MICROFLUIDIC FLOWS OF VISCOELASTIC FLUIDS

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OUTLINE

• Definition, applications and our motivation and past work
• Non-dimensional numbers
• Experimental methods
• Governing equations and numerical methods
• Results
  • Hyperbolic channel: single and series (fluidic diode)
  • Flow focusing
  • Cross slot
  • Mixing-separating channel
  • 2D 4:1
• Closure
DEFINITION AND APPLICATIONS

- Fluid mechanics at the micro-scale: 100 nm - 500 µm
- Handles nano- & picolitre of fluid, miniaturization, coupling w/ electronics
- Applications: inkjet printing, analytical chemistry, micro-rheology, biology, DNA separation and sequencing, medicine, control systems, heat dissipation of micro-electronics, fuel cells, energy & display technology

Inkjet printing, spray drying, precise reactant delivery

Drop fission

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Link et al. PRL 92 (2004) 54503
Motivation: (1) mixing with complex fluids; interaction with fluid elasticity; (2) limit of operation of micro-rheometers

Viscoelastic flow instabilities

Mixing at very low Re  Absence of turbulence

Absence of chaotic advection

Other non-linear effects may help mixing: elasticity

Liquids

Small $\Gamma$, $Pe$ is large

$$Pe = \frac{UL}{\Gamma} = Re.Pr = Re.Sc$$

Short transit times  Poor mixing

$$Re = \frac{\rho UL}{\eta} = \frac{UL}{v}$$

$$De = \frac{t_{fluid}}{t_{flow}} = \frac{\frac{\lambda}{L/UL}}{L/UL} = \frac{\lambda U}{L}$$
RELEVANT PAST WORK

Viscoelastic instabilities in shear flows  

Taylor-Couette flow  
Larson et al., JFM 218 (1990) 573

Cone-plate flow  
McKinley et al., JNNFM 40 (1991) 201

Lid driven cavity flows  
Pakdel & McKinley, PRL 77 (1996) 2459

Underlying mechanism  
McKinley et al, JNNFM 67 (1996) 19  
Pakdel & McKinley, PRL 77 (1996) 2459

\[
\left( \frac{\lambda U}{R} \frac{\tau_{11}}{\tau_{12}} \right) \geq M_{crit}^2 
\]

on curved streamlines

Instability growth to elastic turbulence  
Groissman & Steinberg, Nature 405 (2000) 53  

Microfluidics & viscoelasticity  
Squires & Quake, Rev. Mod. Phys. 77 (2005) 977
EXPERIMENTAL METHODS: MICROFABRICATION BY SOFT LITHOGRAPHY

1. Silicon Wafer

2. Spin coat photoresist SU-8 and prebake

3. Spin coat barrier coat (CEM-BC7.5) and contrast enhancer (CEM 388SS) (vertical walls).

4. Chrome Mask over coated wafer

5. UV Exposure – cross-link SU-8

6. Wash barrier coat and contrast enhancer

7. Post-bake and develop SU-8

8. Pour PDMS over substrate and cure (80°C, 25 mins)

9. Peel off substrate

10. Treat surfaces with air plasma, seal with glass slide

Needs access to fairly clean environment

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MICROGEOMETRIES

Planar hyperbolic contraction- sudden expansion

**Abrupt contraction-expansion**
(CR=ER=16)

Accuracy of dimensions to within 5%
Near vertical walls:
tapering angle $87^\circ < \alpha < 92^\circ$

**Hyperbolic contraction ($\varepsilon_H = 2$)**

![Image of hyperbolic contraction](image)

SEM Images

![SEM Images of microfluidic structures](image)

**Microfluidic flows of viscoelastic fluids**
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EXPERIMENTAL METHODS: FLOW VISUALIZATION & MICRO-PIV

**Streakline imaging**
- 1 µm fluorescent particles
- Mercury lamp
- Long exposure
- 10X lens (NA=0.3, measurement depth= 30 µm)

**µPIV**
- 500 nm fluorescent particles
- Double-pulsed laser, Volume illumination
- Double-frame camera
- 20X lens (NA=0.5, measurement depth= 12 µm
- 32x32 pixel interrogation, 50% overlap

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EXPERIMENTAL METHODS: FLOW VISUALIZATION (2)

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Data aquisition card (NI-6218)

