In-line rheometry and flow characterisation of dense slurries in pipe flow using acoustic methods

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Background and outline (1/2)

- Nuclear Research Group at Leeds has expertise in acoustic characterisation of multiphase flow, with specific interest in nuclear-engineering applications, examples of which are shown below

a. Particle concentration [1]

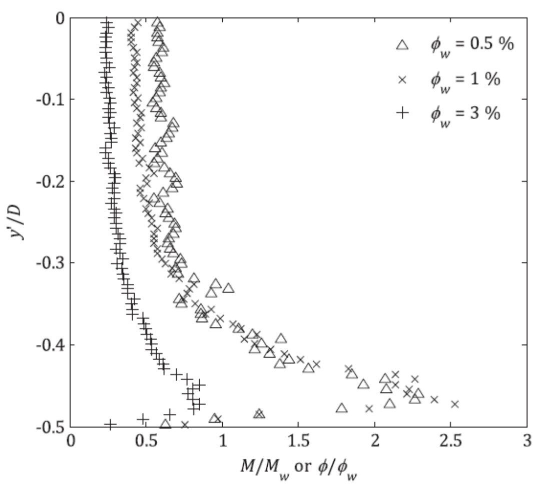
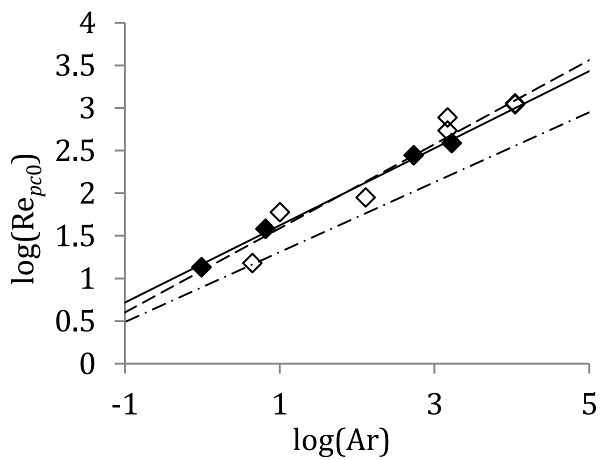


Fig. 3. Normalised concentration profiles, M/M_w or ϕ/ϕ_w, *vs.* reduced distance from centreline, y'/D. Small glass spheres (Honite 22, d_{50}=41.0 μm) at Re=53 100, 52 700 and 52 100; ϕ_w=0.5%, 1% and 3%; M_w=12.4, 24.7 and 72.8 kg m^{-3} (M_s=13.4, 27.4 and 79.9 kg m^{-3}), respectively. Lower half of flow shown.

b. Critical flow velocity [2]



c. Bedform evolution [3]

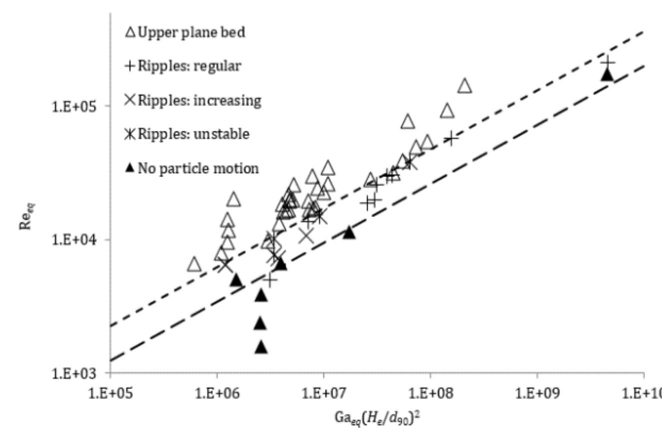


Figure 1: Phase diagram with new variables.

