FLOW OF A NEWTONIAN AND A SHEAR-THINNING VISCOELASTIC FLUID THROUGH 3D CONTRACTIONS: EXPERIMENTS AND SIMULATIONS

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MOTIVATION

Contraction flows through planar and axisymmetric arrangements are the most common studied;

- Well predicted using 2D numerical simulations;

Flows with 3D effects are scarse;

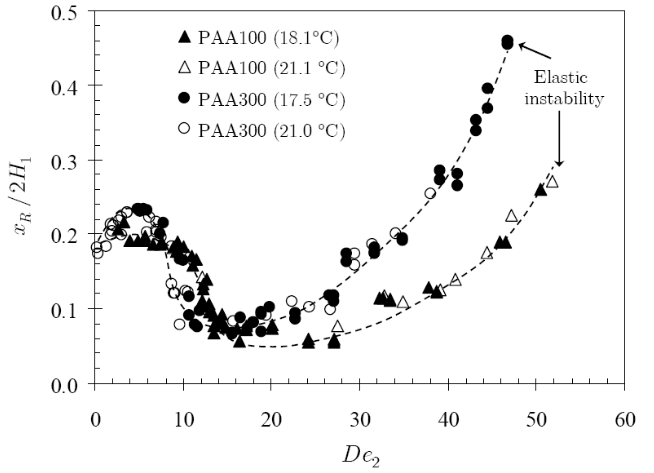
- Important for validation of 3D numerical codes

Visualizations of Boger fluid flows in a 4:1 square–square contraction,
M.A. Alves, F.T. Pinho, P.J. Oliveira, AIChE J. 51 (2005) 2908–2922.

Experimental and numerical (Newtonian) work;

Boger fluid (polyacrylamide, PAA-based);

4:1 Square-Square contraction;



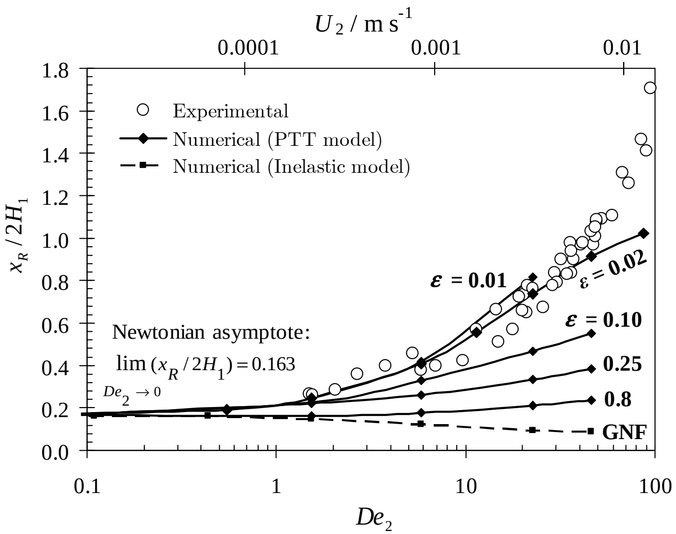
MOTIVATION

Viscoelastic flow in a 3D square/square contraction: visualizations and simulations
M.A. Alves, F.T. Pinho, P.J. Oliveira, J. Rheol. 52 (2008) 1347–1368.

Experimental and numerical work;

Shear-thinning fluid (PAA-based, 500 ppm);

4:1 Square-Square contraction;



Previous work

Three-dimensional flow of Newtonian and Boger fluids in square–square contractions

P.C. Sousa, P.M. Coelho, M.S.N. Oliveira and M.A. Alves

J. Non-Newtonian Fluid Mech. 160 (2009) 122–139

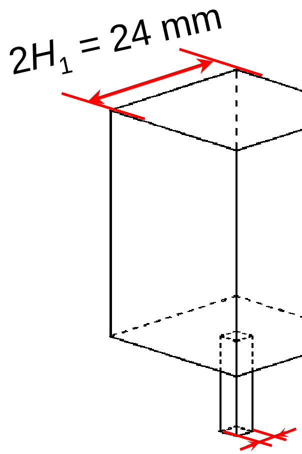
SUMMARY

Study of 3D SQ-SQ contraction flows

Different contraction ratios, CR

Fluids studied:
Newtonian
Viscoelastic

Numerical ↔ **Experimental**



$$CR = \frac{H_1}{H_2}$$

$CR = 2.4, 4, 8$ and 12

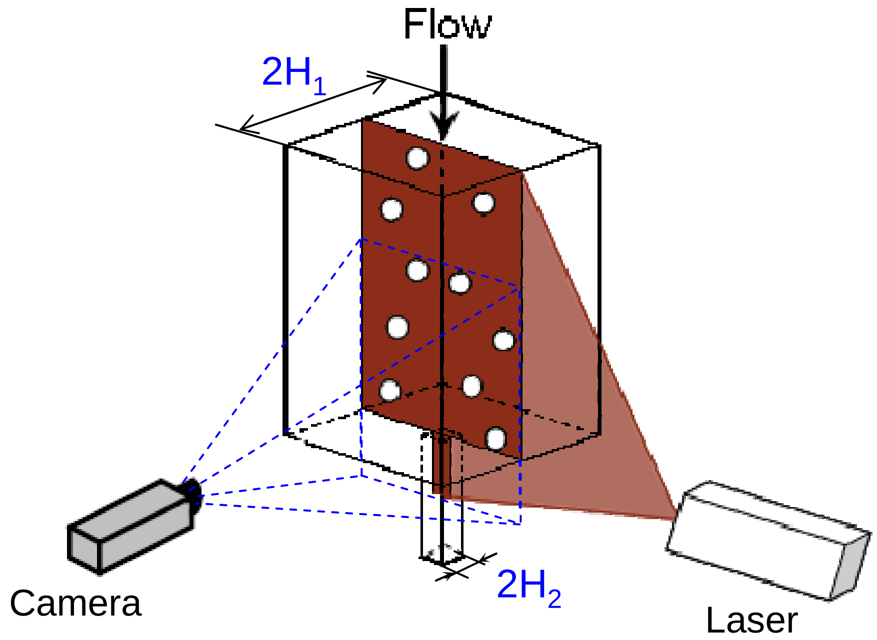
Experimental set-up made of transparent acrylic

Working Fluids:

Newtonian: 85 wt.% aqueous solution of glycerol;

Viscoelastic: 600 ppm aqueous solution of polyacrylamide with 60% glycerol

Seeded with 10 μm PVC tracer particles

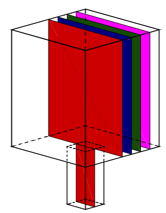


Experimental Techniques used:

Streak line photography

Particle Image Velocimetry (PIV)

Investigation of the flow at different planes of the square duct.



