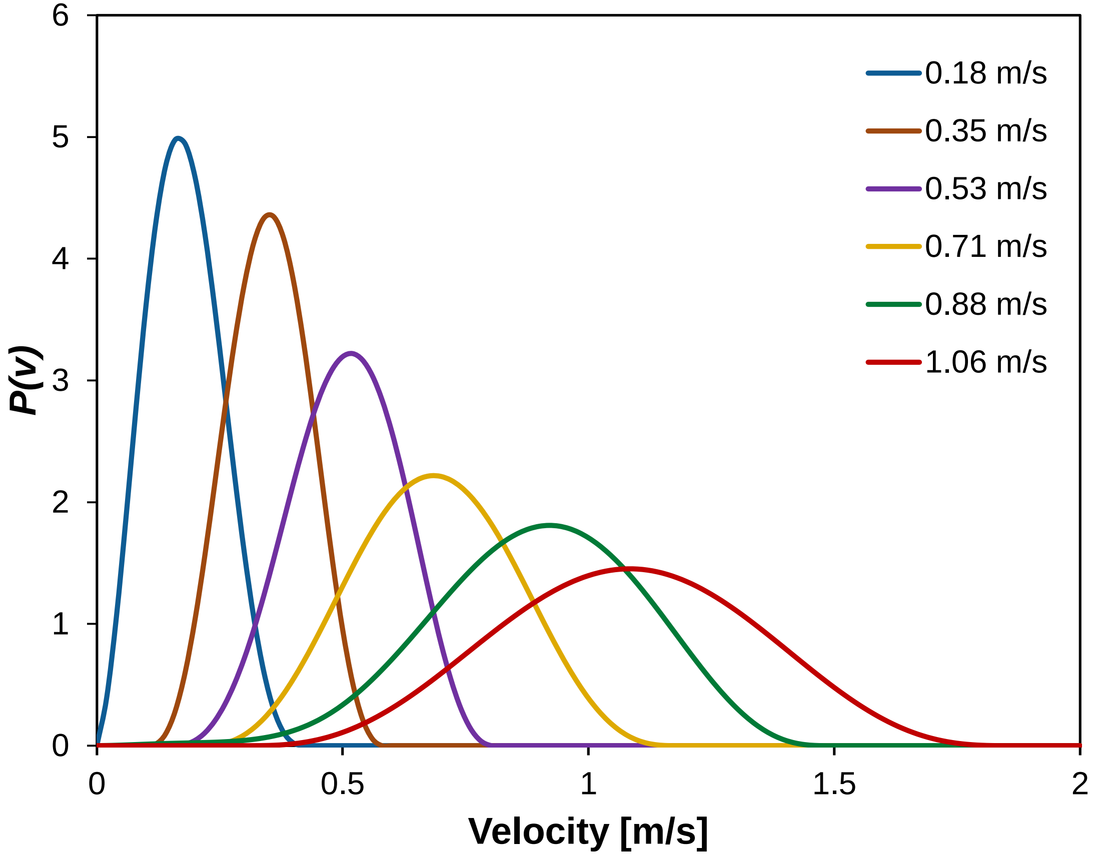
Experimental conditions

Single phase water flows at 4 – 52 L/min (0.08 – 1.15 m/s)

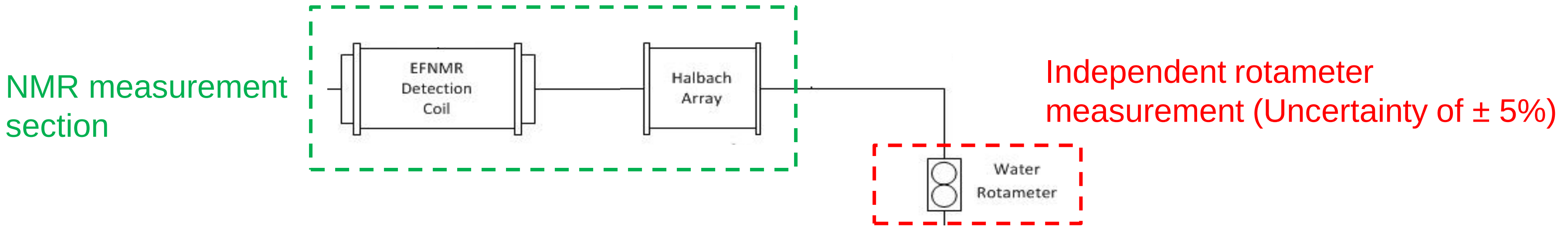
Experimental NMR signals fit using regularisation

