time-stepping structure. Enhanced pressure drop, stress fields and vortex dynamics are analysed, where evidence of new upstream vortices and its relationship with N_2 is obtained. These flows have importance in industrial oil-reservoir recovery and the plastics industry, biological and food flow applications, typically provoking thixotropy, yield stress and shear banding. To obtain high-We solutions, both micellar and EPTT constitutive equation f-functionals have been amended by (a) adopting their absolute values, and (b) through a change of stress variable, $\Pi = \tau_p + (\eta_{p0}/\lambda_1)I$, that prevents loss of evolution in the underlying initial value problem. A boundary condition is imposed at the centreline, for which the shear gradients vanish identically. As a consequence, highly non-linear solutions are now attainable, given at impressively high We. For example and with micellar fluids, the numerical breakdown is shifted from critical states of We_{lim}=4.9 without correction, to $We_{lim}=\mathcal{O}10^3$ with correction. Furthermore, such constitutive correction has been found to have general applicability.

Thursday 14:20 Johann-Peter-Hebel FM10

Symmetry-breaking bifurcations in T-channel flows: effects of fluid viscoelasticity

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It is well known that, beyond a critical aspect-ratio-dependent Reynolds number, the flow in a three-dimensional T-channel junction, i.e. two-opposing planar channel streams joining and turning through 90 degrees, can break symmetry [1-2]. For the case of two square cross-section inlets and an outlet arm of equal area (i.e. aspect ratio of two) this bifurcation is to a steady asymmetric flow. This flow bifurcation has been proposed as a method of enhancing mixing in microfluidic channels where significant increases in mixing quality are observed beyond the bifurcation. In the current work we investigate numerically the effects of viscoelasticity on this supercritical pitchfork bifurcation. The three-dimensional numerical simulations make use of a finite-volume technique based on the log-conformation formulation [3], together with the high-resolution "CUBISTA" scheme for the convective terms in the momentum and constitutive equations. Results from both the upper-convected Maxwell and Oldroyd-B models, using three consistently refined meshes, show that the instability occurs at lower Reynolds numbers for viscoelastic fluids in comparison to the Newtonian base case. The influence of the Deborah number and solvent-viscosity ratio are analysed. At higher Deborah numbers the transition leads directly to an unsteady flow. A map of flow patterns produced shows demarcation zones for the different flow regimes, i.e. symmetric steady, asymmetric steady and unsteady flow. Knowledge of such zones may prove useful in the design of micro-fluidic chips for enhanced mixing, for example.

[1] Kockmann, N., Föll, C. and Woias, P., 2003. In the International Society for Optical Engineering. San Jose, CA, 2003. SPIE

[2] Poole, R.J. Alfateh, M. and Gauntlett, A.P., 2013. Chem. Eng. Sci. 104 pp 839–848

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Thursday 14:40 Johann-Peter-Hebel FM11

Time-dependent secondary flows of FENE-CR fluids in a curved duct of square cross-section

Joana M. Malheiro*[1], Paulo J. Oliveira[1], Fernando T. Pinho[2]

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Great efforts have been devoted to study time-dependent flows in curved ducts, especially in relation to blood flow in vessels, in order to better understand blood circulation and vascular diseases. Such flows exhibit complex flow patterns, oscillating between one-pair to multiple-pairs of vortices, from symmetric to asymmetric pairs of vortices, and also from stable to unstable flow patterns. Despite all this interest, most studies of unsteady flows in curved ducts have been carried out for viscous incompressible fluids obeying the Navier-Stokes equations, and relatively less attention has been paid to the flow of viscoelastic fluids.

In the present numerical study, we present results of simulations for three-dimensional unsteady laminar flows of viscous and viscoelastic incompressible fluids through a curved rigid duct, in order to better understand the time-dependent developing flows and Dean instabilities. The time development of such a flow along a square cross-section curved duct at 180 degrees will be described in detail, based on numerical solutions with a finite volume method on a collocated mesh arrangement. A fully developed velocity profile is assumed at the entrance

duct to the curve and, due to the possibility having flow asymmetries, the whole geometry is considered in the simulations. The problem is solved for Newtonian viscous fluids and the viscoelastic FENE-CR fluid model, which describes the behaviour of dilute polymer solutions. Numerical simulations were carried out for different Dean and Weissenberg numbers, in the case of the viscoelastic fluid. Velocity and stress profiles are analysed in both space, across the duct square cross-section, and time. Our results reveal stationary and time-dependent instabilities when inertia and elasticity are increased, and show significant variations in the distribution of stress and velocity together with complex secondary flow patterns.