[1] Rice HP, Fairweather M, Peakall J *et al.* (2015), Chem. Eng. Sci. 126, 745-758
[2] Rice HP, Fairweather M, Peakall J *et al.* . (2015), Chem. Eng. Sci. 126, 759-770; Soepyan FB *et al.* (2014), AIChE Journal 60 (1), 76-122
[3] Rice HP *et al.*, in preparation

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Background and outline (2/2)

- Aim to develop new acoustic methods for characterisation of dense slurries, as follows:

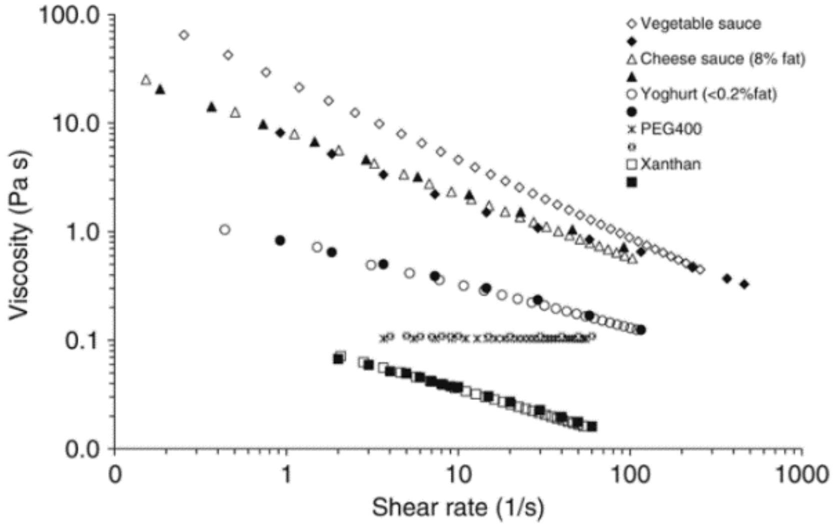
  1. In-line pipe rheometry using pressure drop-velocimetry method
  2. Concentration profile measurement with dual-frequency method
  3. Time-domain velocimetry for increase accuracy
  4. Commissioning of new flow loop laboratory

In-line pipe rheometry (1/3)

- When access difficult, in-line rheometry means samples do not need to be taken for off-line analysis
- In-line velocimetry-pressure drop rheometry method used, as follows:

$$\mu(r) = \frac{\tau(r)}{\dot{\gamma}(r)}; \dot{\gamma}(r) = -\frac{\mathrm{d}U(r)}{\mathrm{d}r}; \tau(r) = \frac{\Delta P}{2L} r$$

where $U(r)$ is from velocimetry and ΔP from pressure sensors over length L



Comparison of in-line and conventional rheometry results for food substances [1]

[1] Wiklund J and Stading S (2008), Flow Measurement and Instrumentation 19 (3-4), 171-179

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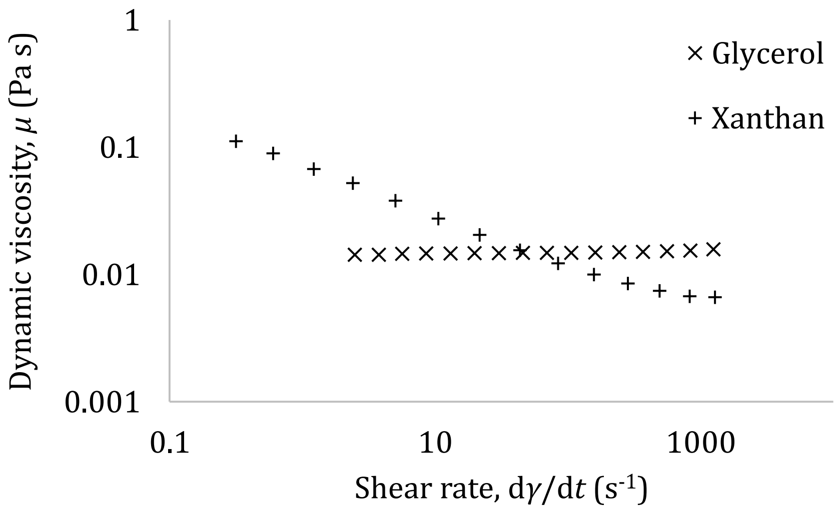
In-line pipe rheometry (2/3)