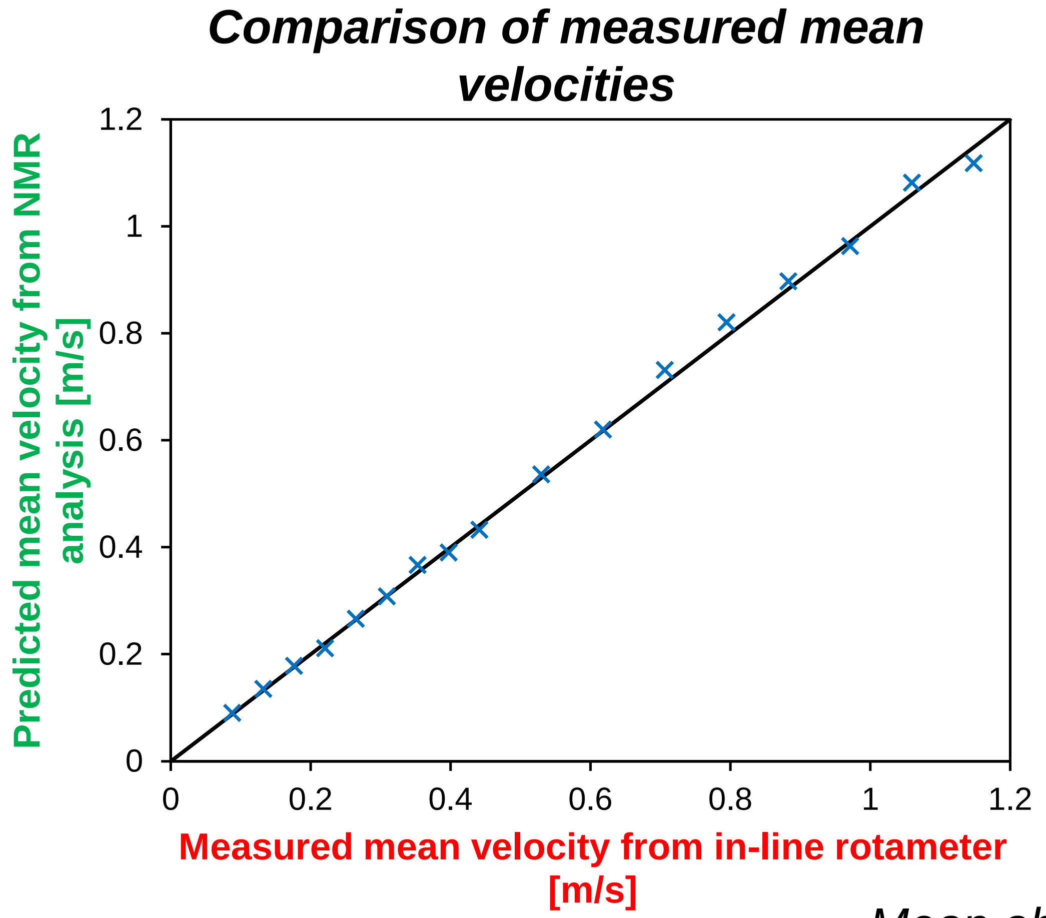


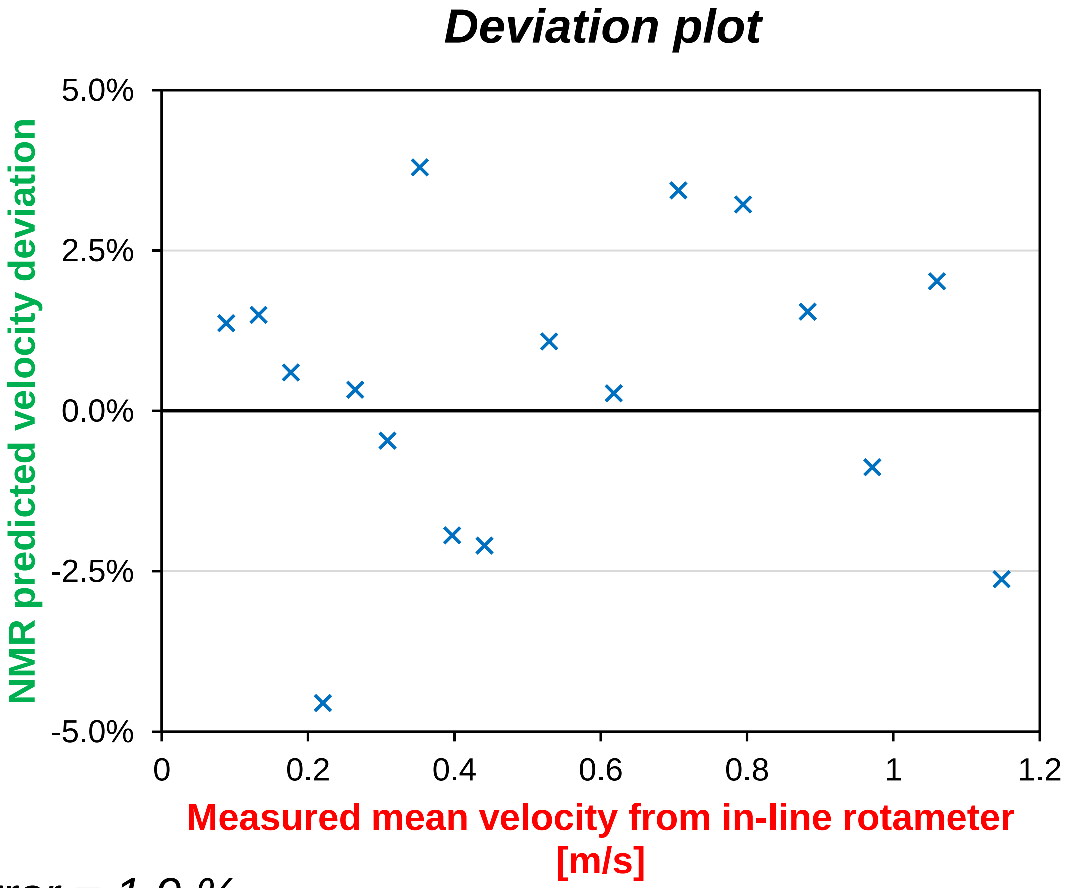
Corresponding velocity probability distributions