Thursday 15:00 Johann-Peter-Hebel FM12

Fiber spinning under filament pull-out conditions: a stability analysis

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In wet-spinning, a polymeric fluid is pushed through a spinneret die. Subsequently, the extrudated filament is taken up downstream at a higher velocity than the average extrusion velocity and cooled (e.g. in a water bath) to form a solidified fiber. As the take up velocity increases, a periodic variation of the filament diameter can occur beyond a critical draw ratio which is generally referred to as the draw resonance instability. Also, if the fluid strength is sufficiently high, upon increasing the take up velocity or, with an increase of the stretching force, the filament may be pulled out from the extrusion die. At a high Trouton ratio, filament pull-out is the phenomenon where the upstream fluid detaches from the die wall which is known to occur in isothermal solution spinning of silk by spiders as well as solution spinning high performance polymers. This pull-out condition complicates the dynamic stability analysis in the sense that the upstream boundary conditions are no longer constant but depend on the deformation history of the polymeric fluid in the spinning die. Moreover, the upstream boundary conditions depend on the position of the detachment point as the filament length can vary in time.
In this work we determine, and obtain an understanding of, the stability limits in fiber spinning under pull-out conditions. This includes the stability analysis depending on the upstream conditions in the die, i.e. the dynamic contact point when pull-out of the filament occurs. The approach incorporates the full viscoelastic computational analysis of the fiber spinning dynamics where also possible slip phenomena of the melt/solution with the extrusion die wall are taken into account. In addition, we perform experimental validation of our analysis using a well-defined IUPAC-A polymer melt.

Thursday 15:50 Johann-Peter-Hebel FM13

Finite element simulations of the displacement of a thin blade in an elasto-viscoplastic medium

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This work investigates the flow around a flat thin blade of finite length as it travels at constant speed in an incompressible elasto-viscoplastic medium. The mechanical model is composed of the usual mass and momentum balance equations, coupled with a modified Oldroyd-B equation that accommodates the dependence of the relaxation and retardation times as well as of the viscosity on the structuring level of the microstructure, represented by the structure parameter field.
The model is approximated by a 2-D stabilized four-field Galerkin least-squares finite-element method in terms of the fields of the structure parameter, the extra-stress tensor, the pressure, and the velocity vector. The influence of the elastic modulus, yield stress and blade velocity on the fields of velocity and pressure, as well as on the fields of the intensities of stress and strain rate is investigated for relevant ranges of these parameters. The field of elastic strain in both the yielded and unyielded regions is also given. Finally, the dependence of the thickness of the yielded region near the blade as a function of the governing parameters is determined.

TIME-DEPENDENT SECONDARY FLOWS OF FENE-CR FLUIDS IN A CURVED DUCT OF SQUARE CROSS-SECTION

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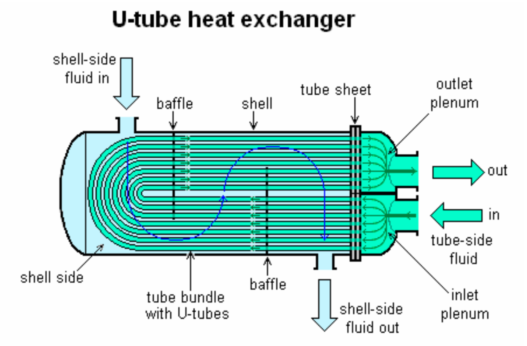
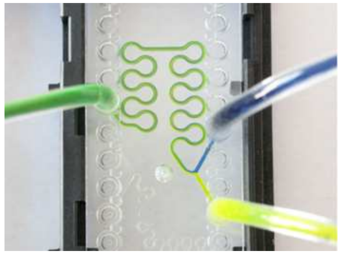
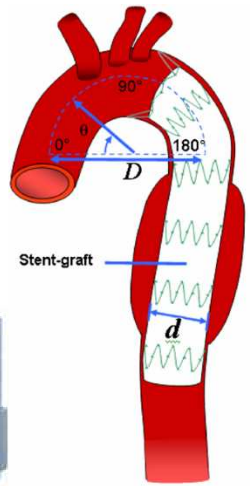
CURVED DUCTS