- Method tested with fluids with known rheological properties: water, glycerol solution (both Newtonian) and xanthan gum-water suspension (shear-thinning)

Pipe flow loop in Sorby Laboratory, with acoustic and pressure transducers attached



Off-line rheometry of glycerol (60 % by mass) and xanthan gum (0.1 % by mass) at 15° C, cup and bob geometry

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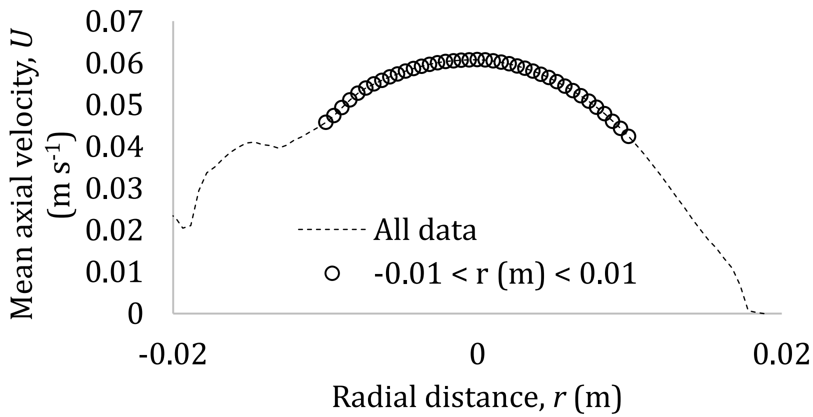
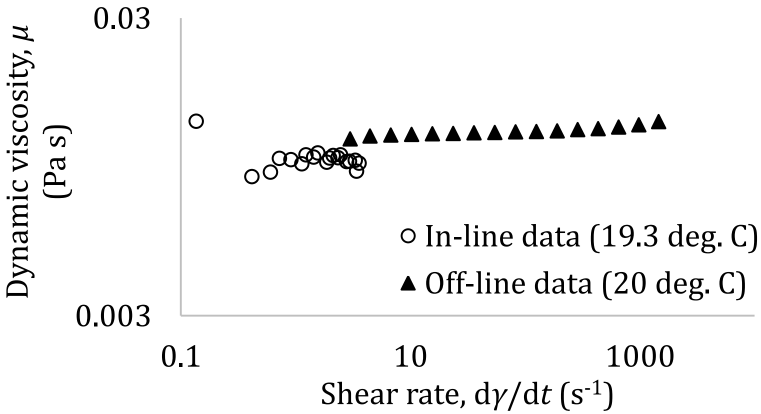
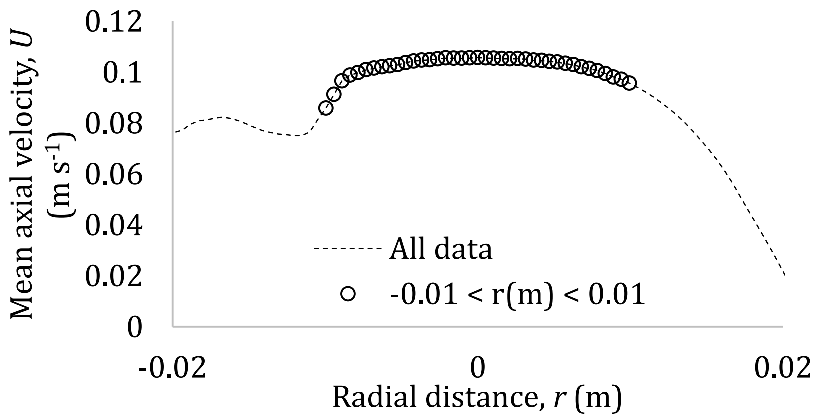
In-line pipe rheometry (3/3)