Velocity comparison





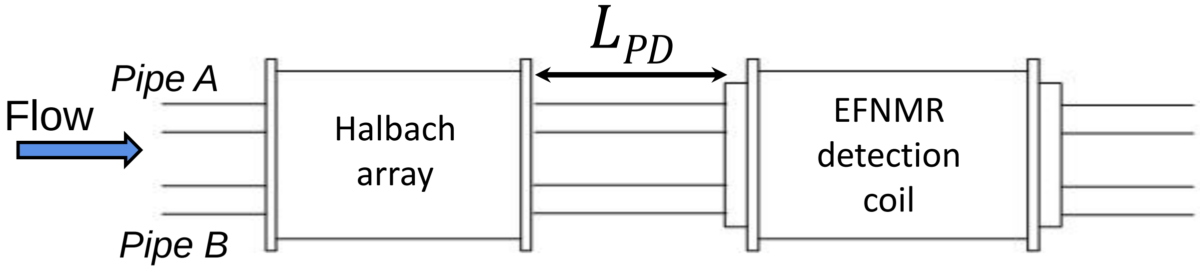


Mean absolute error = 1.9 %

Two pipe analysis

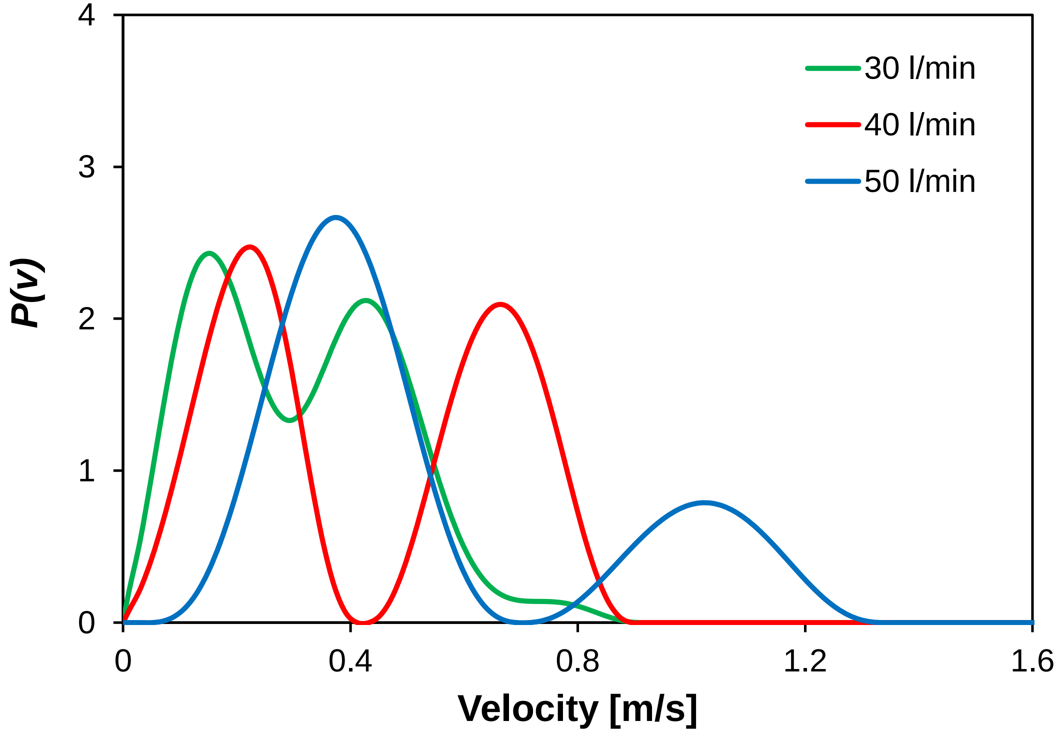
Experimental conditions

- Overall flow rates:
  15 – 50 L/min
- Separation distance (L_{PD}):
  0.68, 0.78. 0.88 and 0.98 m

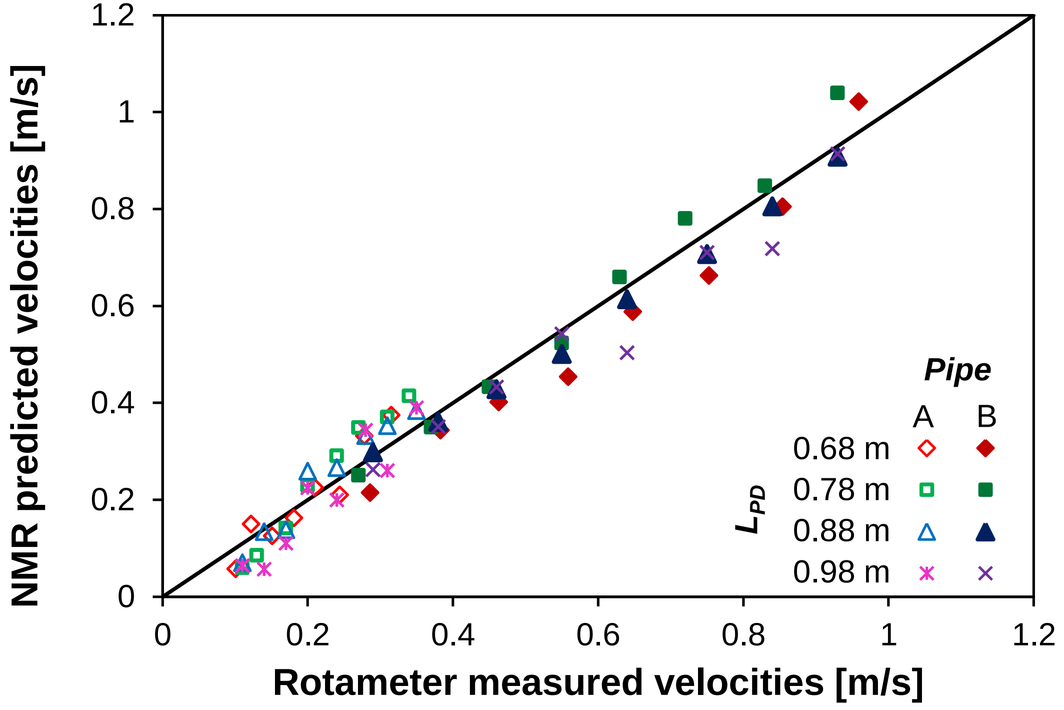


Velocity (pipe A) ~ 33% of velocity (pipe B)