Microscope
Leica DMI5000 M

Digital camera (Leica DFC 350 FX)

Syringe pump (Harvard apparatus PHD 2000)

Syringes

Mercury lamp

Filter cube
Emission filter BP 530-545 nm
Dichroic 565 nm
Barrier filter 610-675 nm

Objectives used:
10x0.25NA
5x0.12NA

Differential pressure sensor (Honeywell 26PC series)
EXPERIMENTAL METHODS: RHEOLOGY - DATA FOR FLOW FOCUSING

Newtonian fluid: water
Viscoelastic fluid: PAA 125 ppm + 1% NaCl
PAA ($M_w = 18 \times 10^6$ g/mol)

Shear, *Physica MCR 301*
(cone-plate, $d = 75$ mm, 1°)

Onset of inertial instabilities
20X the minimum measurable torque ($1 \times 10^{-7}$ Nm)

Oliveira et al. JNNFM 160 (2009) 31-39

**Extensional rheology, Haake CaBER I**

$D_p = 6$ mm; $AR = 0.33$ & 1.56; $\varepsilon = 1.53$

$\eta_0 = 0.00131$ Pa.s

$\lambda_{CaBER} = 12.4 \pm 0.2$ s

$\rho = 1005$ kg/m$^3$

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*Microfluidic flows of viscoelastic fluids*

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GOVERNING EQUATIONS (1)

- Continuity: \( \frac{\partial u_i}{\partial x_i} = 0 \)
- Momentum: \( \rho \frac{\partial u_i}{\partial t} + \rho u_k \frac{\partial u_i}{\partial x_k} = - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ik}}{\partial x_k} \)
- Constitutive equation: \( \tau_{ij} = 2\eta_s D_{ij} + \tau_{ij,p} \)

\[ D_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]

\[ f\left(\tau_{kk,p}\right)\tau_{ij,p} + \lambda \left[ \frac{\partial \tau_{ij,p}}{\partial t} + \frac{\partial \left( u_k \tau_{ij,p} \right)}{\partial x_k} - \tau_{jk,p} \frac{\partial u_i}{\partial x_k} - \tau_{ik,p} \frac{\partial u_j}{\partial x_k} + \xi \left( \tau_{jk,p} D_{ik} + \tau_{ik,p} D_{jk} \right) \right] + \frac{\alpha \lambda}{\eta_p} \tau_{ik,p} \tau_{kj,p} \]

\[ f\left(\tau_{kk,p}\right) = \exp\left( \frac{\varepsilon \lambda}{\eta_p} \right) \]

- Newtonian solvent
- Polymer

\[ f\left(\tau_{kk,p}\right) = \begin{cases} 
\exp\left( \frac{\varepsilon \lambda}{\eta_p} \right) & \alpha = 0; \xi = 0, \varepsilon = 0: UCM or Oldroyd-B \\
\frac{\alpha \lambda}{\eta_p} \tau_{kk,p} \end{cases} \]

\[ f\left(\tau_{kk,p}\right) = 1 + \frac{\varepsilon \lambda}{\eta_p} \tau_{kk,p} \]

\[ \xi = 0, \varepsilon = 0: \text{Giesekus model} \]
GOVERNING EQUATIONS (2)

• Scalar (energy, species):
  \[ \frac{\partial (\rho \phi)}{\partial t} + \frac{\partial (\rho u_i \phi)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \Gamma \frac{\partial \phi}{\partial x_i} \right) + S \]

Modifications for standard conformation and log-conformation

\[ \rho \frac{\partial u_i}{\partial t} + \rho u_k \frac{\partial u_i}{\partial x_k} = -\frac{\partial p}{\partial x_i} + \eta_s \frac{\partial^2 u_i}{\partial x_i \partial x_k} + \frac{\eta_p}{\lambda} \frac{\partial A_{ik}}{\partial x_k} \]

\[ \tau_{ij,p} = \frac{\eta_p}{\lambda} \left( A_{ij} - \delta_{ij} \right) \]

\[ \lambda A_{ij} = -Y \left( A_{kk} \right) \left( A_{ij} - \delta_{ij} \right) \]

\[ Y \left( A_{kk} \right) = 1 + \varepsilon \left( A_{kk} - 3 \right) \]

\[ \frac{\partial \Theta_{ij}}{\partial t} + u_k \frac{\partial \Theta_{ij}}{\partial x_k} - \left( R_{ik} \Theta_{kj} - \Theta_{ik} R_{kj} \right) - 2E_{ij} = -\frac{Y \left( e^{\Theta_{ik}} \right)}{\lambda} \left( e^{-\Theta_{ij}} - \delta_{ij} \right) \]


\[ \Theta_{ij} = \log A_{ij} \]