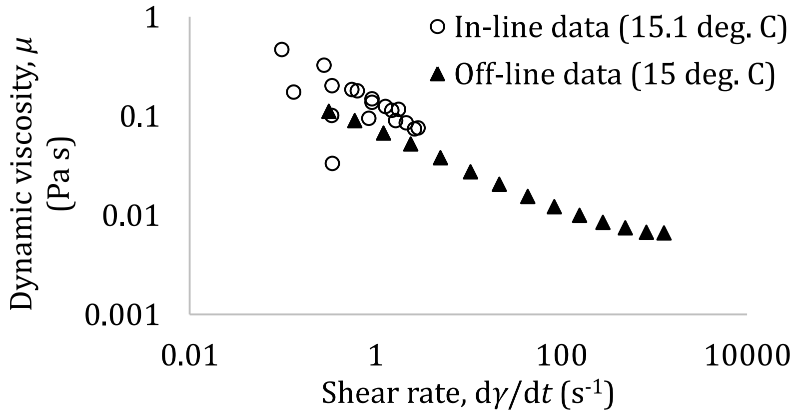
1. Glycerol test run: 60% by mass





2. Xanthan test run: 0.1% by mass





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Calibration of new acoustic instrument (1/2)

- Acoustic backscatter strength, V, from suspension of particles depends on particle size, d, particle concentration, M, and the material properties of the particles, most importantly α_s, attenuation due to particles; ξ_h is acoustic attenuation coefficient in homogeneous case and can be measured as given below.
- Attenuation coefficient measured with new instrument and compared against previous study [1] for validation purposes

$$V = \frac{K}{\psi r} M^{1/2} e^{-2(\alpha_w + \alpha_s)r} \qquad \alpha_s = \frac{1}{r}\int_0^r \xi(r')\, M(r')\mathrm{d}r' = \xi_h M$$

$$G = \ln(\psi r V) \qquad \xi_h = -\frac{1}{2}\frac{\partial^2 G}{\partial M \partial r}$$

Stirred mixing vessel with multi-frequency transducer pointing downwards and attached to new acoustic instrument

New acoustic instrument, with cover removed [2]

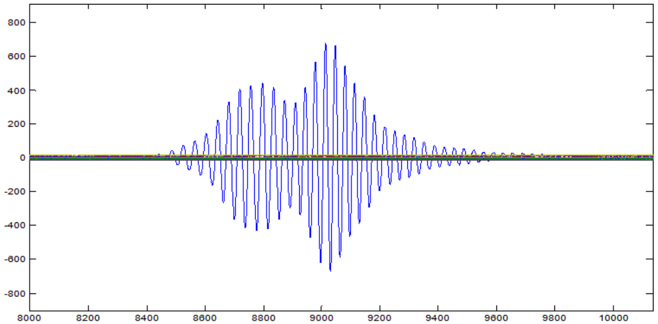

Image of reflected acoustic pulse, with components from front and back of reflective surface superimposed

[1] Rice HP, Fairweather M, Hunter TN *et al.* (2014), J. Acoustical Society of America 136 (1) 156-169; Rice HP, Fairweather M, Peakall J *et al.* (2014), Chemical Engineering Science 126 745-758; datum courtesy of Iain Smith, M.Sci. student
[2] Images courtesy of Dr. David Cowell, School of Electronic and Electrical Engineering

