ON-LINE SLURRY VISCOSITY AND CONCENTRATION MEASUREMENT AS A REAL-TIME WASTE STREAM CHARACTERIZATION TOOL

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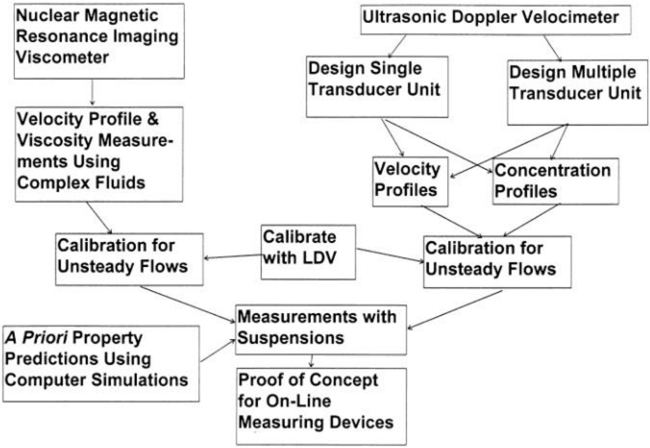
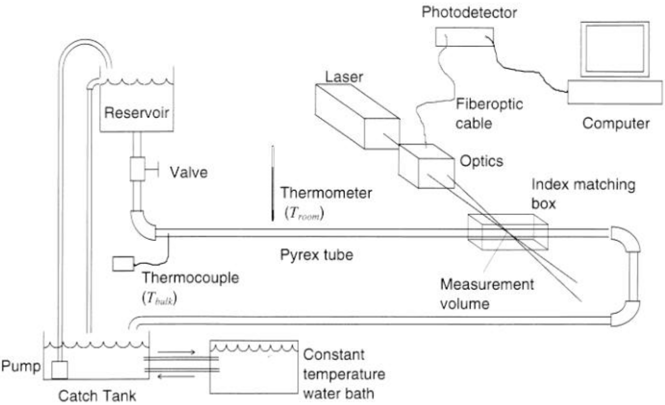
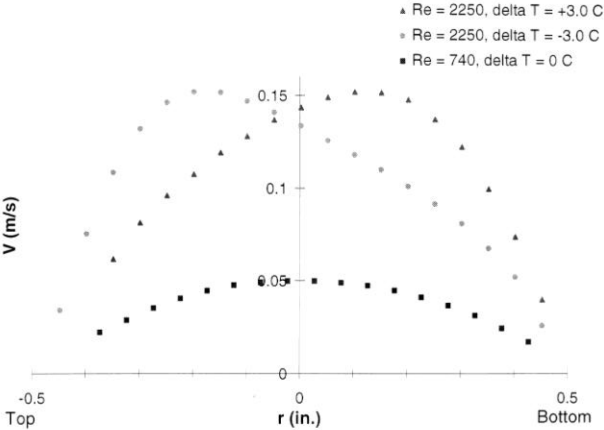

Nuclear Magnetic Resonance Imaging Viscometer
Velocity Profile & Viscosity Measurements Using Complex Fluids
Ultrasonic Doppler Velocimeter
Design Single Transducer Unit
Design Multiple Transducer Unit
Velocity Profiles
Concentration Profiles
Calibration for Unsteady Flows
Calibrate with LDV
Calibration for Unsteady Flows
Measurements with Suspensions
A Priori Property Predictions Using Computer Simulations
Proof of Concept for On-Line Measuring Devices

Experimental System





Re = 2250, delta T = +3.0 C
Re = 2250, delta T = -3.0 C
Re = 740, delta T = 0 C
V (m/s)
0.15
0.1
0.05
0
-0.5
Top
0
r (in.)
0.5
Bottom

$\Delta T = T_{room} - T_{bulk}$

Where T_{bulk} = bulk temperature of fluid
≈ Temperature at the location midway between centerline of tube and wall

$Re = UD/\nu$

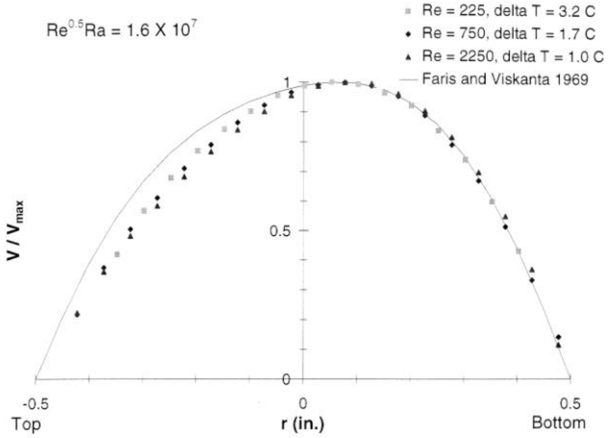
Where: U = average velocity across the tube
D = diameter of tube
ν = kinematic viscosity of the fluid