More details for FVM:
Afonso et al. JNNFM 157 (2009) 55-65
NUMERICAL METHODS: SOLUTION OF THE GOVERNING EQUATIONS

- Finite-volume method (in-house code)
- Collocated block-structured mesh
- Non-orthogonal coordinates (Cartesian velocity and stress tensor)
- Diffusion: central differences (2\textsuperscript{nd} order in uniform mesh)
- SIMPLEC algorithm
- Rhie-and-Chow to couple velocity and pressure
- Special scheme to couple velocity and extra stress


- Advection: CUBISTA high-resolution scheme (based on QUICK, 3\textsuperscript{rd} order)


- Standard formulation and log-conformation formulation (allows higher De)


HYPERBOLIC SINGLE CHANNEL FLOW
Newtonian & Viscoelastic
Velocity Profiles along the Lateral Direction

Water

\[ Q = 1 \text{ ml/h} \]

\[ Re = 3.21 \]

Centre plane (y=0): experimental versus numerical

\[ Q = 3 \text{ml/h} \]
\[ Re = 9.62 \]

Predicted Streamlines

Numerical

Velocity Magnitude Contour Plot

Numerical

Experimental

Velocity magnitude (m/s)

0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00

Nearly constant acceleration on centreline

Purely extensional flow


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0.3% PEO

Hencky Strain $e_H = 2$

$Q = 1 \text{ ml/h}, \ Re = 13.2$
$De = 1.13$

$Q = 3 \text{ ml/h}, \ Re = 39.6$
$De = 3.40$

$Q = 5 \text{ ml/h}, \ Re = 66.0$
$De = 5.66$

$Q = 7 \text{ ml/h}, \ Re = 92.3$
$De = 7.93$

$Q = 9 \text{ ml/h}, \ Re = 119$
$De = 10.2$

$Q = 11 \text{ ml/h}, \ Re = 145$
$De = 12.5$
HYPERBOLIC CONTRACTION: VISCOELASTIC FLUIDS (2)

0.3% PEO: Q=0-0.2 ml/h

0.3% PEO: Q=7 ml/h
HYPERBOLIC FLUID RECTIFIER
FLUIDIC DIODE: HYPERBOLIC CONTRACTION

Planar geometry with hyperbolic shape

Nearly constant acceleration on centreline

Hencky strain, $\varepsilon_H = \ln(D_1/D_2) = 2.18$

42 identical elements, uniform depth= 50 µm

Sousa et al. JNNFM 165 (2010) 652-671
$Q = 0.1 \text{ ml h}^{-1} \quad Re = 0.594$

$Q = 5 \text{ ml h}^{-1} \quad Re = 29.7$

$Q = 20 \text{ ml h}^{-1} \quad Re = 119$

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No fluidic rectification effect

Sousa et al. JNNFM 165 (2010) 652-671
HYPERBOLIC FLUIDIC DIODE: VISCOELASTIC FLUID (I)

Sousa et al. JNNFM 165 (2010) 652-671

0.1% aqueous solution of PEO ($M_w=8\times10^6$ g mol$^{-1}$)

- Flow rate
  - 8x's higher
  - Similar Re

\[
De = \lambda \dot{\gamma} = \frac{\lambda U^2}{D^2/2}
\]

\[
Wi = \lambda \dot{\varepsilon} = \frac{\lambda (U_2 - U_1)}{L}
\]

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0.1% aqueous solution of PEO ($M_w=8\times10^6$ g mol$^{-1}$)

Rectifier effect:
more resistance in forward
Diodicity

\[ D_i \left|_Q \right. = \frac{\Delta p_{\text{forward}}}{\Delta p_{\text{backward}}} \]