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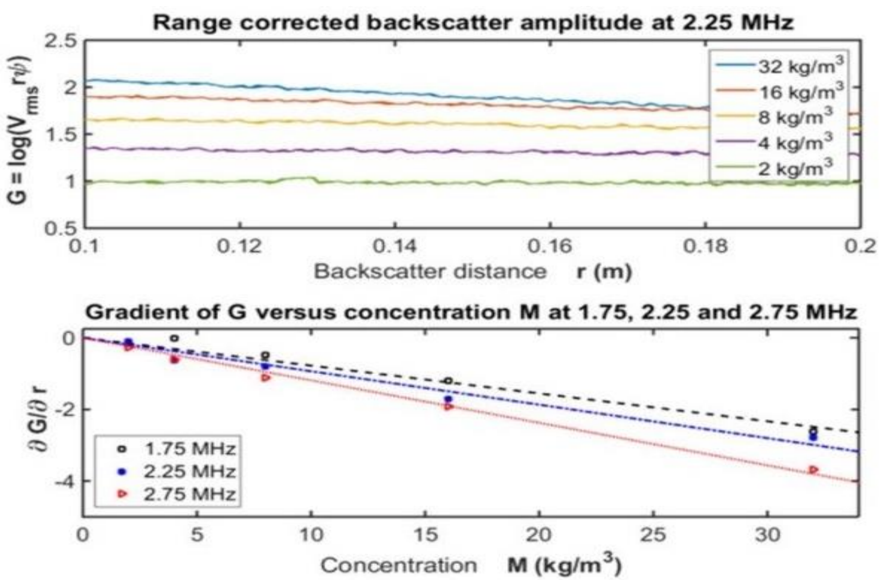
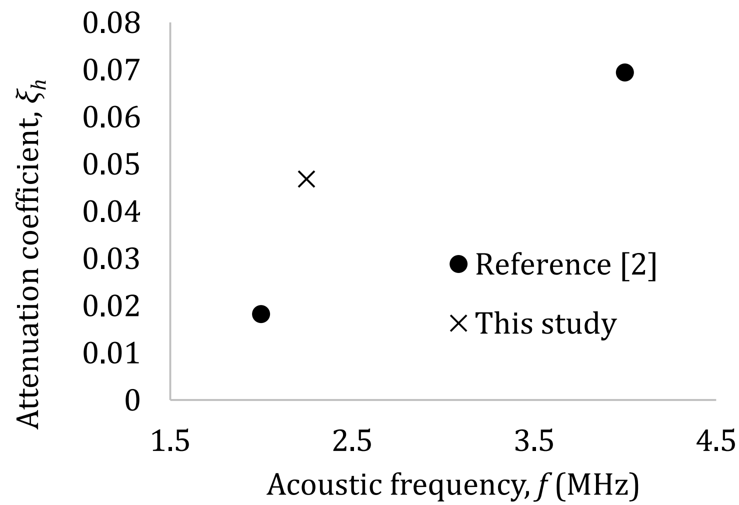
Calibration of new acoustic instrument (2/2)



Backscatter amplitude results from stirred mixing tank with suspensions of glass spheres using new acoustic instrument [4]



Acoustic attenuation coefficients measured with new instrument, compared to previous study [2]

- Preliminary results agree well with previous measurements
- Aim to apply method to suspensions of nuclear-simulant materials to determine particle concentration field using dual-frequency method [3]

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[2] Rice HP, Fairweather M, Hunter TN *et al.* (2014), J. Acoustical Society of America 136 (1) 156-169; Rice HP, Fairweather M, Peakall J *et al.* (2014), Chemical Engineering Science 126 745-758; datum courtesy of Iain Smith, M.Sci. student
[3] Hurther D, Thorne PD, Bricault M *et al.* (2011), Coastal Engineering 58 (7) 594-605
[4] Images courtesy of Dr. David Cowell, School of Electronic and Electrical Engineering

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Time-domain velocimetry (1/2)

- Method offers potential improvement over more common Doppler methods in terms of data quality, aliasing/bandwidth and near-wall measurements
- Cross-correlation function used to find delay between signals from two parallel transducers; particle velocity then calculated as separation distance is known