RHEOLOGICAL CHARACTERISATION

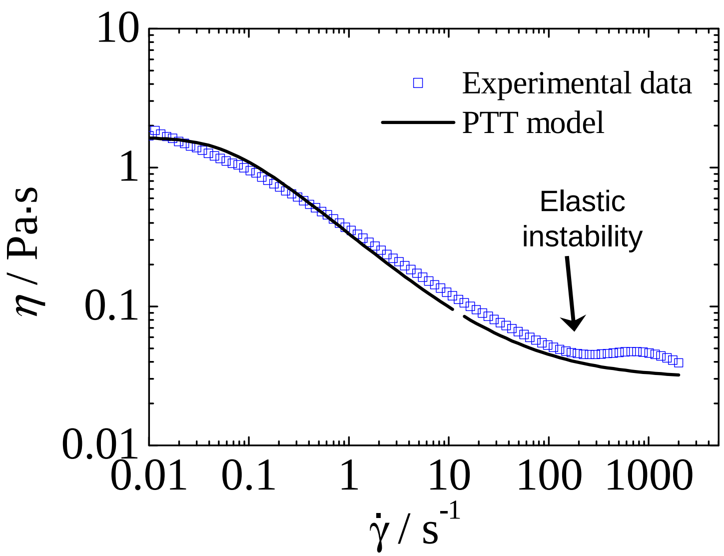
• Steady shear measurements were performed with a shear rheometer (Anton Paar, model Physica MCR 301) → 20.0 ºC

Newtonian:

$\rho\,|_{20ºC}$ (kg·m^{-3})	$\eta\,|_{20ºC}$ (Pa·s)
1221	0.0982

Viscoelastic:

$\rho\,|_{20ºC}$ (kg·m^{-3})
1156



Experimental data fitted using a **PTT model**:

- One mode with solvent contribution;

- Parameters:

ε = 0.06
λ = 32 s
$\eta_{polymer}$ = 1.62 Pa·s
$\eta_{solvent}$ = 0.03 Pa·s
$\zeta = 0$

NUMERICAL METHOD

Laminar flow of an incompressible viscoelastic fluid;

Mass conservation

$$\nabla \cdot \mathbf{u} = 0$$

Momentum conservation

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \eta_S \nabla^2 \mathbf{u}$$

Constitutive equation, based on the CONFORMATION TENSOR, A)

$$\lambda\left(\frac{D\mathbf{A}}{Dt} - (\nabla\mathbf{u})\mathbf{A} - \mathbf{A}(\nabla\mathbf{u})^T\right) = -Y(\mathrm{tr}\mathbf{A})(\mathbf{A}-\mathrm{I})$$

Phan-Thien and Tanner model (0<β<1);

$$\beta \equiv \frac{\eta_S}{\eta_0} = \frac{\eta_S}{\eta_S + \eta_P}$$

⇓

$$\boldsymbol{\tau} \equiv \frac{\eta_P}{\lambda}(\mathbf{A} - \mathbf{I})$$

NUMERICAL METHOD

Finite Volume Method;

(Oliveira, Pinho, Pinto, J. Non-Newt. Fluid Mech. **79** (1998) 1–43)

Log-conformation;

(Afonso, Oliveira, Pinho and Alves, J. Non-Newt. Fluid Mech. **157** (2009) 55–65)

Discretisation

Diffusive terms - **Central differences;**

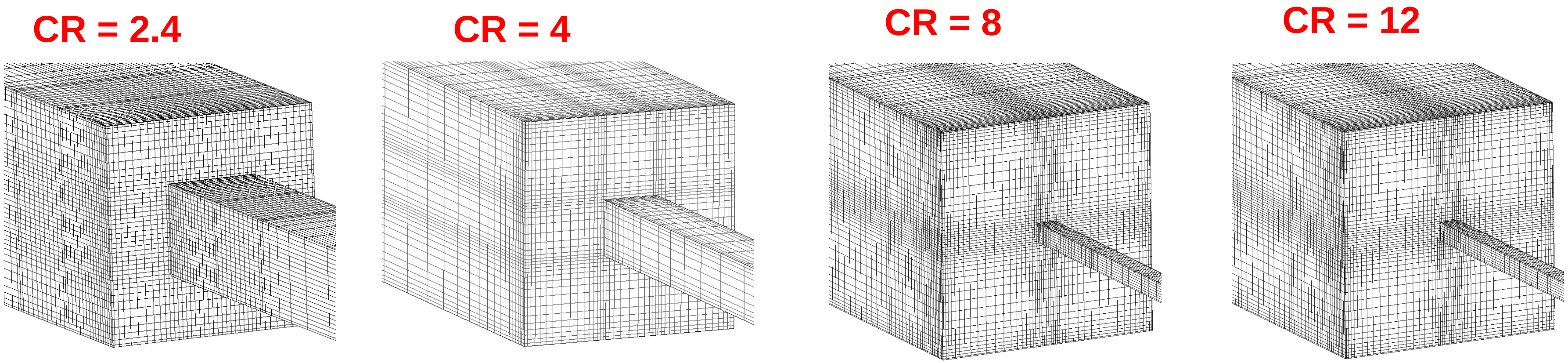
Time derivative terms – **2nd order scheme;**

Advective terms – High resolution scheme – **CUBISTA;**

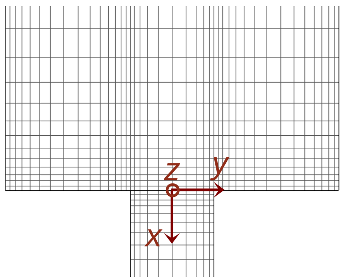
(Alves, Oliveira, Pinho, Int. J. Numer. Methods Fluids **41** (2003) 47–75)

COMPUTATIONAL MESHES

Orthogonal blocks and non-uniform cells;



	CR = 2.4	CR = 4	CR = 8	CR = 12
Total number of cells	82000	51000	83300	113664
$\Delta x/2H_1$	2.08×10^{-2}	1.31×10^{-2}	7.50×10^{-3}	1.29×10^{-4}
$\Delta y/2H_1 = \Delta z/2H_1$	1.99×10^{-2}	1.25×10^{-2}	7.50×10^{-3}	1.14×10^{-4}



Boundary conditions: - No-slip at the walls;

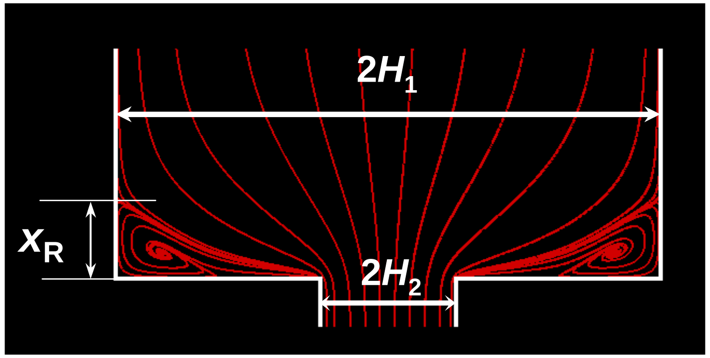
- Inlet and outlet located far from the contraction plane;
- Fully developped flow conditions.