PEO-8M: 0.1% wt aqueous solution PEO \((M_w=8 \times 10^6 \text{ g mol}^{-1})\)
PEO-2M: 0.1% wt aqueous solution PEO \((M_w=2 \times 10^6 \text{ g mol}^{-1})\)
PEO-8M+Glyc: 0.1% wt aqueous solution PEO \((M_w=8 \times 10^6 \text{ g mol}^{-1}) + 40 \text{ wt}% \text{ glycerol}\)
PEO-8M 100: 100 ppm aqueous solution PEO \((M_w=8 \times 10^6 \text{ g mol}^{-1})\)
PAA: 100 ppm aqueous solution of PAA \((M_w=8 \times 10^6 \text{ g mol}^{-1}) + 13 \text{ wt}%. \text{ sucrose} + 1 \text{ wt}.\% \text{ NaCl}\)

Microfluidic flows of viscoelastic fluids

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CROSS SLOT
2D CROSS SLOT: MOTIVATION

Newtonian (Re < 10^{-2})

PAA Boger fluid (Re < 10^{-2}, De=4.5)

Newtonian (Re = 0)

UCM (De=0.4)

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Due to the closer proximity of the sidewalls, simulations without rounded corners tend to mask this vertical streamline remains perfectly straight. Similar where the extensional birefringence strand is formed, the stresses are generated, while along the vertical line are clearly visible along the horizontal transient flow from rest to with rounded corners (specifically it corresponds to a one at higher elasticity albeit in this case in a geometry situation corresponding to a lower De towards an unstable plot of streamlines when the flow evolves from a stable instability. The inset of Fig.

In addition to identifying the physical mechanism for the appearance of perturbations that eventually lead to the bifurcation to asymmetric flow, our simulations also pro-

Consequence of continuity, fluid is pushed towards the central section of the horizontal channels and, as a two streams. This feature tends to reduce momentum on centerline velocity profile also included in Fig.

For the concave profile: fluid pushed towards center (smaller R)

High compressive stresses

Newtonian

\( De = 0.3 \)

\( De = 0.5 \) (symmetry imposed)

\( u_{(y = 0)} \)
Inertia decreases degree of asymmetry and stabilizes the flow

Inertia with UCM

Symmetric

Unsteady asymmetric

Steady asymmetric

Poole et al., PRL 99 (2007) 164503
Increasing the solvent viscosity
Increases $\text{De}_{\text{CR}}$
For $\beta > 3/9$ flow becomes asymmetric unsteady (as in flow focusing)
Increasing $\text{Re}$

- Increases $D_{CR}$
- Decreases degree of asymmetry

For $\text{Re} > 2$ unsteady asymmetric flow

Poole et al., SoR 2007
2D CROSS SLOT: OLDROYD-B — STABILITY MAP

$\beta = \frac{1}{9}$

Symmetric

Unsteady asymmetric

Steady asymmetric

Poole et al., SoR 2007
Increasing $\varepsilon$
- Increases $D_{ecr}$
- Decreases degree of asymmetry ($\varepsilon < 0.04$)
- Increases degree of asymmetry and extension in $De$ ($\varepsilon > 0.04$)
- Asymmetric stable flow disappears for $\varepsilon > 0.08$

Qualitatively as in flow focusing

Poole et al., SoR 2007

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2D CROSS SLOT: SPTT — STABILITY MAP

\[ \beta = \frac{1}{9} \]

Poole et al., SoR 2007

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FLOW FOCUSING
(Alternative extensional flow)
Operational Variables

\[ Q_1, Q_2 \]

\[ Q_3 = 2 \times Q_2 + Q_1 \]

Dimensionless Variables

\[ FR = \frac{Q_2}{Q_1} \]

\[ VR = \frac{U_2}{U_1} \quad (= FR) \]

\[ Re = \frac{\rho U_2 D}{\eta_0} \quad \left\{ \begin{array}{l} El = \frac{De}{Re} \\ De = \frac{\lambda U_2}{D} \end{array} \right. \]

All dimensions kept constant in experiments and calculations
FLOW FOCUSING: NEWTONIAN

Separation streamlines: nearly hyperbolic shape

Growing $Q_2$

$Q_1 = 0.01$ ml/h

$Q_2 = 0.3$ ml/h
$VR = 1, Re_3 = 2.8$

$Q_2 = 0.9$ ml/h
$VR = 3, Re_3 = 6.5$

$Q_2 = 15$ ml/h
$VR = 50, Re_3 = 94.2$

$Q_2 = 18$ ml/h
$VR = 60, Re_3 = 112.8$

$\epsilon_H = \ln \left( \frac{D_1}{D_3} \right) = \ln \left[ \frac{3}{2} (1 + 2VR) \right]$

