OUTLINE

- CEFT: brief outline of research areas
- CEFT: Non-Newtonian Fluid Mechanics and Microfluidics
- Definition, applications and motivation. Non-dimensional numbers.
- Experimental and numerical methods
- Some results
  - Hyperbolic contraction: single & fluidic diode, Newtonian & viscoelastic
  - Blood analogues in hyperbolic contraction
  - Elastic instabilities: cross slot, flow focusing
  - Deformation of RBCs in a hyperbolic channel
  - Motion of RBCs in µ-converging bifurcation (another presentation/poster)
  - Microfluidic device for RBC separation (another presentation/poster)
- Closure
**RELEVANCE & MOTIVATION**

- (1) Complex fluids: biological systems, man-made systems (micro and macro systems), challenging/interesting

- (2) Microfluidics with complex fluids: new phenomena, new applications: ex. 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

\[
Re = \frac{pUL}{\eta} = \frac{UL}{V}
\]

\[
De = \frac{t_{\text{fluid}}}{t_{\text{flow}}} = \frac{\lambda}{L} = \frac{\lambda U}{L}
\]

Small \( \Gamma, Pe \) is large

\[
Pe = \frac{U}{L} = \frac{UL}{L} = Re \cdot Pr = Re \cdot Sc
\]

Short transit times

Poor mixing

**DEFINITION AND APPLICATIONS**

- Fluid mechanics at the micro-scale: 100 nm - 500 \( \mu \)m
  nanofluidics: 10 nm - 1 \( \mu \)m

- Handles nano- & pico-liters 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**

**EXPERIMENTAL METHODS: MICROFABRICATION BY SOFT LITHOGRAPHY**

1. Silicon Wafer

2. Spin coat photosist SU-8 and prebake

3. Spin coat barrier coat (CEM-BC7.5) and contrast enhancer (CEM 38SSS) (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

**Boiling heat transfer**

\[ \text{Zhang et al., JMS 11 (2002) 12-19} \]

**Cross-slot:**

extension of single DNA molecules

\[ \text{Perkins et al. Science 276 (1997)2016} \]

**More Applications**

Capillary instabilities:
flow focusing and droplet formation

\[ \text{Anna et al., APL 82 (2003) 364} \]

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MICROGEOMETRIES

Planar hyperbolic contraction-sudden expansion

Abrupt contraction-expansion (CR=ER=16)

Hyperbolic contraction (ε = 2)

Accuracy of dimensions to within 5%
Near vertical walls: tapering angle 87° < θ < 92°

SEM Images

400 µm

54 µm

50 µm

87° < θ < 92°

Cross-slot and flow focusing devices

Confocal µPIV

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

EXPERIMENTAL METHODS: FLOW VISUALIZATION & MICRO-PIV

Digital camera (Leica DFC 350 FX)
Syringe pump (Harvard apparatus PHD 2000)

Data acquisition card (NI-6218)
Microscope Leica DMI5000 M

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

Objectives used:
10X:0.25NA
5X:0.12NA

Differential pressure sensor (Honeywell 26FC series)

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**EXPERIMENTAL METHODS: PRESSURE MEASUREMENTS**

Acquisition Card

Voltage output, V

Pressure output

Calibration

Pressure sensor

Average steady state region to obtain a single data point (Q, ΔP)

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**EXPERIMENTAL METHODS: RHEOLOGY**

**DATA FOR FLOW FOCUSING**

Viscoelastic fluid: PAA 125 ppm + 1% NaCl

Newtonian fluid: water

Shear, *Physica MCR 301*

(cone-plate, d= 75 mm, 1°)

T = 20°C

GOVERNING EQUATIONS (1)

- Continuity: \( \frac{\partial u}{\partial x} = 0 \)
- Momentum: \( \rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{i,j}}{\partial x_j} \)
- Constitutive equation: \( \tau_{i,j} = 2\eta \frac{\partial D_{i,j}}{\partial x_j} + \tau_{i,j}^{\varepsilon} \)

where:

- \( \tau_{i,j}^{\varepsilon} \) is the stress tensor due to the polymer
- \( \eta \) is the dynamic viscosity
- \( D_{i,j} \) is the rate of strain tensor

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

Newtonian solvent

Polymer

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**Shear rheology, Physica MCR 301**

Extensional rheology, Haake CaBER 1
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

\[ \rho \frac{\partial t}{\partial t} + \rho u_i \frac{\partial t}{\partial x_i} = - \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 t}{\partial x_i^2} + \frac{\partial}{\partial x_i} \left( \frac{\partial t}{\partial x_i} \right) \]

\[ \Gamma = \frac{\eta}{\lambda} \left( A_v - \delta_y \right) \]

\[ v = -Y \left( A_y \right) \left( A_y - \delta_y \right) \]

\[ Y \left( A_y \right) = 1 + e \left( A_y - 3 \right) \]

\[ \Theta_j = \log A_j \]

More details for FVM:


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 (2nd 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, 3rd order)

Alves et al. [NMF, 41 (2003) 47-75.