Two pipe system velocity probability distributions

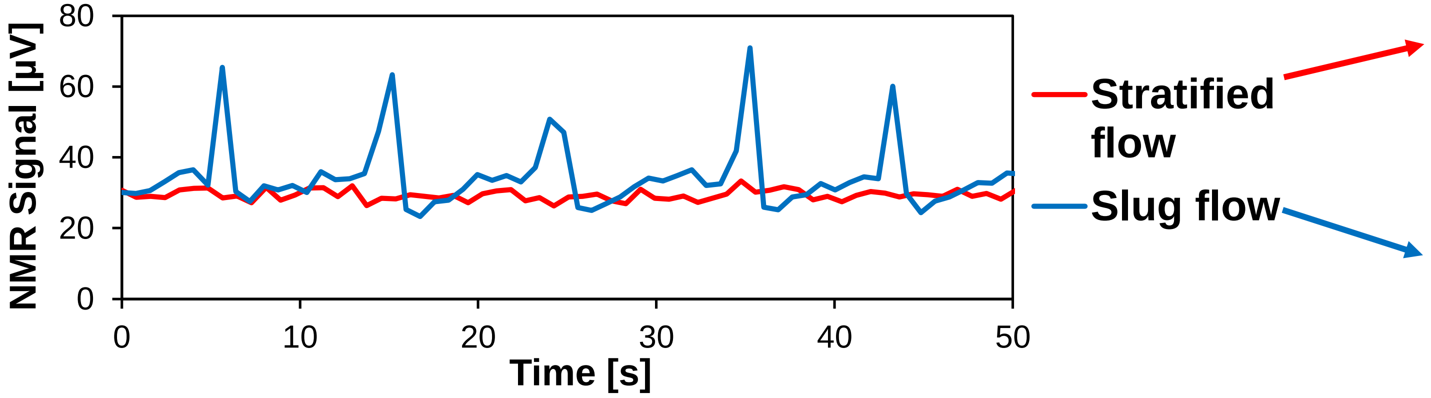


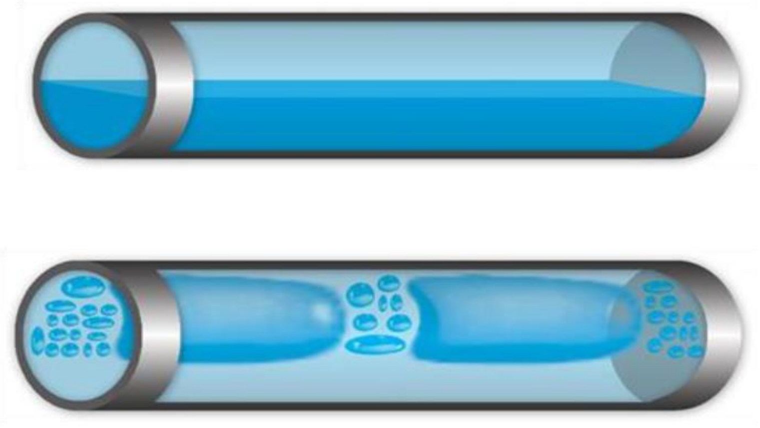
Comparison of measured mean velocities

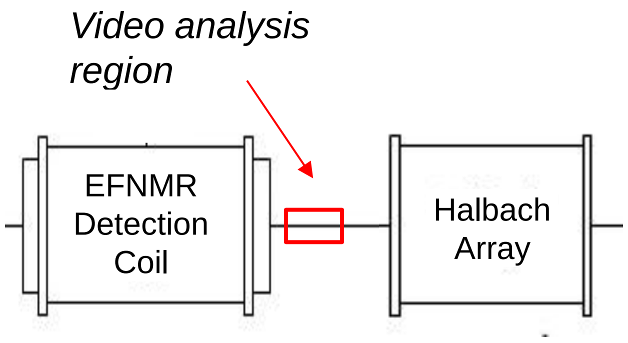


Gas/liquid analysis

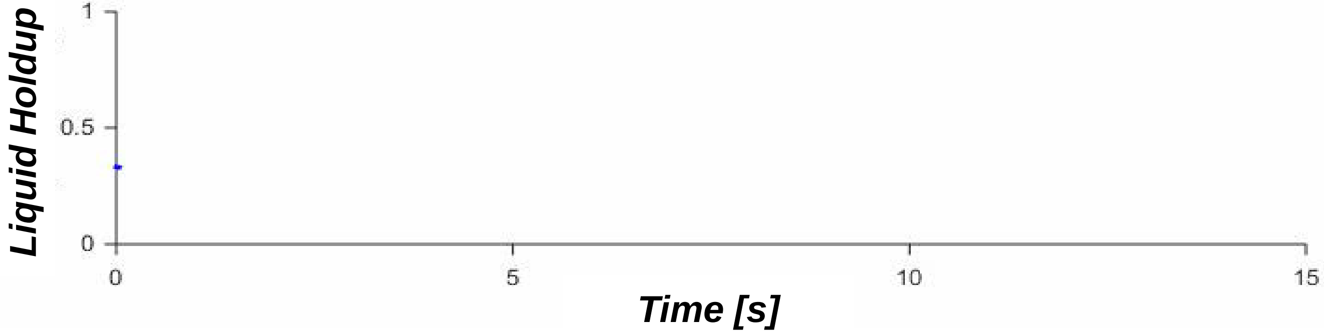
Flow regime identification







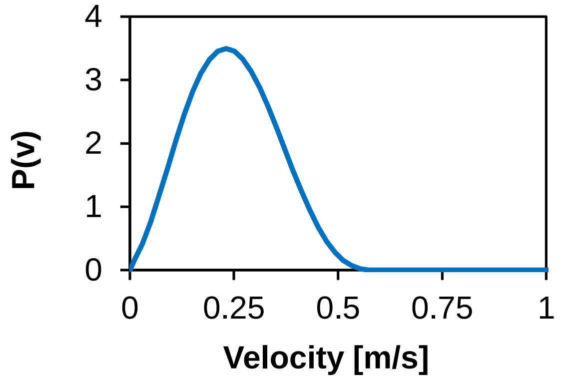
Video analysis



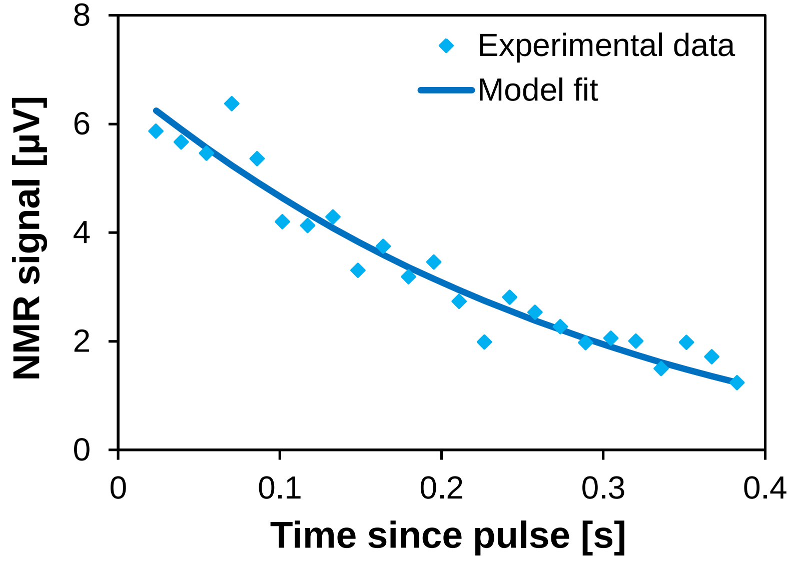
$U_{SL} = 0.13\ m/s$
$U_{SG} = 0.88\ m/s$