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Recirculations

No Recirculations

\( VR = 50 \)
\( Re = 0 \)

\( VR = 50 \)
\( Re = 47 \)
FLOW FOCUSING: VISCOELASTIC INSTABILITIES

Oliveira et al. JNNFM 160 (2009) 31-39

UCM, 2D, Re=0

\[ \xi = \frac{1 - R}{1 + R} \]
\[ R = \frac{tr\mathbf{\tilde{W}}^2}{tr\mathbf{D}^2} \]

Astarita, JNNFM 6 (1979) 69
Thompson et al., JNNFM 86 (1999) 375
Mompean et al., JNNFM 111 (2003) 151

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FLOW FOCUSING: EFFECT OF VR

\[ F^* = \frac{F_W - F_E}{F_3} \]

Bistable flow
High VR:
constant \( D_{Ec} \)
evolution independent of VR
supercritical pitchfork bifurcation

\[ F^* = 0.59\sqrt{De} - 0.33 \]

Oliveira et al. JNNFM 160 (2009) 31-39
FLOW FOCUSING: EFFECT OF $\beta$

$$\beta = \frac{\eta_s}{\eta_s + \eta_p}$$

Oldroyd-B

$\beta$ stabilizes the flow
increases $De_c$
$\beta \geq 6/9$, no steady asymmetry

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FLOW FOCUSING: EFFECT OF $\varepsilon$

$\varepsilon$ stabilizes the flow
increases $D_{Ec}$
decreases degree of asymmetry
$\varepsilon \geq 0.04$ steady asymmetry disappears
(Transition directly to unsteady flow)

Similar levels of normal stresses
achieved near critical conditions
Extensional properties decisive
for onset of flow asymmetry
FLOW FOCUSING: EXPERIMENTS FOR PAA125 (I)

Olivera et al. JNNFM 160 (2009) 31-39

\[ Q_1 = 0.01 \text{ ml/h} \]

increasing \( Q_2 \)

\[ Q_2 = 0.05 \text{ ml/h}, \ VR = 5 \]
\[ Re = 0.23, \ De = 0.38 \]

Symmetric

\[ Q_2 = 0.2 \text{ ml/h}, \ VR = 20 \]
\[ Re = 0.87, \ De = 1.41 \]

Steady Asymmetric

\[ Q_2 = 0.5 \text{ ml/h}, \ VR = 50 \]
\[ Re = 2.15, \ De = 3.479 \]

Unsteady 3D
FLOW FOCUSING: NUMERICAL VERSUS EXPERIMENTS (PAA 125)

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Q_1 = 0.01 ml/h

Viscoelastic Experimental

Q_2 = 0.05 ml/h, VR = 5
Re = 0.23, De = 0.38

Q_2 = 0.1 ml/h, VR = 10
Re = 0.45, De = 0.723

Q_2 = 0.2 ml/h, VR = 20
Re = 0.87, De = 1.41

UCM 2D Calculations

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FLOW FOCUSING: UCM VERSUS OLDROYD-B

$Q_1 = 0.01 \text{ ml/h}$

UCM

2D Calculations

$Q_2 = 0.05 \text{ ml/h}, \ VR = 5$
$Re = 0.23, \ De = 0.38$

$Q_2 = 0.2 \text{ ml/h}, \ VR = 20$
$Re = 0.87, \ De = 1.41$

$Q_2 = 0.35 \text{ ml/h}, \ VR = 35$
$Re = 0.87, \ De = 1.41$

Oldroyd-B

2D Calculations

Unsteady 3D

Oliveira et al. JNNFM 160 (2009) 31-39
FLOW FOCUSING: NUMERICAL VERSUS EXPERIMENTS (PAA 125)
Oliveira et al. JNNFM 160 (2009) 31-39

 Experimental
PAA 125 + NaCl

 Numerical
UCM, 2D, Re=0

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3D CROSS SLOT
Uniaxial and biaxial
Planar extension

Uniaxial extension

\[ \dot{\varepsilon}_{ij} = \dot{\varepsilon}_0 \begin{bmatrix} -(m+1) & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

\[ m = 1 \]

\[ m = -\frac{1}{2} \]

\( \mathbf{l}_0 = 2:4 \)