Standard formulation and log-conformation formulation (higher De)


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HYPERBOLIC SINGLE CHANNEL FLOW
Newtonian & Viscoelastic

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HYPERBOLIC CONTRACTION: NEWTONIAN FLUIDS (1)

Water

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

\[ Re = 3.21 \]

Centre plane (y=0): experimental versus numerical


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**HYPERBOLIC CONTRACTION: NEWTONIAN FLUIDS (2)**

Centre plane (y=0): experimental versus numerical

Q = 3 ml/h
Re = 9.62

Nearly constant acceleration on centreline

**Predicted Streamlines**
- Numerical
- Experimental

**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

Purely extensional flow


**HYPERBOLIC CONTRACTION: VISCOELASTIC FLUIDS (1)**

0.3% PEO

0.3% PEO: Q=0-0.2 ml/h
0.3% PEO: Q=7 ml/h

**0.3% PEO**
- Q = 1 ml/h, Re = 13.2, De = 1.13
- Q = 3 ml/h, Re = 39.6, De = 3.40
- Q = 5 ml/h, Re = 66.0, De = 5.66

- Q = 7 ml/h, Re = 92.3, De = 7.93
- Q = 9 ml/h, Re = 119, De = 10.2
- Q = 11 ml/h, Re = 145, De = 12.5

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**HYPERBOLIC CONTRACTION: VISCOELASTIC FLUIDS (2)**

**0.3% PEO:**
- Q=0-0.2 ml/h
- Q=7 ml/h

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**MICROFLUIDICS: RELEVANT PAST WORK ON ELASTIC INSTABILITIES**


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**

\[
\frac{\lambda U}{\nabla \cdot e_{11}} \geq M_{\text{crit}}^2
\]

on curved streamlines

**Instability growth to elastic turbulence**

Groissman & Steinberg, Nature 405 (2000) 53

**Microfluidics & viscoelasticity**

Squires & Quake, Rev. Mod. Phys. 77 (2005) 977

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HYPERBOLIC FLUID RECTIFIER

FLUIDIC DIODE: HYPERBOLIC CONTRACTION
- Planar geometry with hyperbolic shape
- Nearly constant acceleration on centreline
  
  \[ \text{Hencky strain, } \varepsilon_H = \ln\left(\frac{D_1}{D_2}\right) = 2.18 \]

Purely extensional flow

42 identical elements, uniform depth = 50 µm

**HYPERBOLIC FLUIDIC DIODE: NEWTONIAN FLUID (1)**

\[ Q = 0.1 \text{ ml h}^{-1} \quad Re = 0.594 \]
\[ Q = 5 \text{ ml h}^{-1} \quad Re = 29.7 \]
\[ Q = 20 \text{ ml h}^{-1} \quad Re = 119 \]

No fluidic rectification effect

**HYPERBOLIC FLUIDIC DIODE: NEWTONIAN FLUID (2)**

Pressure drop

\[ \Delta P / \text{kPa} \]

\[ Q / \text{ml h}^{-1} \]

No fluidic rectification effect
BLOOD ANALOGUES: RHEOLOGY

Sousa et al., BioMicrofluidics 5 (2011) 14108

500 ppm XG + water
125 ppm PAA + water

POLYACRYLAMIDE (PAA) ANALOGUE: FORWARD

Sousa et al., BioMicrofluidics 5 (2011) 14108

XANTHAM GUM (XG) ANALOGUE: FORWARD

Sousa et al., BioMicrofluidics 5 (2011) 14108
ELASTIC INSTABILITIES

CROSS SLOT
2D CROSS SLOT WITH UCM: EFFECT OF INERTIA

Poole et al., PRL 99 (2007) 164503

Inertia with UCM

Inertia decreases degree of asymmetry and stabilizes the flow

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2D CROSS SLOT: OLDROYD-B — EFFECT OF SOLVENT — CREEPING FLOW

Poole et al., SoR 2007

Increasing the solvent viscosity
Increases \( \beta \)
For \( \beta > 3/9 \) flow becomes asymmetric unsteady (as in flow focusing)

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2D CROSS SLOT: OLDROYD-B — SOLVENT AND INERTIA

Poole et al., SoR 2007

Increasing Re
Increases \( \beta \)
Decreases degree of asymmetry
For Re > 2 unsteady asymmetric flow

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2D CROSS SLOT: OLDROYD-B — STABILITY MAP

Poole et al., SoR 2007

\( \beta = \frac{\eta_s}{\eta_s + \eta_p} \)

Unsteady asymmetric
Steady asymmetric
Symmetric

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Increasing $\varepsilon$ increases degree of asymmetry ($\varepsilon < 0.04$).
Decreases degree of asymmetry and extension in $De$ ($\varepsilon > 0.04$).
Asymmetric stable flow disappears for $\varepsilon > 0.08$.

Qualitatively as in flow focusing.

ELASTIC INSTABILITIES
FLOW FOCUSING
(Alternative extensional flow)

FLOW FOCUSING

Outflow $Q_3$,

Inflow $Q_1$, $Q_2$

$Q_3 = 2 \times Q_2 + Q_1$

Operational Variables

$FR = \frac{Q_3}{Q_1}$

$VR = \frac{U_2}{U_1}$

$Re = \frac{\rho U_1 D}{\eta_0}$

$De = \frac{\lambda U_1 D}{\eta_0}$

$El = \frac{De}{Re}$

Dimensionless Variables

All dimensions kept constant in experiments and calculations.