Velocity and holdup determination

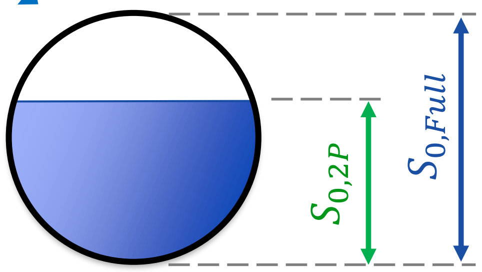
Velocity probability distribution



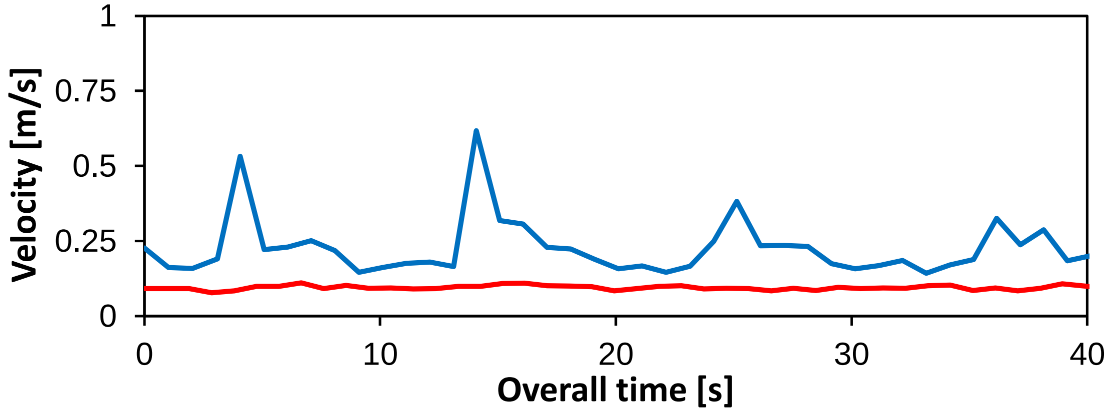
Processed signal & model fit

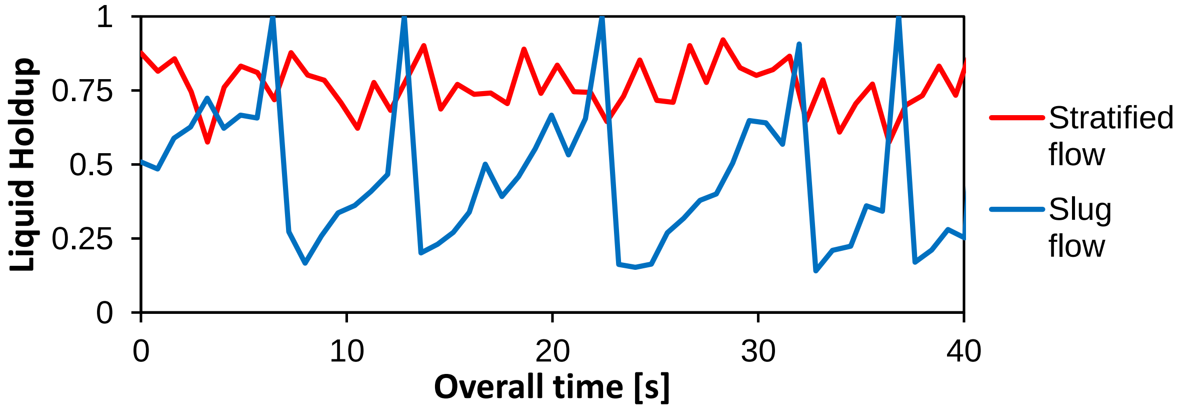


Liquid holdup determination



$$x_L = \frac{S_{0,2P}}{S_{0,Full}}$$

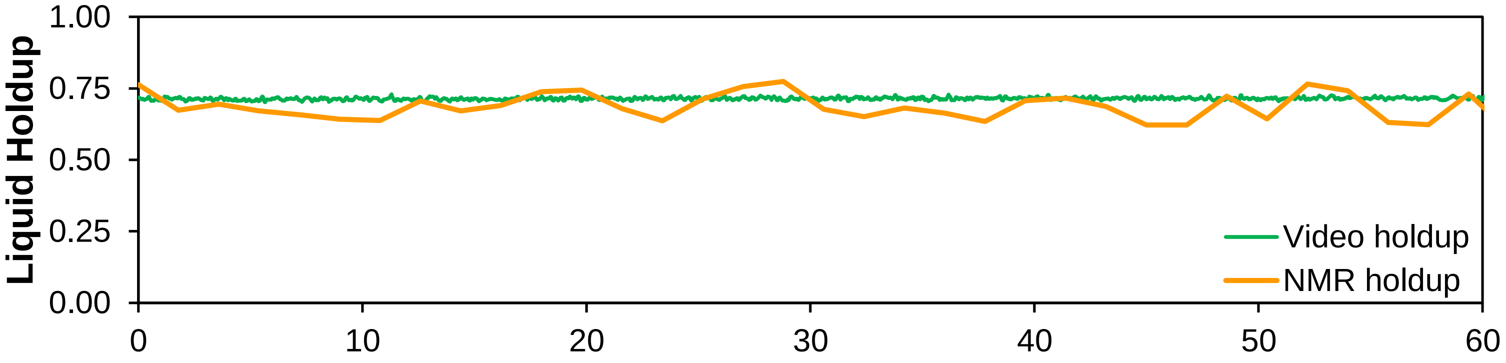


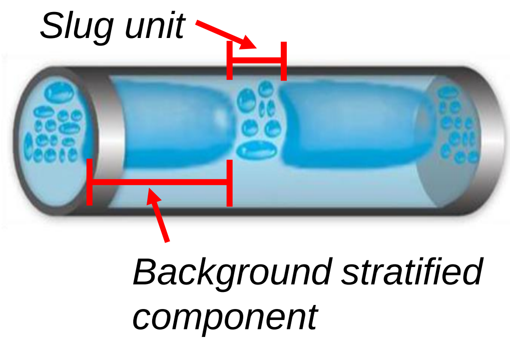


Holdup analysis comparison

Stratified flow