RESULTS – Newtonian Fluid Flow

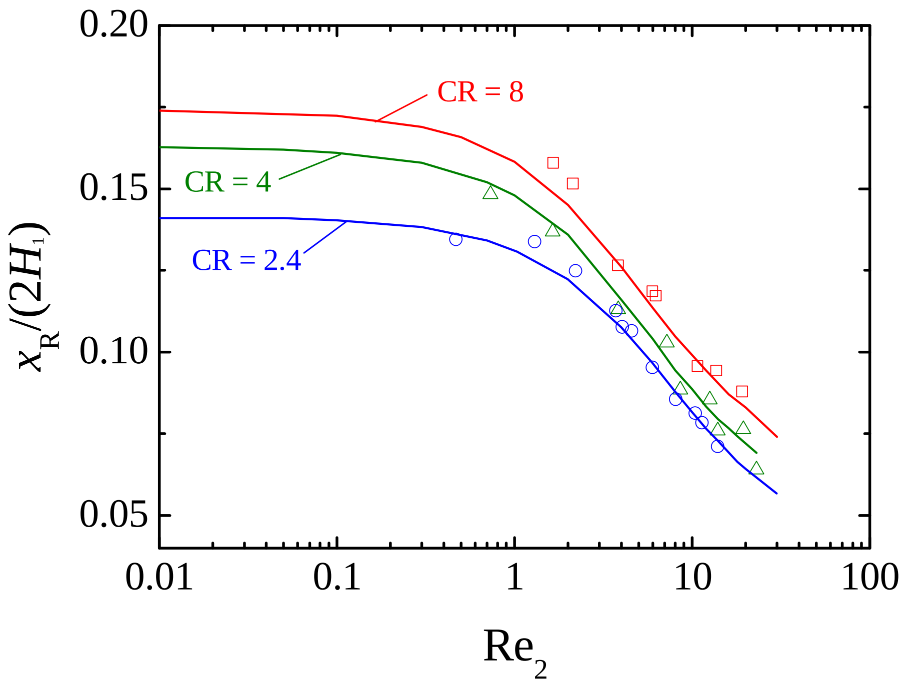
Reynolds Number

$$Re_2 = \frac{\rho U_2 (2H_2)}{\eta}$$

$\eta(\dot{\gamma})$



Vortex Length – Centre plane



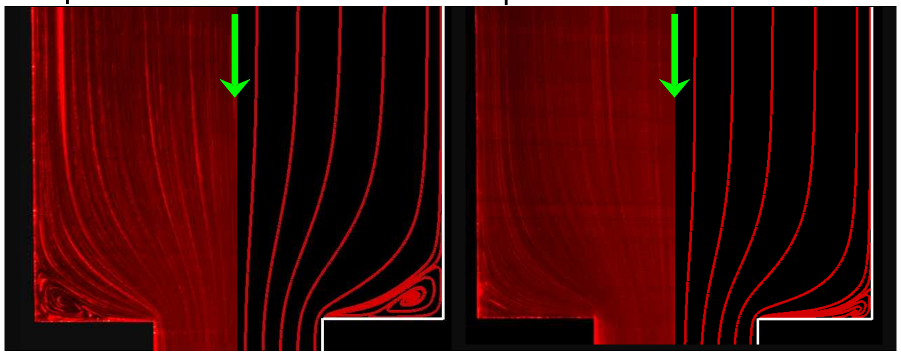
- Increasing the inertia of the flow, the vortex length decreases;
- When $Re_2 \rightarrow 0$, the vortex length tends to an asymptotic value dependent on CR;

RESULTS – Newtonian fluid flow

Flow Patterns – Centre plane

CR = 2.4

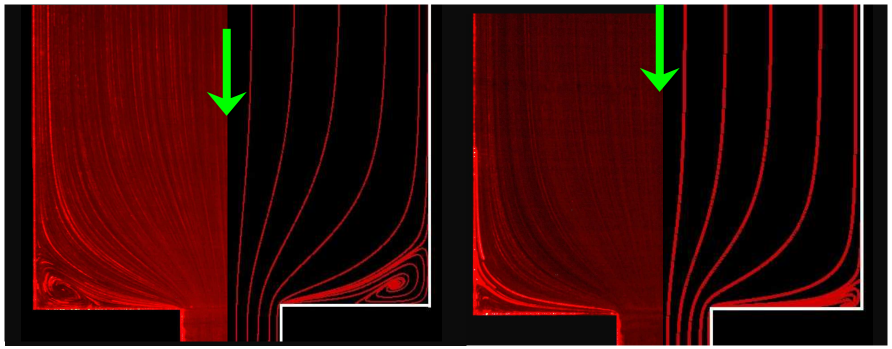
Experimental Numerical Experimental Numerical



$Re_2 = 0.468$ $Re_2 = 14.0$

CR = 4

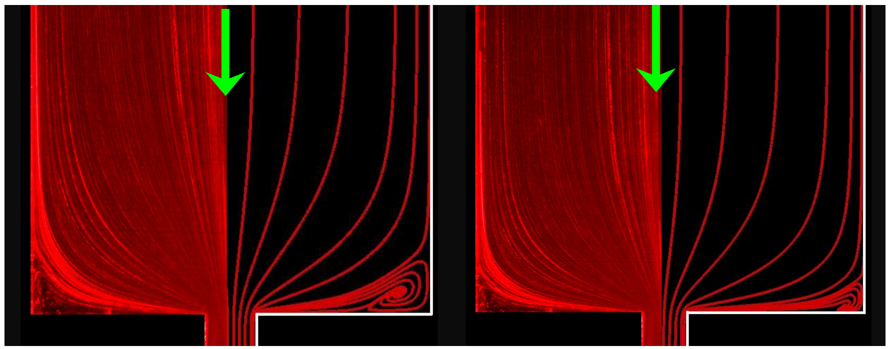
Experimental Numerical Experimental Numerical