\( \mathbf{l}_0 = 4:2 \)
3D CROSS SLOT: UNIAXIAL VERSUS BIAXIAL EXTENSION

Afonso et al., JNNFM 165 (2010) 743-751

Uniaxial

Biaxial

No steady asymmetric flow
MIXING SEPARATING CHANNEL
Non-dimensional gap size:
\[ \theta = \frac{g}{H} \]

Non-dimensional thickness:
\[ \alpha = \frac{a}{H} \]

Deborah number:
\[ De = \frac{\lambda U}{g} \]

Reynolds number:
\[ Re = \frac{\rho U H}{\eta} \]

Degree of flow reversal:
\[ R_r = \frac{q_2}{Q_1} \]
Weak effect of thickness (thin plates)
Reversed flow increases with $\alpha$ (gap size)

Inertia enhances flow reversal ($Re > 1$)

Agrees with experiments

Streamlines
\( \theta > 2 \)  
\( R_r \) increases with \( De \)

1.7 < \( \theta < 2 \)  
Steady bistable bifurcation

\( \theta < 1.7 \)  
\( R_r \) decreases with \( De \)

\( De_c \) varies slightly with \( \theta \)

Purely elastic instability and supercritical behavior never seen before, probably because of inertia.
Effect of inertia

At \( \text{De}=0 \), inertia raised \( R_r \)

Inertia delays bifurcation to higher \( \text{De} \)

Dramatic effect at large \( \theta \)
Trend reversed

\( \theta > 2 \) & large \( \text{De} \)
Inertia reduces \( R_r \)

\( 1.7 < \theta < 2 \)
Mixed behavior

\( \theta < 1.7 \)
Inertia raises \( R_r \)
PLANAR SUDDEN CONTRACTION
Very high Deborah number flows
Benchmark flow case (25 years ago)

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Two formulations:
StrT: low De
LogT: low & high De
De > 2.5: unsteady flow (StrT diverges at De = 3)

Very small Δt: \[ \Delta t = 10^{-5} \rightarrow \frac{n^o \text{ time steps}}{\lambda} = [5000; 25000] \]
2D 4:1 SUDDEN CONTRACTION: LIP VORTEX GROWTH REGIME

Lip vortex growth ($2.5 < De < 4.5$)


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Merging growth (4.5 < De < 8)

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Rio de Janeiro, Brazil, 14-16th July 2010

2D 4:1 SUDDEN CONTRACTION: ELASTIC VORTEX GROWTH REGIME

Elastic vortex growth (8 < De < 12)


Microfluidic flows of viscoelastic fluids
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2D 4:1 SUDDEN CONTRACTION: THIRD VORTEX GROWTH REGIME

Third vortex growth (12 < De < 17.5)

2D 4:1 SUDDEN CONTRACTION: VORTEX BACK SHEDDING

Vortex back-shedding (17.5 < De < 100 ?!!)


Microfluidic flows of viscoelastic fluids
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2D 4:1 SUDDEN CONTRACTION: OTHER RESULTS

Couette correction

\[ El = \frac{De}{Re} = \frac{\lambda \nu}{L^2} \]

Effect of inertia

Microfluidic flows of viscoelastic fluids
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Microfluidics: low Re & large De (contrasts with macro fluid dynamics)

Need to micro-fabrication of high quality: requires clean environments

Elastic instabilities observed & calculated at Re ≈ 0 → improved mixing

Distinct transitions: steady symmetric to steady asymmetric; steady asymmetric to unsteady flow; steady symmetric to unsteady

Log-conformation allows numerical calculations at very high De/Wi flows

Rich transitions in plane sudden contraction: path to elastic turbulence?

Other challenges: complex fluids with electrokinetic effects, surface tension gradients, surface patterning
ACKNOWLEDGEMENTS

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• Hatsopoulos Microfluidics Laboratory at MIT: Gareth McKinley, Chris Pipe, Soulages
• Dr. Rob Poole at University of Liverpool
• Prof. Paulo Oliveira at Universidade da Beira Interior
V BRAZILIAN CONFERENCE ON RHEOLOGY

July 14-16, 2010
Hotel Marina Palace
Rio de Janeiro, RJ, Brasil

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Promotion
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Palestras Convidadas/Invited Lectures

July 14, 9:00 am
Carbon nanotubes fluids: simple or complex?
Prof. M. Pasquali
Department of Chemical & Biomolecular Engineering and Chemistry, Rice University, Houston, TX, USA

July 14, 2:00 pm
A study on the flow, failure and rupture mechanisms of branched polyethylene in controlled-stress uniaxial extensional flow
Prof. J. M. Maia
Department of Macromolecular Science & Engineering, Case Western Reserve University, Cleveland, OH, USA

July 15, 9:00 am
Operator-splitting schemes for compressible viscoplastic fluids
Prof. R. R. Huilgol
Flinders University, Adelaide, Australia.