$Ra = \rho\beta g\Delta TD^3/\mu\alpha$
$Gr = Ra/Pr$

Where: ρ = density of the fluid
β = volume expansion coefficient of the fluid
μ = viscosity of the fluid
α = thermal diffusivity of the fluid
$Pr = \mu/(\rho\alpha)$

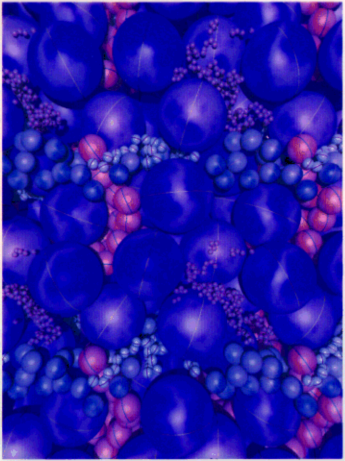
Velocity profiles may depend on:

ReRa (Kyomen et al. 1996)
$Re^{0.5}Ra$ (Faris and Viskanta 1969)
Gr/Re^2 (Buoyancy driven flow)



$Re^{0.5}Ra = 1.6 \times 10^7$
Re = 225, delta T = 3.2 C
Re = 750, delta T = 1.7 C
Re = 2250, delta T = 1.0 C
Faris and Viskanta 1969
V / V$_{max}$
1
0.5
0
-0.5
Top
0
r (in.)
0.5
Bottom

Colloidal Suspensions

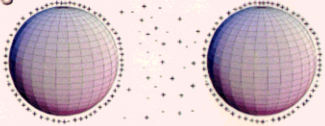


- Basic Problem – prediction of macroscopic properties of suspensions

Current Work:

- Suspensions of hard spheres: bimodal and polydisperse
- Colloidal particles
- Dynamic Simulation in 3-D using Ewald summation
- Running computational experiments

Near Field Two-Body Forces

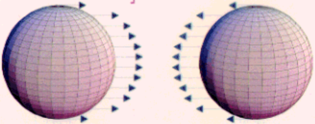


- **DLVO interactions:**

$$F = F^R + F^A$$

- $\mathbf{F}^R$, the electrostatic:

$$F^R = \frac{\varepsilon_R \varepsilon_0 \kappa}{2\left(\frac{1}{a}+\frac{1}{b}\right)\psi_a \psi_b}\left[\left(\psi_a^2+\psi_b^2\right)\left(1-\coth\ \kappa h\right)+2\psi_a\psi_b \operatorname{cosech} \kappa h\right]$$

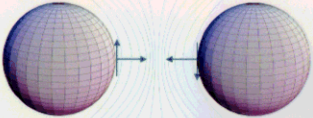


- $\mathbf{F}^A$, van der Waals force:

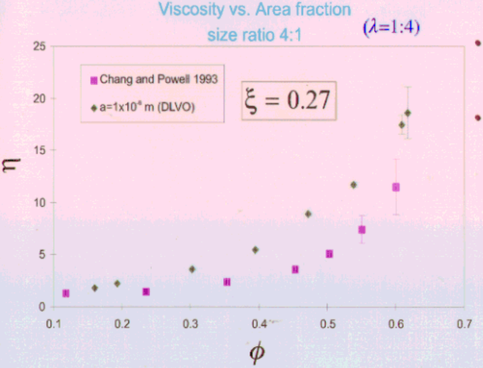
$$F^A = -\frac{Aab}{6h^2(a+b)} \text{(Unretarded)}$$

- **Lubrication**

(Jeffrey and Onishi, 1984 and Jeffrey, 1992)
Yields the two-body lubrication resistance matrix, $\mathbf{R}_{2Body}$



Behavior of Colloids



- Viscosity increases with increasing volume fraction.
- A Colloidal suspension will tend to have greater viscosity at a given volume fraction.