$Re_2 = 0.732$ $Re_2 = 23.1$

CR = 8

Experimental Numerical Experimental Numerical

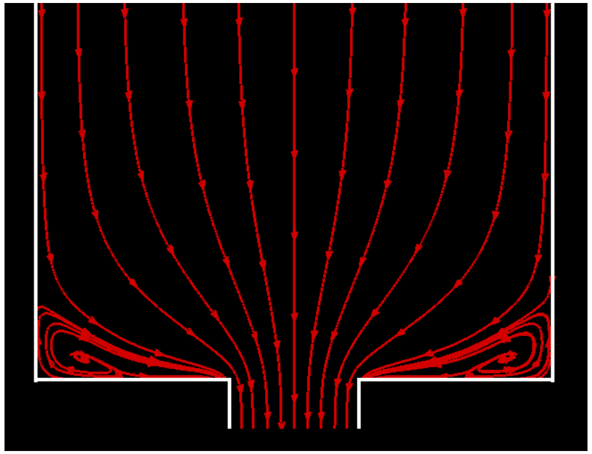


$Re_2 = 1.65$ $Re_2 = 19.1$

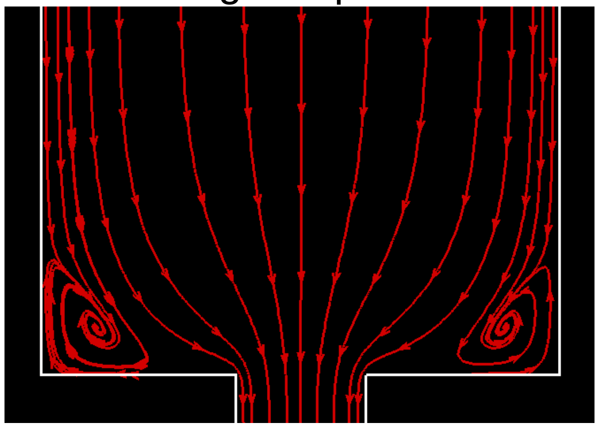
RESULTS – Newtonian Fluid Flow

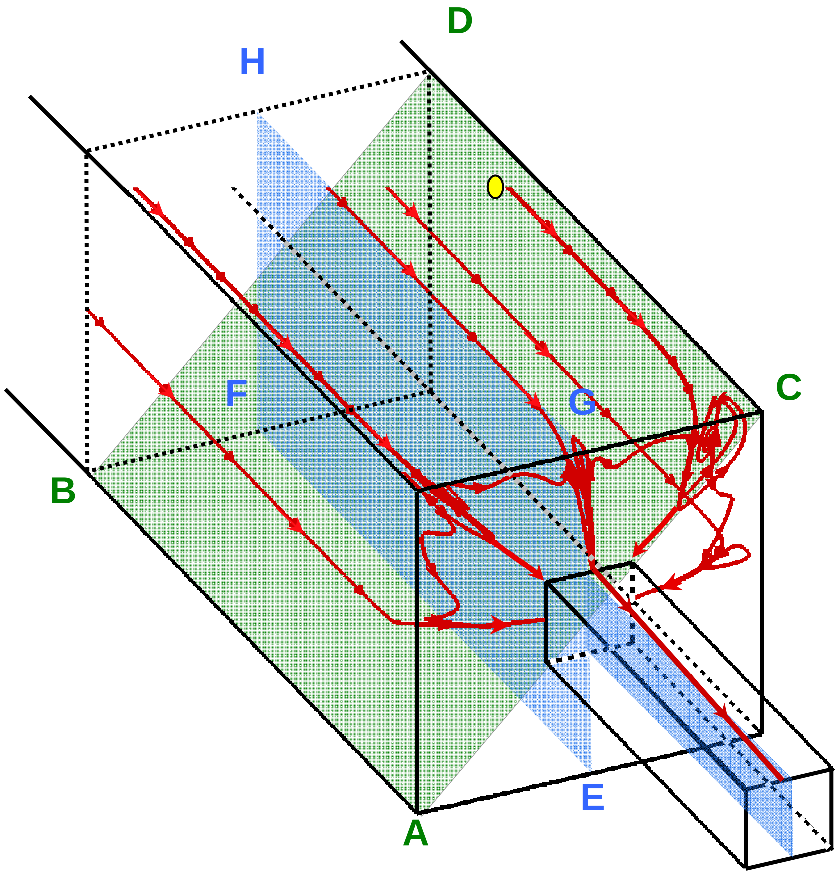
Flow Patterns

Centre plane



Diagonal plane



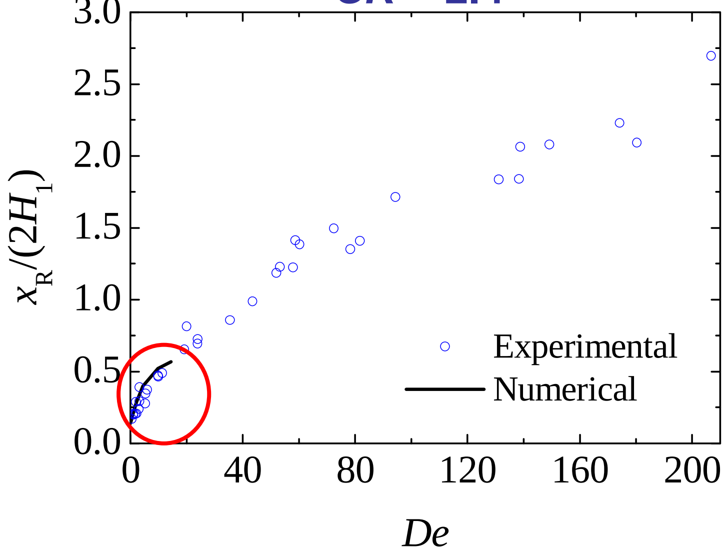


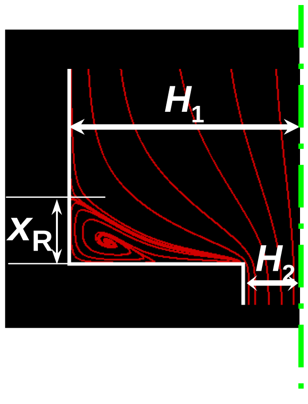
Sousa, Coelho, Oliveira and Alves, J. Non-Newtonian Fluid Mech. **160** (2009) 122–139