Operational Variables

$Q_1, Q_2$

$Q_3 = 2 \times Q_2 + Q_1$

Dimensionless Variables

$FR = \frac{Q_3}{Q_1}$

$VR = \frac{U_2}{U_1}$

$Re = \frac{\rho U_1 D}{\eta_0}$

$De = \frac{\lambda U_1 D}{\eta_0}$

$El = \frac{De}{Re}$

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

Separation streamlines: nearly hyperbolic shape

\[ \epsilon = \ln \left( \frac{D_1}{D_3} \right) = \ln \left( \frac{3}{2} (1 + 2V_R) \right) \]

Increasing \( Q_2 \)

\( Q_1 = 0.01 \text{ ml/h} \)

\( Q_1 = 0.3 \text{ ml/h} \)
\( VR = 1, Re_3 = 2.8 \)

\( Q_1 = 0.9 \text{ ml/h} \)
\( VR = 3, Re_3 = 6.5 \)

\( Q_1 = 15 \text{ ml/h} \)
\( VR = 50, Re_3 = 94.2 \)

\( Q_1 = 18 \text{ ml/h} \)
\( VR = 60, Re_3 = 112.8 \)

FLOW FOCUSING: 3D EFFECTS & NEWTONIAN (2)

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No Recirculations
Recirculations

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

\( VR = 50 \)
\( Re = 47 \)

FLOW FOCUSING: VISCOELASTIC INSTABILITIES

UCM, 2D, Re=0

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: 3D effects & Newtonian (2)

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

Flow focusing: effect of VR

\( F^* = \frac{F_W - F_E}{F_1} \)

Bistable flow
High VR:
constant De:
evolution independent of VR:
supercritical pitchfork bifurcation

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

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FLOW FOCUSING: EFFECT OF $\beta$

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

$\beta$ stabilizes the flow increases $D_e$

$\beta \geq \frac{6}{9}$, no steady asymmetry

FLOW FOCUSING: EXPERIMENTS FOR PAA125 (1)

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

$Q_2 = 0.05 \text{ ml/h}$, $VR = 5$

$Re = 0.23$, $De = 0.38$

$Q_2 = 0.2 \text{ ml/h}$, $VR = 20$

$Re = 0.87$, $De = 1.41$

$Q_2 = 0.5 \text{ ml/h}$, $VR = 50$

$Re = 2.15$, $De = 3.479$

FLOW FOCUSING: NUMERICAL VERSUS EXPERIMENTS (PAA 125)

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

$Q_2 = 0.05 \text{ ml/h}$, $VR = 5$

$Re = 0.23$, $De = 0.38$

$Q_2 = 0.1 \text{ ml/h}$, $VR = 10$

$Re = 0.45$, $De = 0.723$

$Q_2 = 0.2 \text{ ml/h}$, $VR = 20$

$Re = 0.87$, $De = 1.41$
FLOW FOCUSING: UCM VERSUS OLDROYD-B

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

**UCM 2D Calculations**

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

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

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

**Oldroyd-B 2D Calculations**

**Unsteady 3D**

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

FLOW FOCUSING: NUMERICAL VERSUS EXPERIMENTS (PAA 125)

**Experimental**

PAA 125 + NaCl

**Numerical**

UCM, 2D, Re=0

Re = 0.23, De = 0.38

Re = 0.87, De = 1.41

Unsteady 3D

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

3D CROSS SLOT

**Uniaxial and biaxial**

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

3D CROSS SLOT: FLOW CONFIGURATIONS

**Planar extension**

\[ l_o = 2:4 \]

\[ m = 1 \]

\[ \mathbf{e}_1 = \mathbf{e}_6 \begin{bmatrix} -(m+1) & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

**Uniaxial extension**

\[ l_o = 4:2 \]

\[ m = -\frac{1}{2} \]
3D CROSS SLOT: UNIAXIAL VERSUS BIAXIAL EXTENSION
Afonso et al., JNNPM 165 (2010) 743-751

Uniaxial
Biaxial

FLUIDS, GEOMETRY & SET-UP
Yaginuma et al. Nanotech Microtech (2011)

Deformation Index

DI = \frac{X - Y}{X + Y}

DI = 0
DI = 0.5

DEFORMATION OF RED BLOOD CELLS IN A HYPERBOLIC SYSTEM

FLOW

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June 2011

June 2011
FLOW: ZOOMING

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CLOSURE

- Microfluidics: low Re & large De (contrasts with macro fluid dynamics)
- Microfabrication: essential to have good quality & clean environment
- 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?
- Effect of flow on RBC distribution and deformation history (extensional flow)

- Challenges: complex fluids with electrokinetic effects, surface tension gradients, surface patterning, magnetic fields, acoustics
- Flow of blood and blood analogues: complex, requires good rheology

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REFERENCES

Yaginuma et al. Nanotech Microtech (2011)