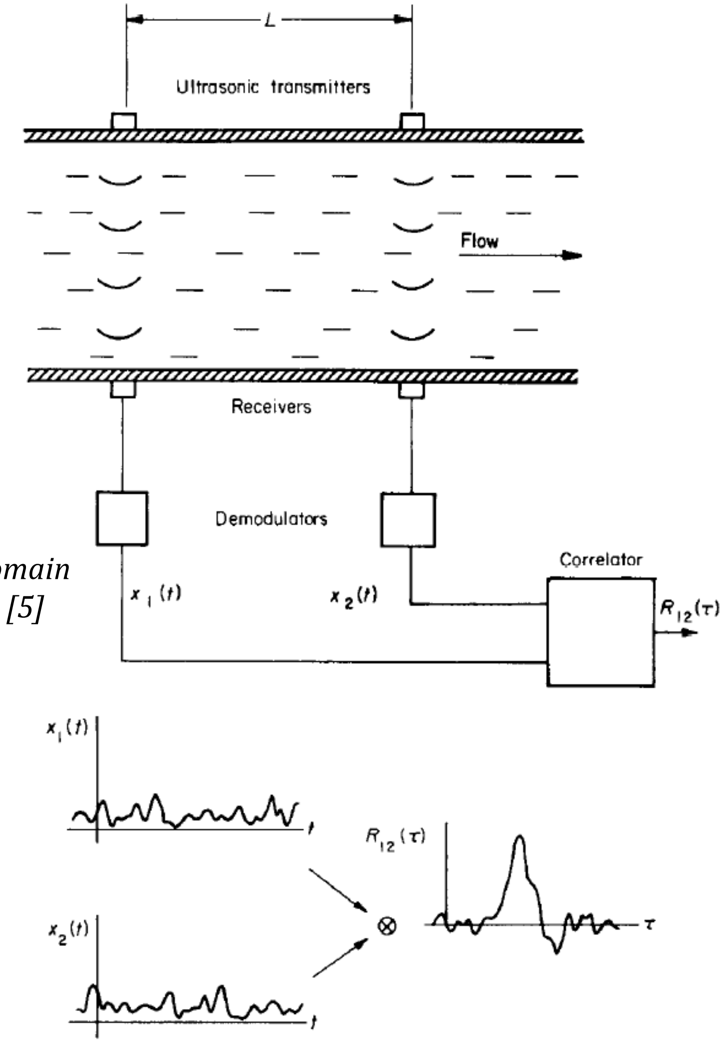
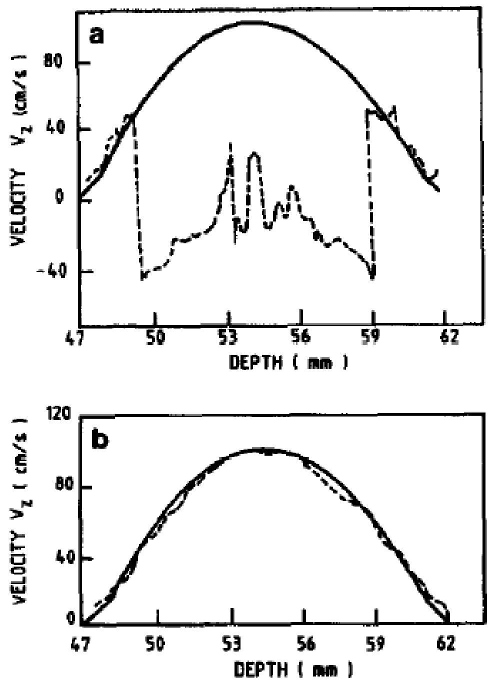


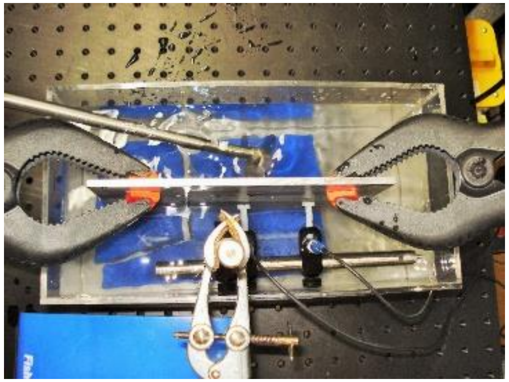
Illustration of time-domain velocimetry method [5]