RESULTS – Viscoelastic fluid flow

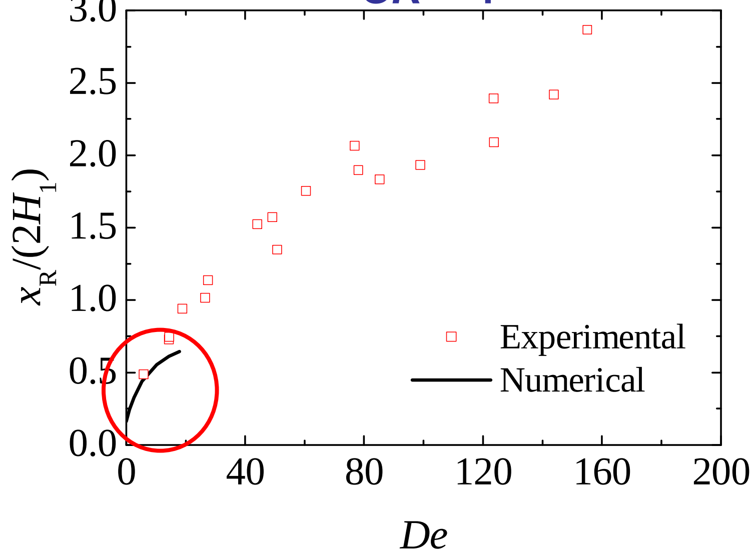
Vortex Length

CR = 2.4

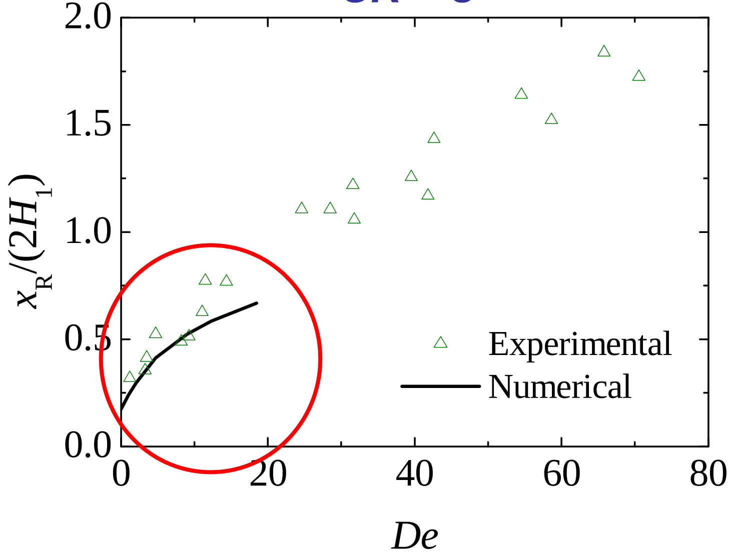




CR = 4



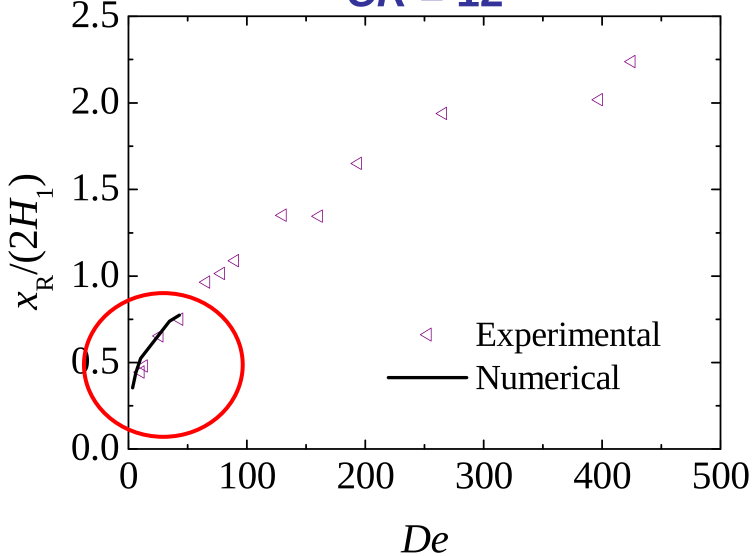
CR = 8



Deborah Number

$$De_2 = \frac{\lambda U_2}{H_2}$$

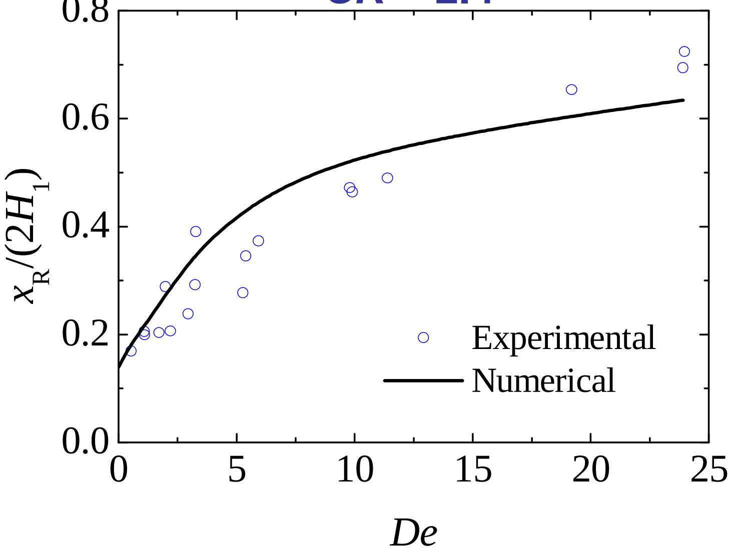
CR = 12

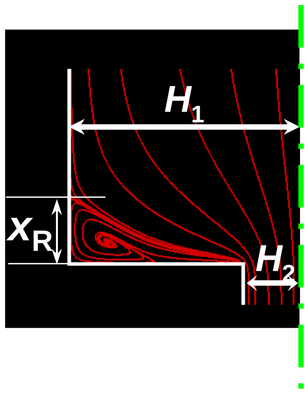


RESULTS – Viscoelastic fluid flow

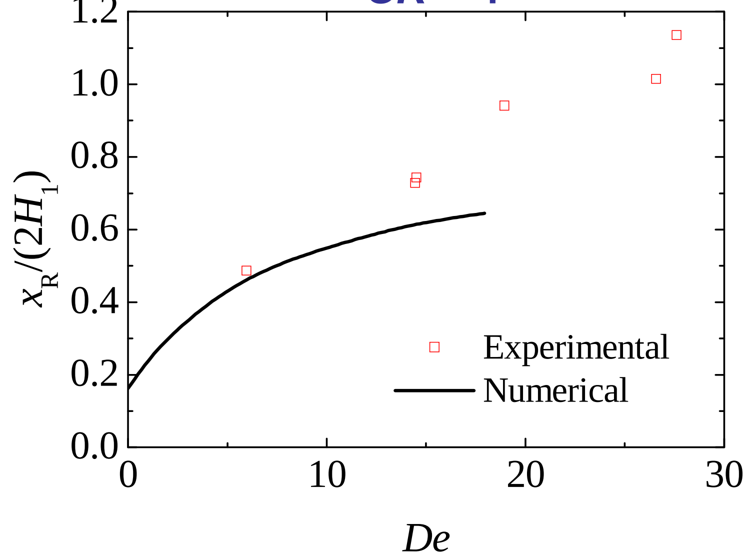
Vortex Length

CR = 2.4





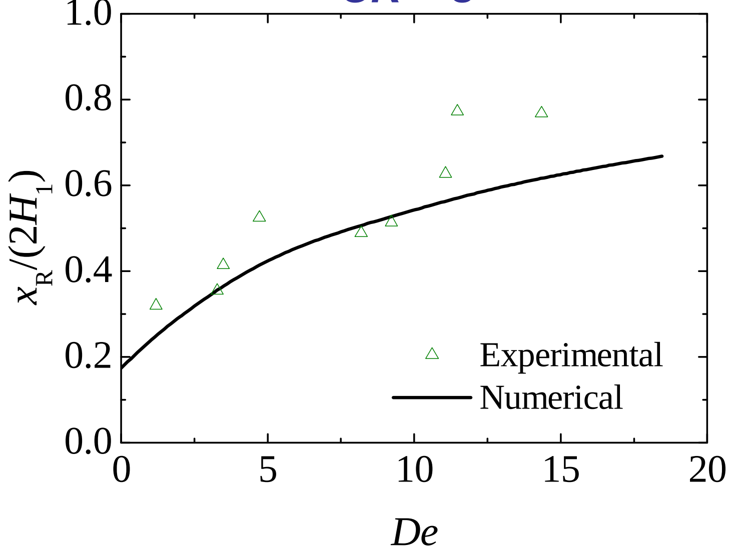
CR = 4