Applications





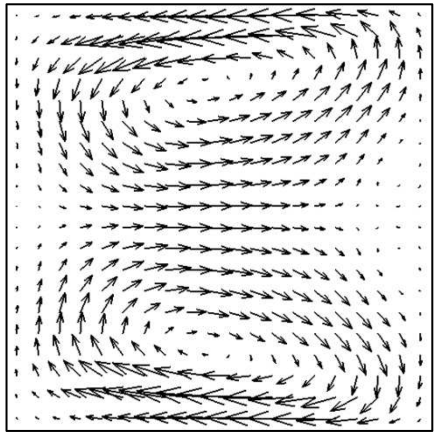


- enhanced:
  - heat exchange
  - mass transfer
  - cross-section mixing
  - …

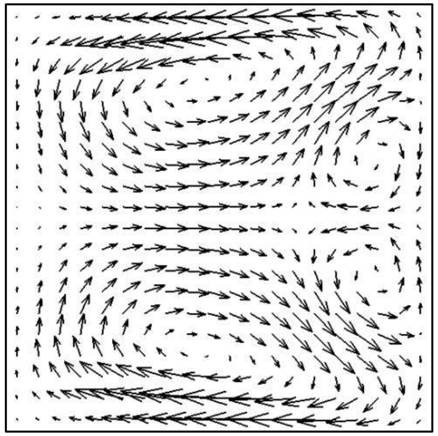
Secondary Flow

FENE-CR, Dn=137, β=0.5, L^2=100, θ = 150°

Wi= 0.1



Wi= 0.5



BACKGROUND

STEADY

- <u>Newtonian</u>:
  - Complex bifurcation diagram of steady solutions(Winters 1987, Modal et al. 2007,2009,2013, Islam et al.2013)
  - Multiple, symmetric and asymmetric solutions(Winters1987, Mees et al.1996, Modal et al. 2007,2009,2013, Islam et al.2013)
  - Inertia promotes complexity (transition from one to two/multiple pairs of vortices)(Malheiro et al.20133, Mees et al.1996,Bara et al.1992)
- <u>Viscoelastic</u>:
  - Inertia, elasticity, …, enhance flow complexity (Malheiro et al. 2013)

UNSTEADY

- <u>Newtonian</u>:
  - Flow unsteadiness of non-turbulent nature (Taylor 1929)
  - Multiple, symmetric and asymmetric solutions: steady-periodic- multiperiodic-chaotic (Mees et al.1992, Islam et al.2013, Modal et al. 2009, 2007, 2013)
- <u>Viscoelastic</u>:
  - ????? (lack of information)

OBJECTIVES

Presentation: Study the development over time of the secondary flow of viscoelastic fluids (FENE-CR model) in curved channels, with variation of elasticity (Wi)

Main: Build diagram of distribution of the unsteady solutions for viscoelastic fluids

GOVERNING EQUATIONS

Assumptions: three-dimensional flow, laminar, isothermal, unsteady flow, incompressible fluid

Mass conservation

$$\nabla \bullet \boldsymbol{u} = 0$$

Momentum

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho \boldsymbol{u}.\nabla \boldsymbol{u} = -\nabla \bullet \boldsymbol{\tau}_{tot}$$

Constitutive

$$\boldsymbol{\tau}_{tot} = \boldsymbol{\tau}_s + \boldsymbol{\tau}$$

NEWTONIAN

$$\boldsymbol{\tau}_s = \eta_s \left(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T \right) = 2\eta_s \boldsymbol{D}$$

where $\boldsymbol{D} = \frac{1}{2}\left(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T \right)$

FENE-CR

$$\boldsymbol{\tau} + \lambda \left(\frac{\overset{\nabla}{\boldsymbol{\tau}}}{f(\boldsymbol{\tau})} \right) = 2\eta_p \boldsymbol{D}$$

where $f = f(tr\boldsymbol{\tau}) = \dfrac{L^2 + (\lambda/\eta_p) tr\boldsymbol{\tau}}{L^2 - 3}$