July 15, 2:00 pm
Rinse and Repeat: Turning liquids into soft adhesives
Prof. G. Fuller
Chemical Engineering Department, Stanford University, Palo Alto, CA, USA

July 16, 9:00 am
New perspectives in the modeling of non-Newtonian fluids
Prof. K. R. Rajagopal
Distinguished Professor, Texas A&M University, College Station, TX, USA

July 16, 2:00 pm
Microfluidic flows of viscoelastic fluids
Prof. F. T. Pinho
Department of Mechanical Engineering, Universidade do Porto, Porto, Portugal
Palestras técnicas/Technical presentations

BCR10-01 (July 16, 11:30am): Effect of sucrose and salt on the functional properties of iota-carrageenan
S. Janaswamy, B. K. Patel and O. H. Campanella

BCR10-02 (July 14, 11:10am): Bingham-Papanastasiou inertia flows simulated by a multi-field Galerkin Least-Squares method
H. P. Soto, M. L. Martins-Costa, C. Fonseca and S. Frey

BCR10-03 (July 15, 12:10pm): Rheo-SAS: small-angle-scattering techniques used in a combination with rheology
J. Lauger

BCR10-04 (July 16, 5:20pm): Differences between stress and strain control in the non-liner behavior of complex fluids
J. Lauger and H. Stettin

BCR10-05 (July 15, 3:00pm): Oil-in-water emulsions flow through constricted micro-capillaries
O. R. Castillo and M. S. Carvalho

BCR10-06 (July 14, 3:00pm): Simultaneous Rheometry and FTIR for the Determination of Molecular Structures
M. Feustel, C. Küchenmeister, H. M. Petri and J. Nijman

BCR10-07 (July 14, 3:20pm): Rheological behavior of mesophase petroleum pitches
A. M. dos Santos, L. D. de Castro, C. H. M. C. Dutra

BCR10-08 (July 16, 10:50am): Analysis of fluidity, yield stress and plastic viscosity of cement pastes with different types of adds of mineral aiming production of concrete self-compacting
M. O. de Vita, M. P. Barbosa, G. F. Maciel and W. L. Repette

BCR10-09 (July 14, 3:40pm): Prediction of rheological behavior with pressure and temperature for synthetic fluid
P. E. Aranha, A. L. Martins and R. A. Gandelman

BCR10-10 (July 14, 12:10pm): Rheological sol-gel transition temperature of high-acyl gellan with monovalent cations
E. Flores-Hicochea, A. Tecante and M. Ramirez-Gilly

BCR10-11 (July 15, 5:00pm): Tixotropic behavior of drilling muds
F. H. Marchesini, A. A. Alicke and P. R. de Souza Mendes

BCR10-12 (July 15, 5:20pm): Rheology of waxy oils
F. H. Marchesini, A. A. Alicke and P. R. de Souza Mendes
BCR10-13 (July 16, 3:40pm): Transitions in low shear by development of the boundary layer
R. da C. Cruz, C. A. V. Junior

BCR10-14 (July 16, 12:10pm): Thermo-rheological characterization of materials
A. Gaspar-Rosas, T. Chen and L. Waguespack

BCR10-15 (July 14, 5:00pm): Effect of enzymatic treatment, shear stress and temperature on the rheological behavior of blackberry (Rubus spp.) juice
M. C. P. de A. Santiago, A. C. M. S. Gouvêa, L. M. C. Cabral, D. S. Couto, R. L. O. Godoy and S. P. Freitas

BCR10-16 (July 14, 4:40pm): Relationship between Physical Stability of Dispersions and their Rheological Properties
D. Lerche and H. M. Petri

BCR10-17 (July 14, 11:30am): A numerical investigation of the inertia influence on SMD fluid flows
D. D. dos Santos, S. Frey and M. F. Naccache