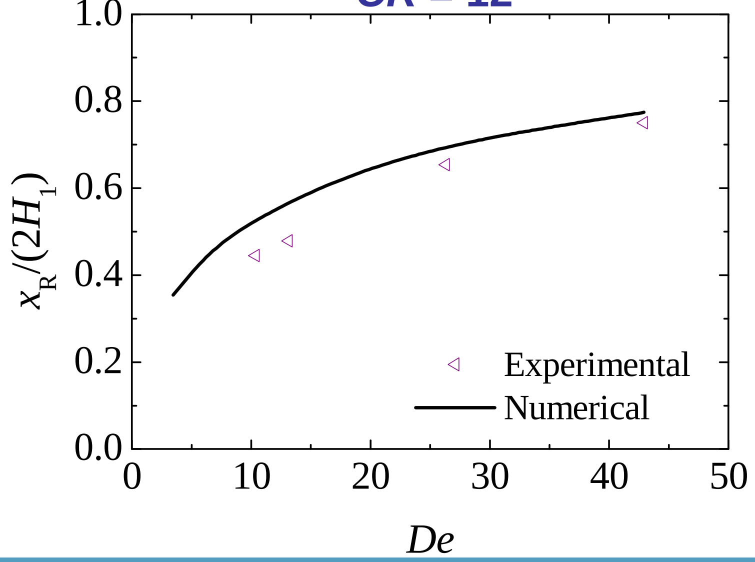
Deborah Number

$$De_2 = \frac{\lambda U_2}{H_2}$$

CR = 8



CR = 12

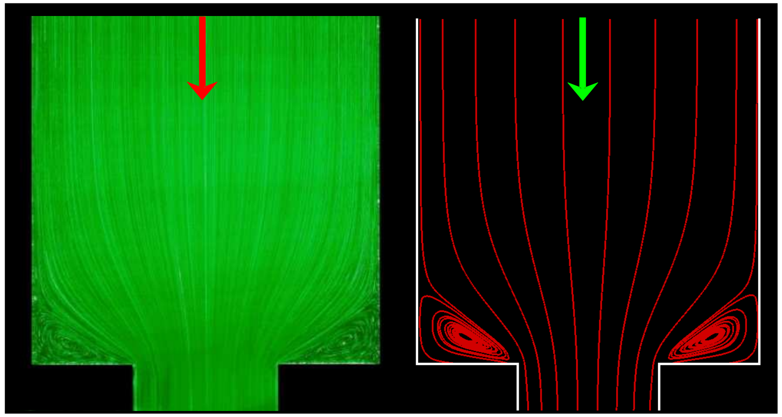


RESULTS – Viscoelastic fluid flow

Flow Patterns – Centre plane

CR = 2.4

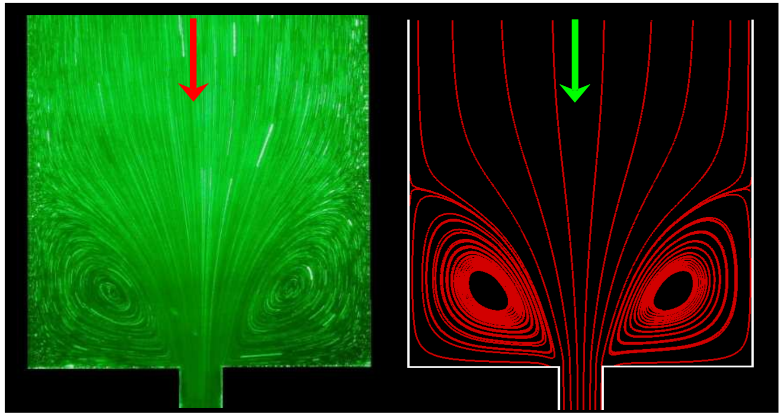
Experimental Numerical



Re = 1.4×10^{-3}, *De* = 1.1

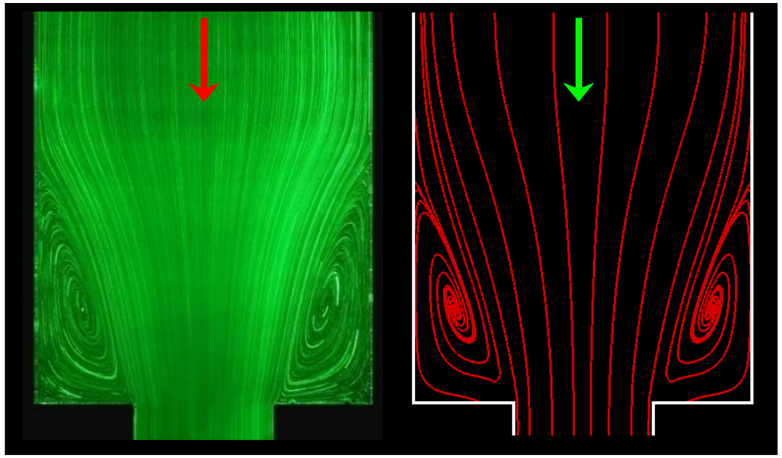
CR = 8

Experimental Numerical



Re = 2.2×10^{-3}, *De* = 9.1

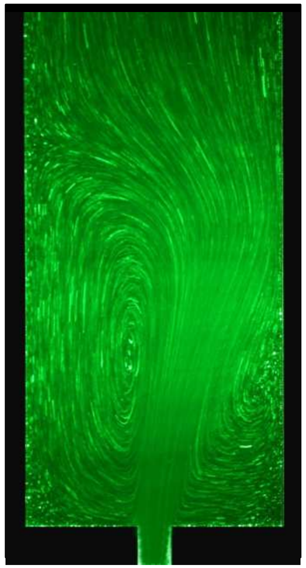
Experimental Numerical



Re = 0.11, *De* = 24

Diverging streamlines