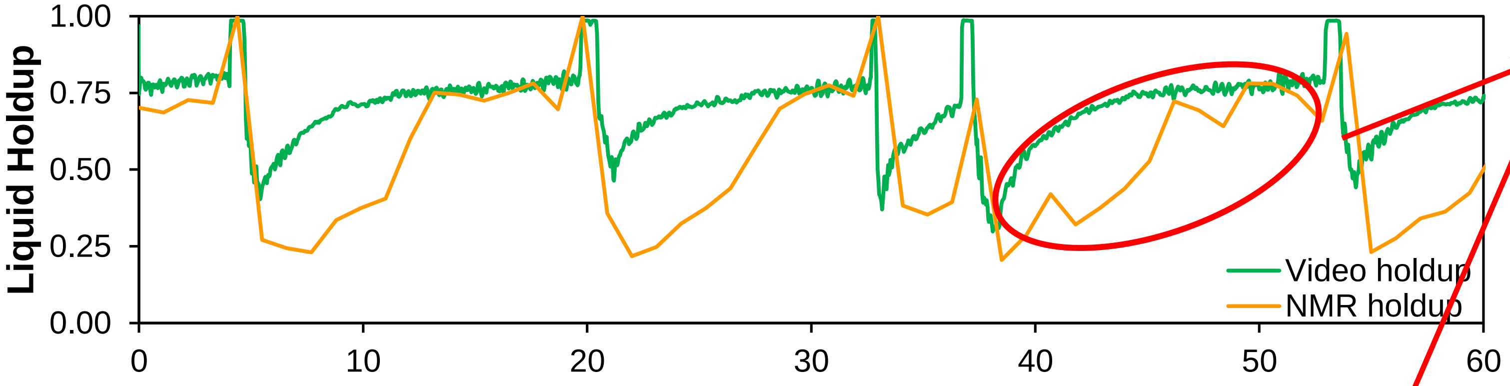
Liquid: 4 L/min
Gas: 40 L/min





Low frequency slug flow

Liquid: 8 L/min
Gas: 40 L/min

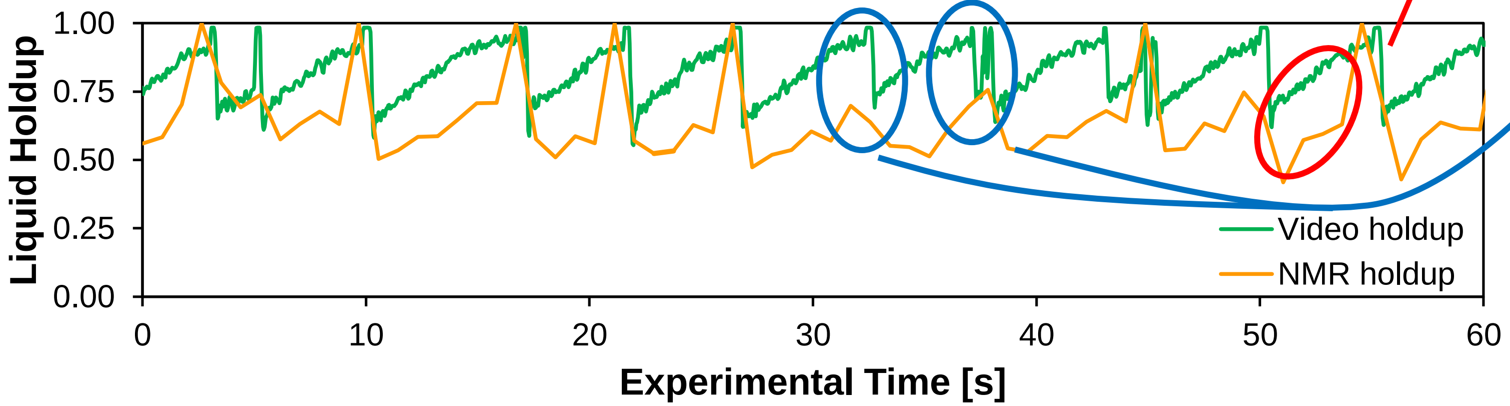


Background stratified under-prediction

- Gas bubbles
- Meniscus
- Increased relaxation

Higher frequency slug flow

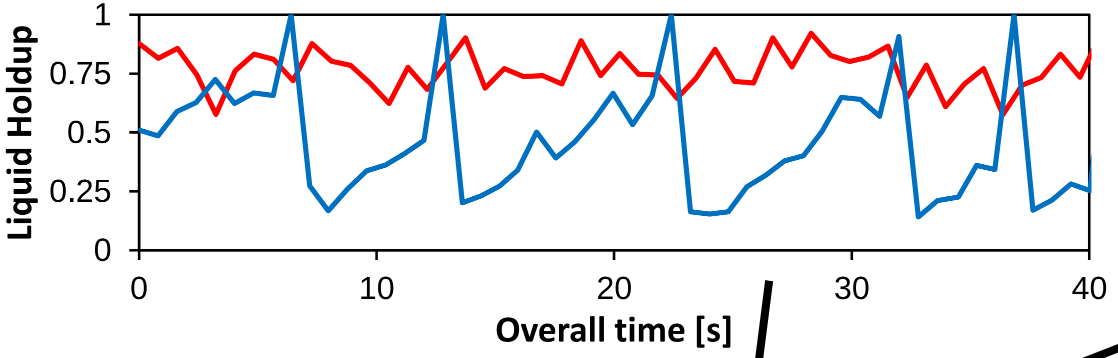
Liquid: 12 L/min
Gas: 20 L/min

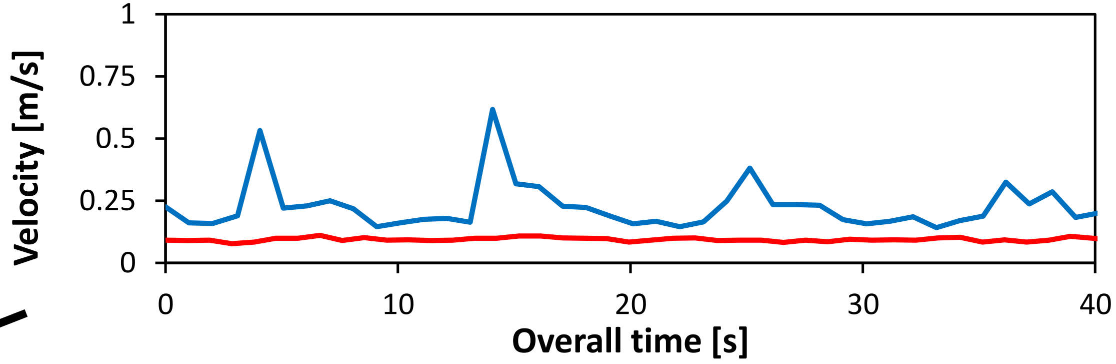


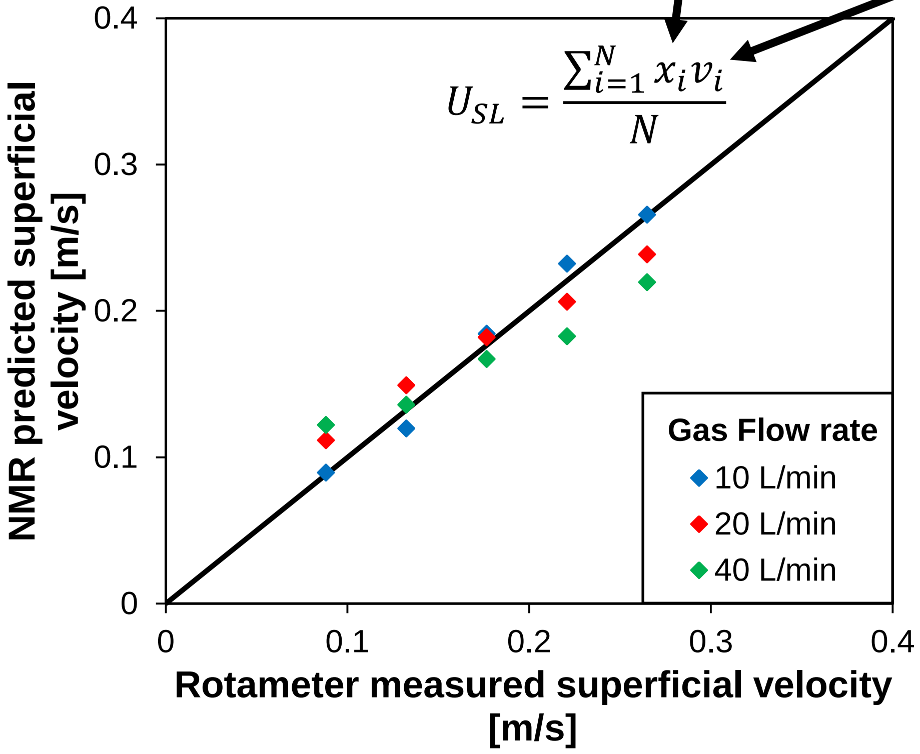