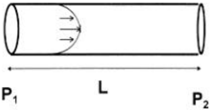
Summary

- Conducted three-dimensional simulation of concentrated colloidal bimodal suspensions using Ewald summation.
- Relative viscosity as a function of time was calculated and analyzed.
- Pair distributions, $g(r)$ and $g(r,\theta)$, were found for the three-dimensional particle suspensions.

Current Research

- Studying viscosity as a function of relative volume fraction
- Studying the effect of shear rate on viscosity (i.e.. *Pe* number)
- Polydisperse suspensions

CENTRAL IDEA: NMRI AND UDV VISCOMETRY



STEADY PRESSURE DRIVEN PIPE FLOW

$$\frac{\partial P}{\partial z} = -\frac{\Delta P}{L} = \frac{P_1 - P_2}{L}$$

Measure ΔP with pressure transducers . Axial component of conservation of linear momentum gives the local shear stress

$$\tau(r) = -\frac{\Delta P}{2L} r$$

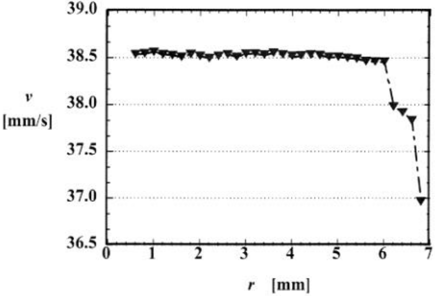
Measure axial velocity profile, w(r), using NMRI or UDV. The local shear rate, $\dot{\gamma}$, is

$$\dot{\gamma} = \frac{dw(r)}{dr} = \dot{\gamma}(r)$$

For each radial position, r, find τ and $\dot{\gamma}$. Eliminating r as the independent variable gives $\tau(\dot{\gamma})$. The shear rate dependent viscosity, $\eta(\dot{\gamma})$ is calculated

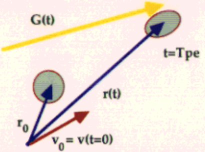
$$\eta(\dot{\gamma}) = \frac{\tau(\dot{\gamma})}{\dot{\gamma}}$$

Determination of Plug Radius (R_0) and Yield Value (τ_0)



$$\tau_0 = \frac{\Delta P}{2L} R_0$$

Haake RV20	3.15	± 0.08
NMRI	3.42	± 0.34



$$\Phi = \gamma \int_0^{T_{pe}} \mathbf{r}(t) \bullet \mathbf{G}(t)\ dt$$

$$\mathbf{r}(t) = \mathbf{r}_0 + \mathbf{v}_0 t + \frac{\mathbf{a}_0}{2} t^2 \ldots$$

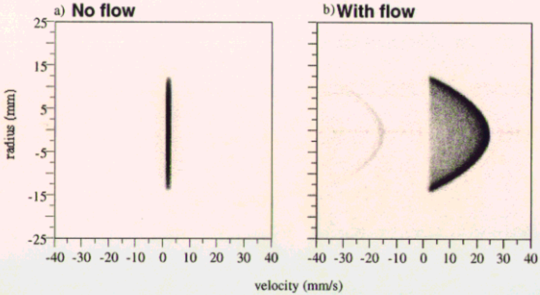
$$\Phi = \gamma \mathbf{r}_0 \bullet \int_0^{T_{pe}} \mathbf{G}(t)\ dt + \gamma \mathbf{v}_0 \bullet \int_0^{T_{pe}} \mathbf{G}(t)\ t dt + \gamma \frac{\mathbf{a}_0}{2} \bullet \int_0^{T_{pe}} \mathbf{G}(t)\ t^2 dt \ldots$$

$$\mathbf{m}_0 = \int_0^{T_{pe}} \mathbf{G}(t)\ dt \qquad \mathbf{m}_1 = \int_0^{T_{pe}} \mathbf{G}(t)\ t dt$$

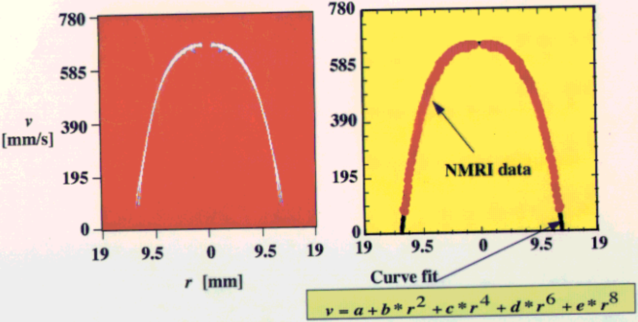
$$\mathbf{m}_2 = \int_0^{T_{pe}} \mathbf{G}(t)\ t^2 dt$$

$$\Phi = \gamma \mathbf{r}_0 \bullet \mathbf{m}_0 + \gamma \mathbf{v}_0 \bullet \mathbf{m}_1 + \gamma \frac{\mathbf{a}_0}{2} \bullet \mathbf{m}_2$$