CR = 4 ⇨ *De* ~ 27



Unstable Flow

CR = 2.4 ➔ *De* $\gtrsim$175

CR = 4 ➔ *De* $\gtrsim$ 290

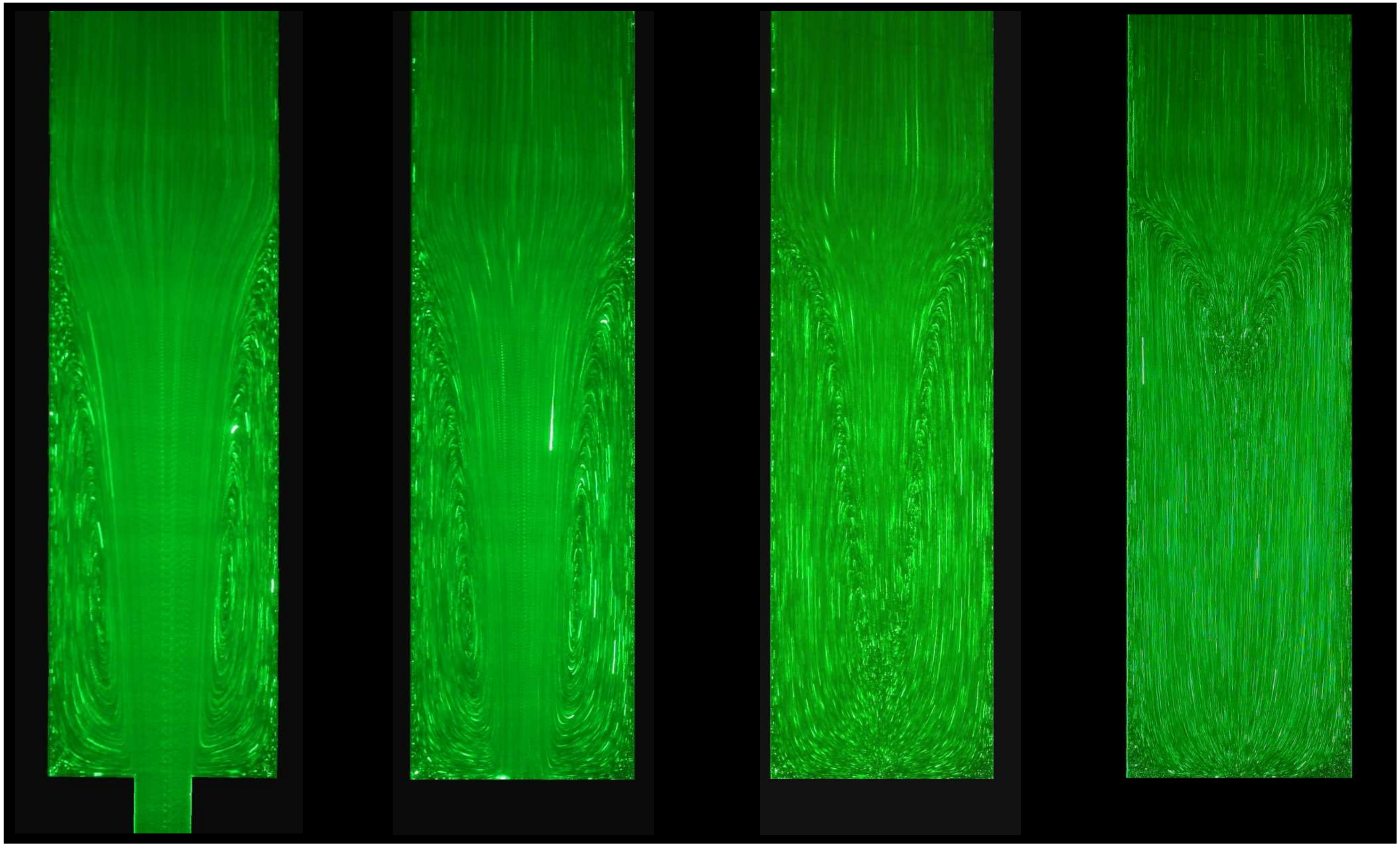
CR = 8 ➔ *De* $\gtrsim$102

CR = 12 ➔ *De* $\gtrsim$510

RESULTS – Viscoelastic fluid flow

Flow Patterns – Different planes

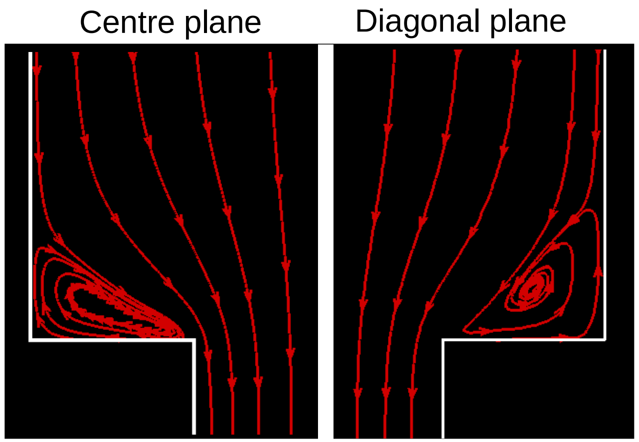
***CR* = 4** $Re_2 = 0.636$ $De_2 = 144$



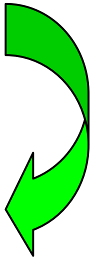
$z/H_1 = 0$ or $y/H_1 = 0$ $z/H_1 = 0.25$ or $y/H_1 = 0.25$ $z/H_1 = 0.50$ or $y/H_1 = 0.50$ $z/H_1 = 0.75$ or $y/H_1 = 0.75$