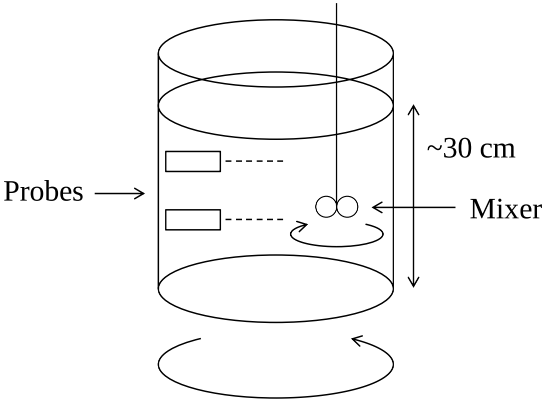


Aliasing effects in Doppler and time-domain methods [6]

[5] Jacobson SA, Denbigh PN and Naude DEH (1985), Ultrasonics 23 (3) 128-132
[6] Bonnefous O, Pesque P (1986), Ultrasonic Imaging 8 (2) 73-85

Time-domain velocimetry (2/2)





Configurations for testing of time-domain velocimetry

- Two test configurations used; first was not successful
- MATLAB code (function "xcorr") used to compute cross-correlation and delay time between signals
- Plastic particles used as scatterers; computed velocities to be compared with Stokes settling velocities at d_{50}:

$$U_{\mathrm{St}} = \frac{2}{9}\frac{gd^2(S-1)}{\nu}$$

- To be combined with pressure-drop measurements and compared with Doppler method in in-line rheometry method

New flow laboratory and future plans

- Using methods described here, aim is to fully characterise settling and non-settling, high-concentration suspensions in terms of velocity and concentration fields, and in-line rheometry at lower flow rates
- Aim to also measure deposition velocity at higher flow rates using method described in recent study [7] and particle image velocimetry (PIV) for validation of acoustic data and for near-wall measurements
- A range of nuclear-simulant materials will be used, e.g. calcium carbonate, magnesium hydroxide and barytes suspensions, with and without flocculating agents
- Two pipe flow loops, internal diameters *D* = 60 and 25 mm; flow can be directed in horizontal, vertical or inclined orientations

Composite photograph of layout of new flow loop laboratory, being commissioned

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[7] Rice HP, Fairweather M, Peakall J *et al*. (2015), Chemical Engineering Science 126 759-770

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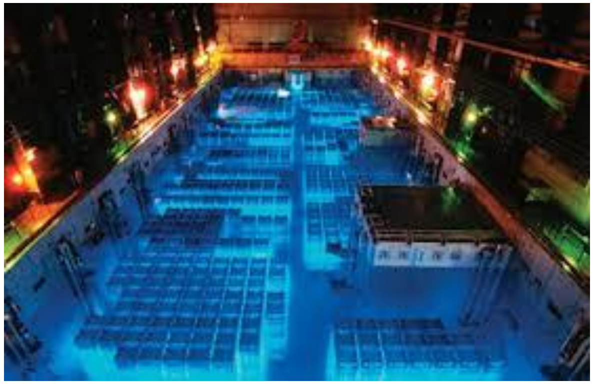
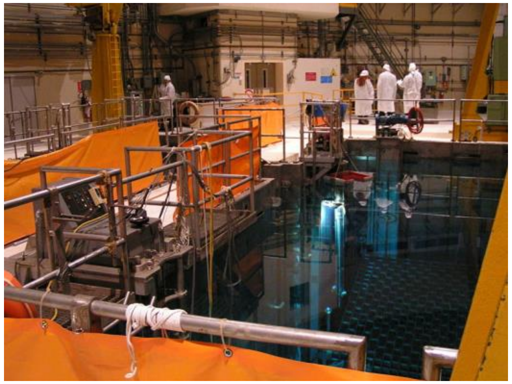
Acknowledgements

Thanks: Peter Dawson[1], David Cowell[2], Gareth Keevil[3], Robert Thomas[3], Olivier Mariette[4]

[1] School of Chemical and Process Engineering
[2] School of Electronic and Electrical Engineering
[3] School of Earth and Environment
[4] *Met-Flow*, Switzerland





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