Volume fraction = 0.0

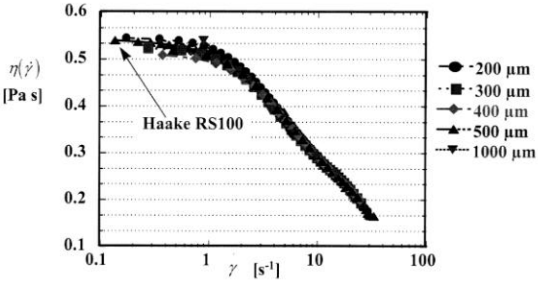


NMR Velocity Profile Image | Image Data



NMR data processed by applying:
Hankel transform transverse to tube axis and a
Fourier transform parallel to tube axis.

NMRI & Haake Data: 1% poly (ethylene oxide) solution



δv = 2.2 mm/s

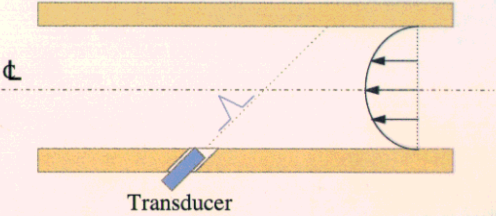
Q=26 ml/s, Reynolds number~7

Ultrasonic Doppler Velocimetry (UDV)

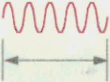
- Accurate velocity profiles obtained using high-resolution ultrasonic pulses
  - Doppler frequency

$$f_D = \frac{2v}{c} f$$

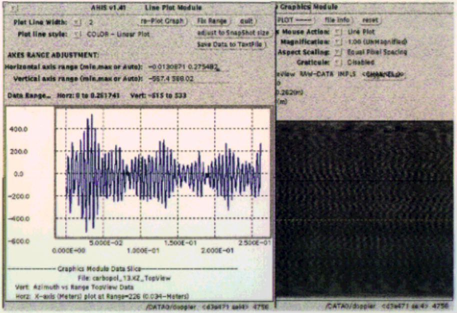
UDV Configuration



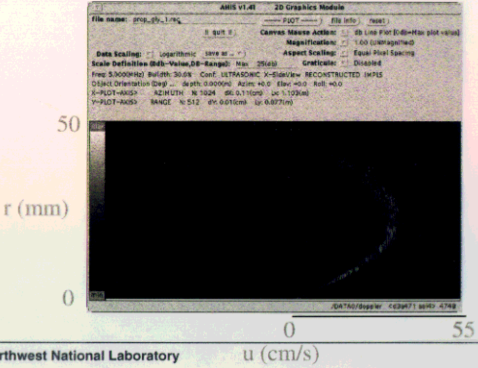
Transmitted Pulse: 5 cycles of 5 MHz

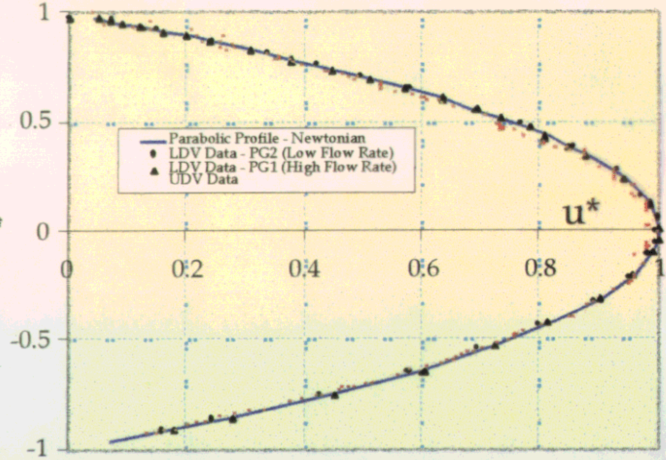


Ultrasonic Doppler Burst



UDV Profile (Propylene Glycol 30 l/min)





1
0.5
0
-0.5
-1
0
0.2
0.4
0.6
0.8
1
u*
Parabolic Profile - Newtonian
LDV Data - PG2 (Low Flow Rate)
LDV Data - PG1 (High Flow Rate)
UDV Data

Non-Newtonian Flow.