DIMENSIONLESS PARAMETERS

Dean Number

$$Dn = \frac{\mathrm{Re}}{\sqrt{R_c}} = 600, \quad R_c = \frac{R_1 + R_2}{2a}$$

Reynolds Number

$$\mathrm{Re} = \frac{\rho U_m a}{\eta} = 2332, \quad \eta = \eta_s + \eta_p$$

Weissenberg Number

$$Wi = \dot{\gamma}\lambda, \quad \dot{\gamma} = U_m / a$$

Retardation parameter

$$\beta = \frac{\lambda_r}{\lambda} = \frac{\eta_s}{\eta}$$

Extensibility

$$L^2 = 100$$

Aspect ratio

$$k = 1$$

Curvature

$$\delta = \frac{a}{R} = 0.066$$

NUMERICAL METHOD & BOUNDARY CONDITIONS

Fully implicit finite-volume method (Oliveira et al.1998)

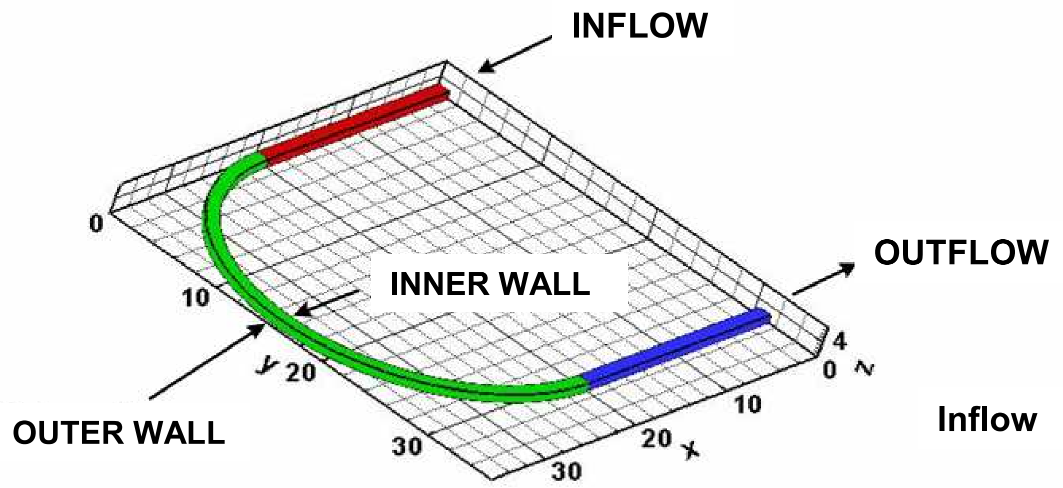
- General non-orthogonal coordinate system
- Collocated mesh
- Spatial discretisation (convective terms): CUBISTA scheme (Alves et al.2003)
- Temporal discretisation (unsteady term): Three-time level (Oliveira 2001)