Partial slug capture

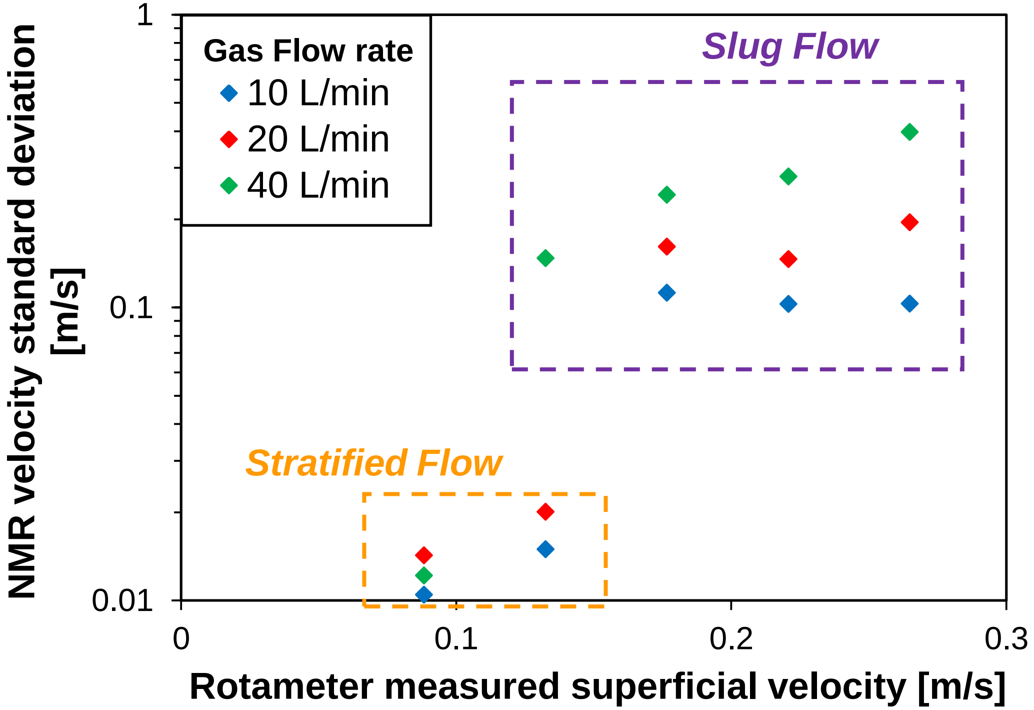
- Slug residence time ~0.2 s
- Scan time ~0.7 s
- Slug not fully captured

Two phase velocity analysis



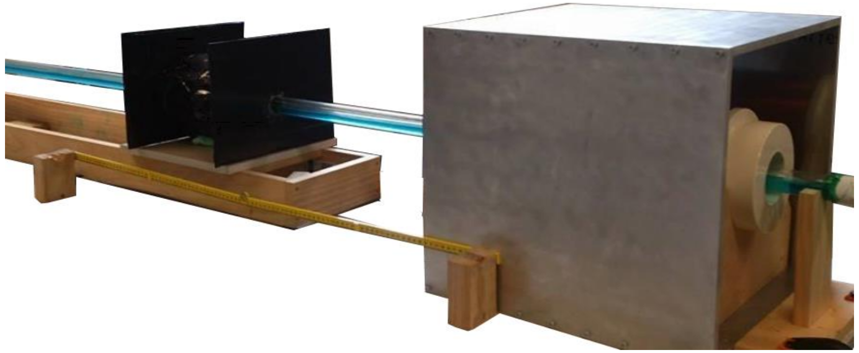




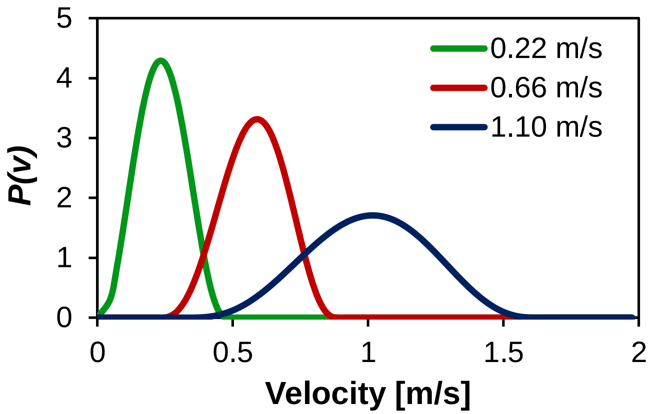


Conclusions

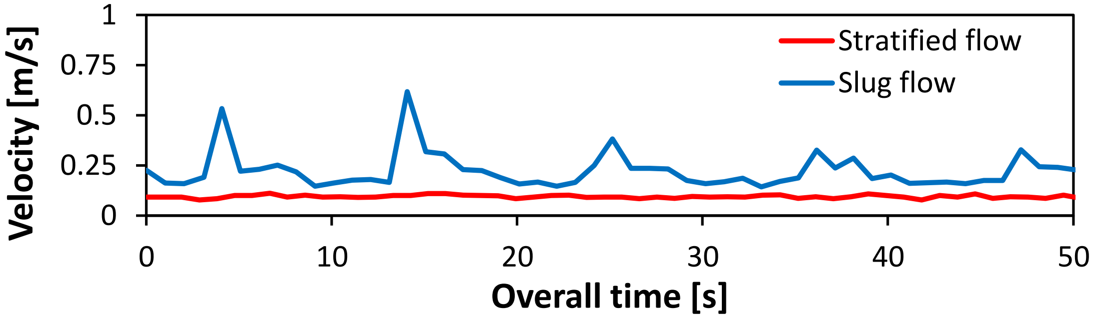
- Can accurately measure and model the FID signal of a moving fluid through the flow metering system