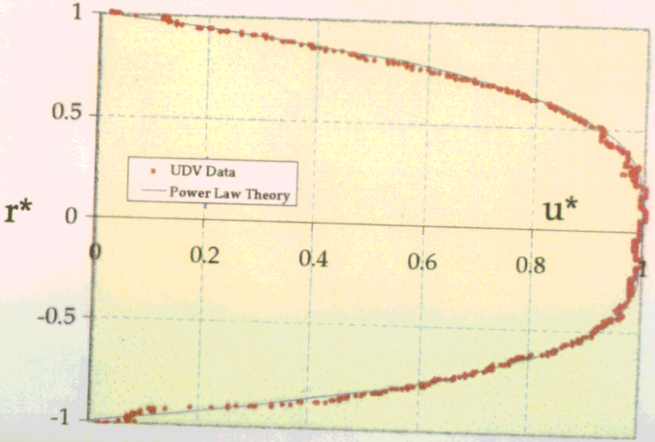
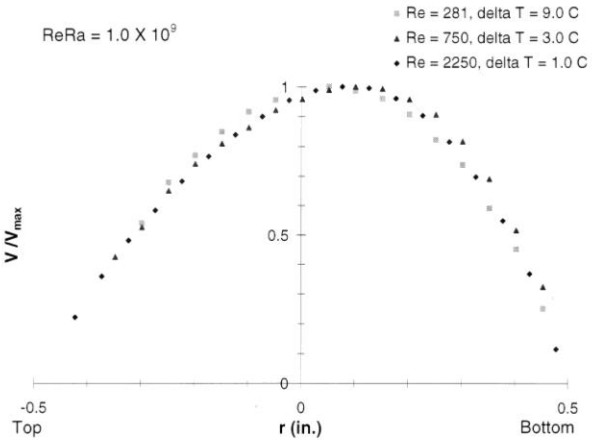
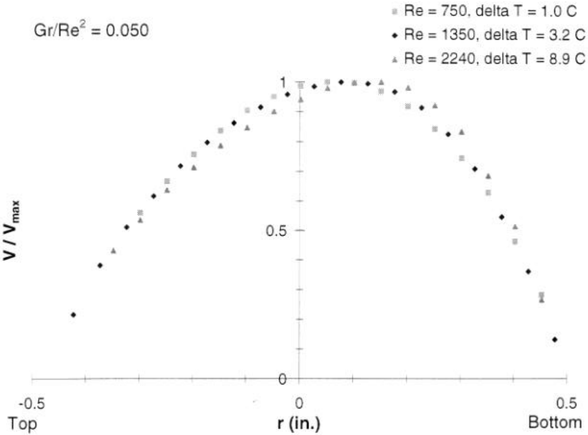


Figure 8. Comparison of UDV Velocity Measurements



ReRa = 1.0 X 10^9
Re = 281, delta T = 9.0 C
Re = 750, delta T = 3.0 C
Re = 2250, delta T = 1.0 C
V /V_max
1
0.5
0
-0.5
Top
0
r (in.)
0.5
Bottom



Gr/Re^2 = 0.050
Re = 750, delta T = 1.0 C
Re = 1350, delta T = 3.2 C
Re = 2240, delta T = 8.9 C
V / V$_{max}$
1
0.5
0
-0.5
Top
0
r (in.)
0.5
Bottom

Skewness of velocity profiles

$$\text{Skewness} = \Sigma(V/V\text{max})_i r_i^{\,3}$$

	Re	Δt	Skewness
ReRa = constant	281	9.0 C	0.0895
	750	3.0 C	0.0922
	2250	1.0 C	0.0537
$Re^{0.5}Ra$ = constant	225	3.2 C	0.0473
	750	1.7 C	0.0479
	2250	1.0 C	0.0537
Gr/Re^2 = constant	750	1.0 C	0.0950
	1350	3.2 C	0.0526
	2240	8.9 C	0.0871

PROJECTS

NUCLEAR MAGNETIC RESONANCE IMAGING VISCOMETER

ULTRASONIC DOPPLER VELOCIMETER

LASER DOPPLER VELOCIMETER

COMPUTER SIMULATION OF SUSPENSIONS