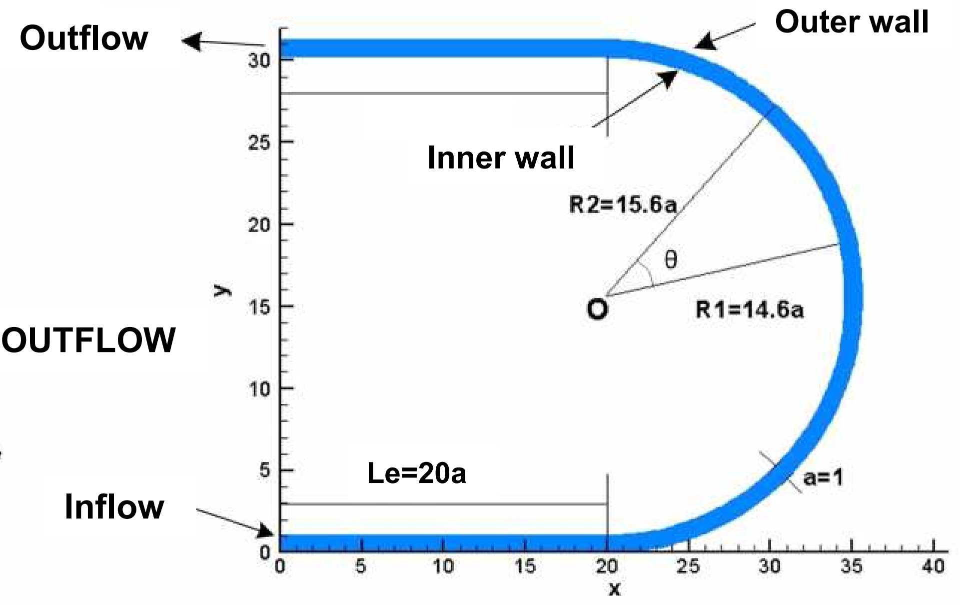
Boundary Conditions

- No-slip conditions at walls
- Fully developed flow at entrance
- Zero velocity axial-gradient and constant pressure gradient at exit
- Full domain considered
- Time step $\Delta t= 0.01$
- Initial conditions: $t= 0$ and $u=v=w= 0$

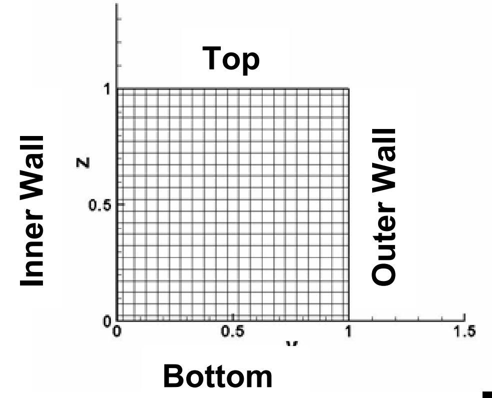
GEOMETRY & MESH

- **Channel:**
  - 180° curved duct coupled to straight ducts at entry and exit
  - Square cross-section