BCR10-18 (July 15, 3:40pm): Use of inclined plane test to determine yield stress of cement pastes
M. P. Barbosa, G. F. Maciel, N. I. O. Barbosa, R. P. Barbosa and R. P. Santos

BCR10-19 (July 14, 5:20am): Rheological characterization of suspensions of cassava starch and maize starch with purified cashew tree gum

BCR10-20 (July 14, 10:10am): Finite element approximations for Maxwell-B fluid flows employing the GLS method
C. Fonseca, L. Adamatti, S. Frey and M. F. Naccache

BCR10-21 (July 16, 10:10pm): Propagation of singular surface in viscoelastic and viscoplastic fluids
R. Huilgol

BCR10-22 (July 14, 10:50am): A stabilized mixed FEM for Ellis constitutive model
J. Karam F., J. N. C. Guerreiro and A. F. D. Loula

BCR10-23 (July 16, 3:00am): Rheological behavior and drag reduction evaluation of poly (acrylamide-G-polyoxide) dispersions
R. V. Pires, R. S. de Oliveira and E. F. Lucas

BCR10-24 (July 15, 3:20pm): Evaluation of the rheological behavior of crude oil emulsions
N. A. Ramos, M. A. Sant’Anna, R. V. Pires, M. Khalil and E. F. Lucas

BCR10-25 (July 15, 4:40pm): Fluidity evaluation of the n-paraffin, used as drilling fluids, through rheological measurements

BCR10-26 (July 15, 11:30am): Numerical-experimental confrontation of roll waves in mud
G. H. Fiorot, G. F. Maciel, C. Kitano and F. O. Ferreira

BCR10-27 (July 16, 3:20pm): Compositional influence on cement slurries rheological properties
J. M. Rocha, V. Calado and F. Tavares

BCR10-28 (July 16, 4:40pm): Liquid-liquid displacement flows in a hele-shaw cell including non-newtonian effects
P. R. de Souza Mendes, P. R. Vargas, P. Emidio, A. T. de A. Waldman and A. L. Martins

BCR10-29 (July 14, 4:00pm): Applications of rheology for cosmetic emulsion stability prediction

BCR10-30 (July 16, 9:50am): An asymptotic non-newtonian model for well cementation process
F. C. Gomes and M. S. Carvalho

BCR10-31 (July 14, 11:50am): Computational analysis of some diameter dependent blood rheological models
M. A. Bortoloti and J. Karam F.

BCR10-32 (July 16, 11:50am): Rheological properties of suspensions model which imitate broths fermentation using a mixer viscometer
D. Cantú-Lozano, V. R. N. Telis and J. Telis-Romero

BCR10-33 (July 16, 5:00pm): Emulsion flow in porous media: network model and experiments
M. Romero, V. Alvarado and M. S. Carvalho

BCR10-34 (July 15, 11:10am): Breakup of viscoelastic liquid curtain
M. Becerra and M. S. Carvalho

BCR10-35 (July 15, 11:50am): Rheological properties of thermolyzed yeast paste
V. R. N. Telis, C. H. Garcia-Cruz and J. Telis-Romero

BCR10-36 (July 16, 11:10am): Rheological behavior of fermented dairy beverages obtained from the ultra-high pressure homogenization

BCR10-37 (July 15, 9:50am): Elastic effects in viscoplastic liquids flowing through an expansion followed by a contraction
M. F. Naccache, P. R. de Souza Mendes and B. Nassar

BCR10-38 (July 14, 9:50am): Jeffreys-like model for elasto-viscoplastic thixotropic fluids
P. R. de Souza Mendes
BCR10-39 (July 15, 4:00pm): Startup flow of gelled crudes in pipelines
P. R. de Souza Mendes, F. S. M. A. Soares and C. Ziglio

BCR10-40 (July 15, 10:50am): In the way of integrating rheometry with computational fluid dynamics for the polymer industry
T. M. Farias, J. L. Favero, A. R. Secchi, J. Oliveira and N. Cardozo

BCR10-41 (July 15, 10:10am): Fraction of residual mass and flow regimes in capillary liquid displacement with power-law and visco-plastic materials as displacing fluids
J. F. Freitas, E. J. Soares and R. L. Thompson

BCR10-42 (July 16, 5:20am): A measure of the Deborah number
K. R. Rajagopal and R. L. Thompson