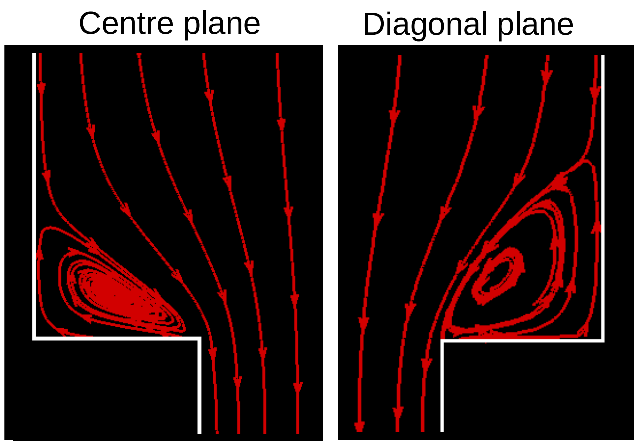
RESULTS – Viscoelastic fluid flow

Flow Patterns



$Re = 6.27\times10^{-4}$, $De = 0.55$





$Re = 1.35\times10^{-3}$, $De = 1.11$

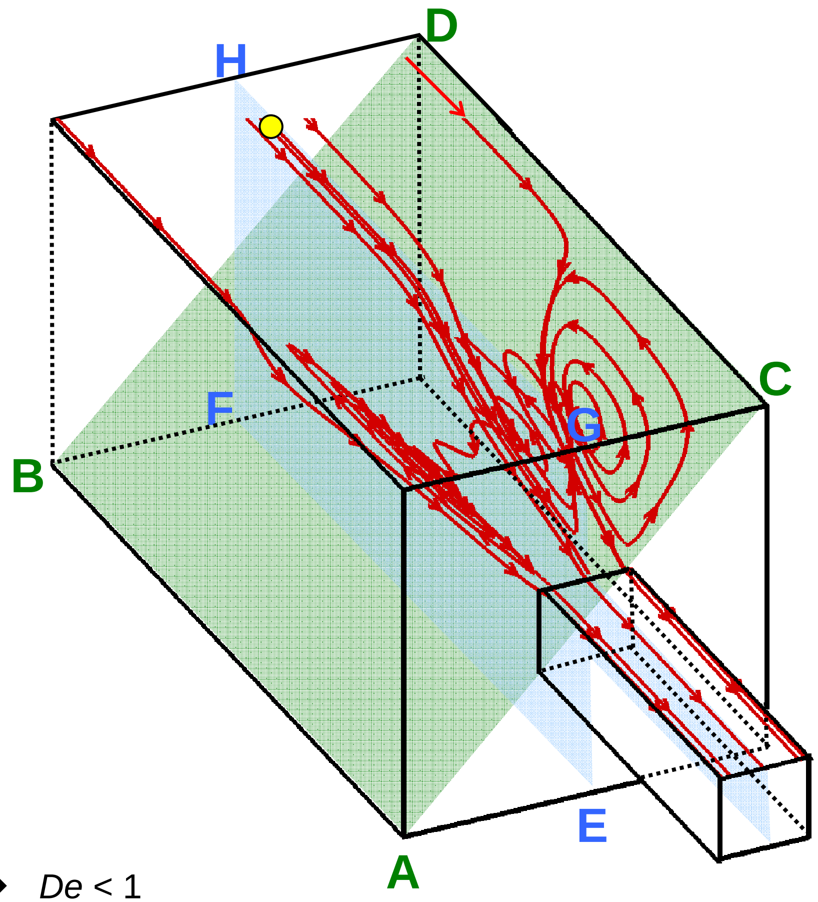
$CR = 2.4$

$CR = 4$

$CR = 8$

$CR = 12$

➔ $De < 1$

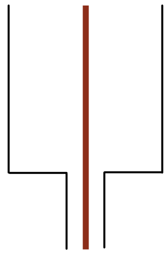


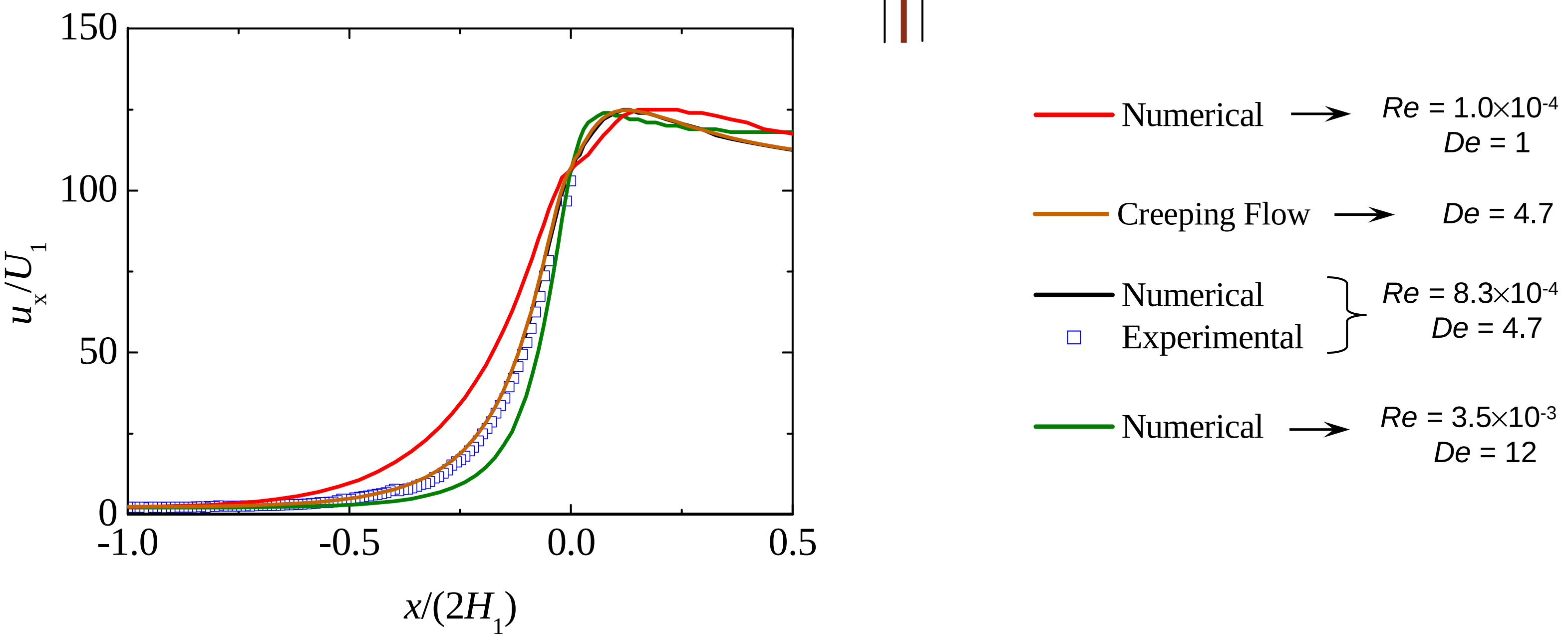
Alves, Pinho and Oliveira, J. Rheol. **52** (2008) 1347–1368.

RESULTS – Viscoelastic Fluid Flow

Velocity Field

Centreline velocity profiles – ***CR* = 8**





- Fluid accelerates near the contraction ➔ $x/2H_1 \gtrsim -0.5$;
- Velocity overshoot after $x/2H_1 \approx 0$;
- Inertial effects negligible;

CONCLUSIONS

Newtonian fluid flow:

- vortex length decreases with an increase in the *Re;*
- numerical results capture very well the flow characteristics;

Viscoelastic fluid flow:

- the vortex length increases with *De* and becomes very large*;*
- the numerical simulations predict the vortex enhancement and flow reversal;
- experimental and numerical results are in good agreement;

ONGOING/FUTURE WORK

- Numerical Simulations with more refined meshes;
- Study the influence of the rheological model parameters (e.g. ε) on the numerical results.

ACKNOWLEDGMENTS

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- REEQ/262/EME/2005;
- REEQ/928/EME-2005
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