- Can determine the velocity probability distribution of liquid moving in the system via Tikhonov regularisation

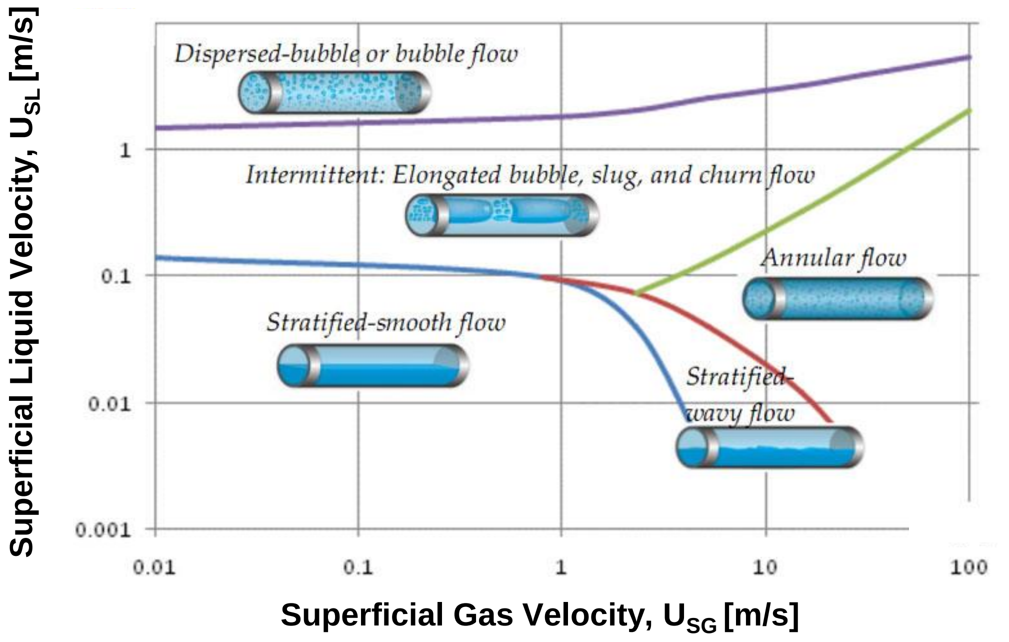


- Able estimate the liquid velocity and holdup over time for stratified and slug flow



Future work

- Analyse fluid flow in further air/water flow regimes
- Incorporate oil into flow metering system
- Apply dynamic nuclear polarisation for signal enhancement
- Fully develop analysis techniques to be able to interpret three phase flow (oil/gas/water)



Hogendoorn, J., et al., Magnetic resonance multiphase flowmeter: measuring principle and multiple test results, in Upstream Production Measurement. 2015: Houston.

Acknowledgements

Supervisors

Michael Johns, Einar Fridjonsson and Paul Stanwix



Final Year Project Students

Adeline Klotz and Jason Collis

Thank you for your attention!

Questions?

Tikhonov regularisation

The inverse problem;

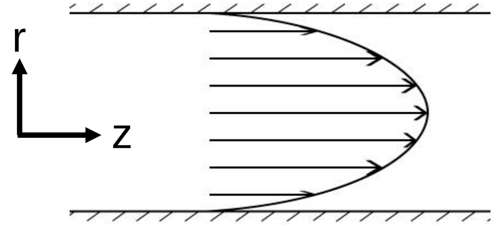
$$\mathrm{A} \times P(v) = S \quad \rightarrow P(v) = \mathrm{A}^{-1} \times S$$

Model transfer matrix

Velocity probability distribution

NMR Signal

Pipe velocity distribution

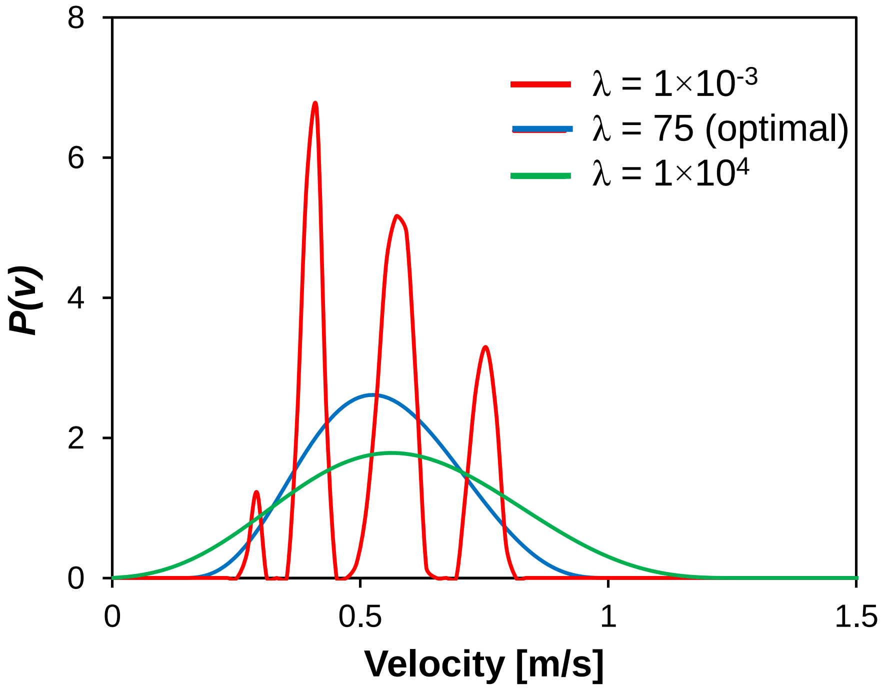


Apply Tikhonov regularisation;

$$\min(\|\mathrm{A} \times P(v) - S\|^2 + \lambda \|P(v)\|^2)$$

Residual norm

Second moment of *P(v)*



Generalised cross validation method is used to optimise the smoothing parameter (λ)

Comparison to a theoretical model

Theoretical turbulent power law distributions

$$U(r) = V_M \frac{n+1}{n}\left(1 - \frac{r}{R}\right)^{\frac{1}{n}}$$

$$n = f(Re)$$

$$n\left(0.44\,\frac{m}{s}\right) = 5.37$$

(Zagarola et al. 1997)

Experimental and theoretical distributions at v = 0.44 m/s