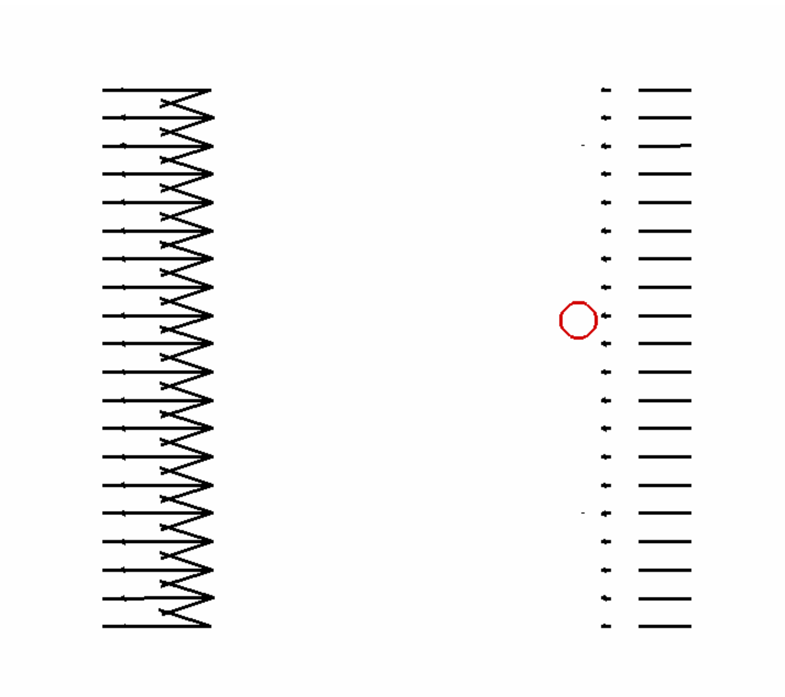


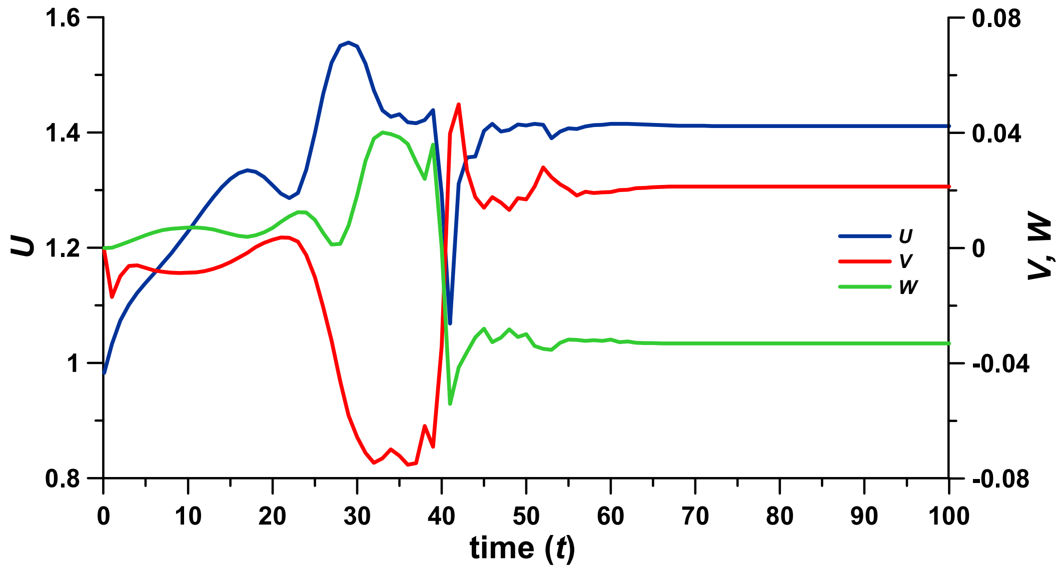
- **Mesh:**
  - Non-uniform at entrance and exit channels
  - Uniform at curved part and cross-section
  - Total control volumes (CV): 366 141



RESULTS – NEWTONIAN:

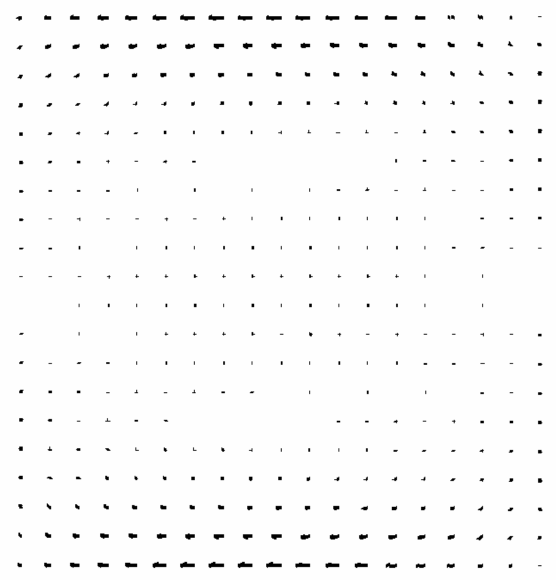
Newtonian, *Dn* = 600, θ = 150°, (*y*, *z*)= (0.87, 0.57)

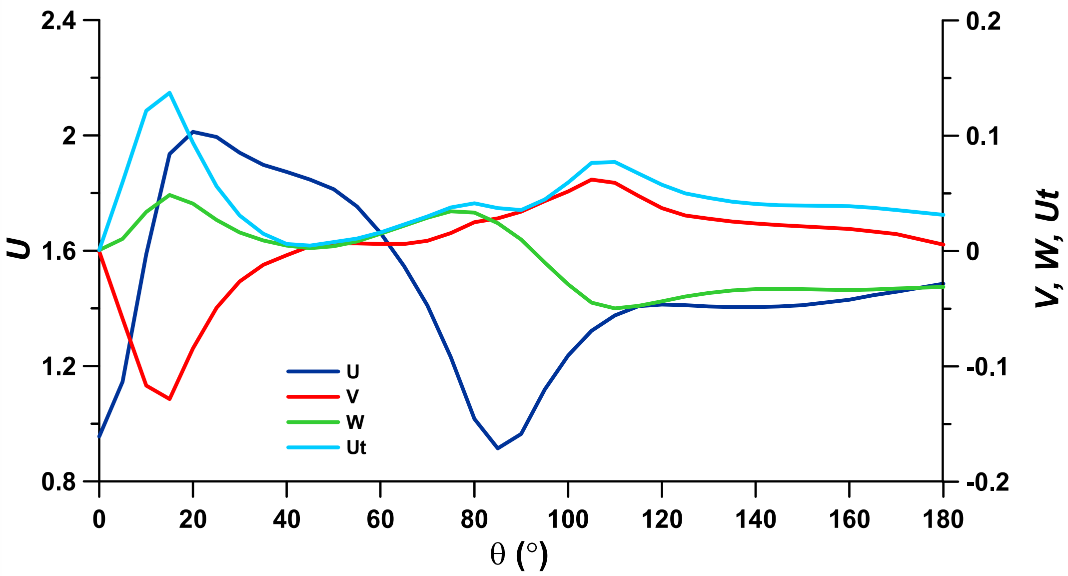




RESULTS – NEWTONIAN:

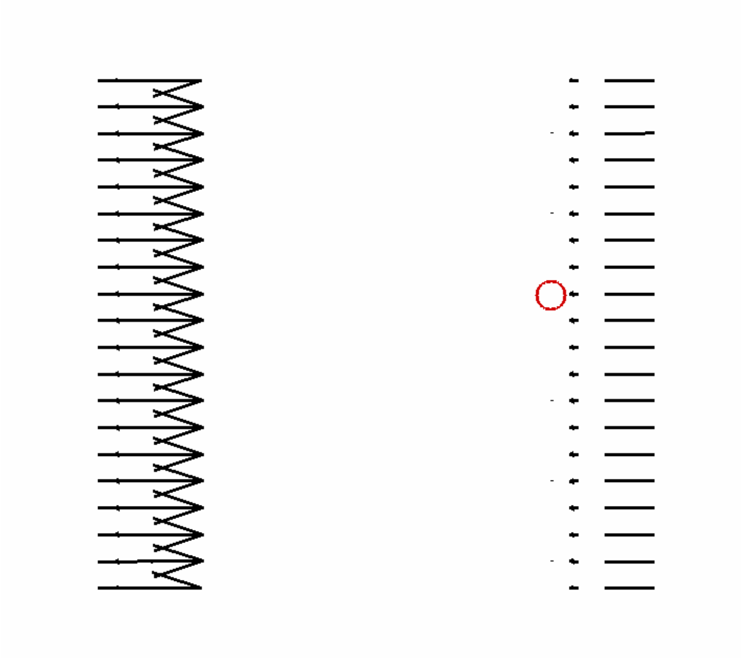
Newtonian, *Dn* = 600, *t* = 120, (*y*, *z*)= (0.87, 0.57)

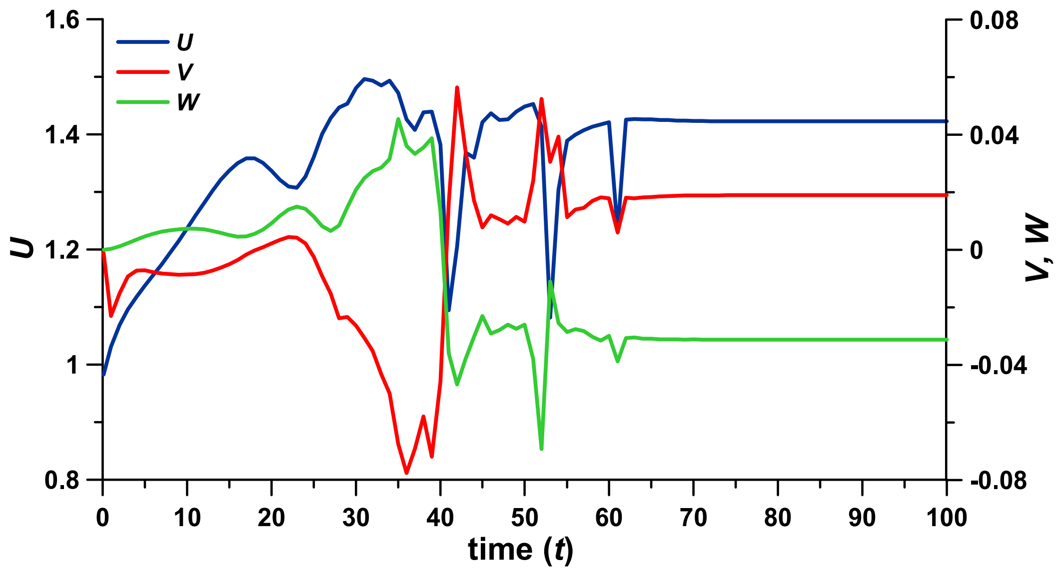




RESULTS – FENE-CR:

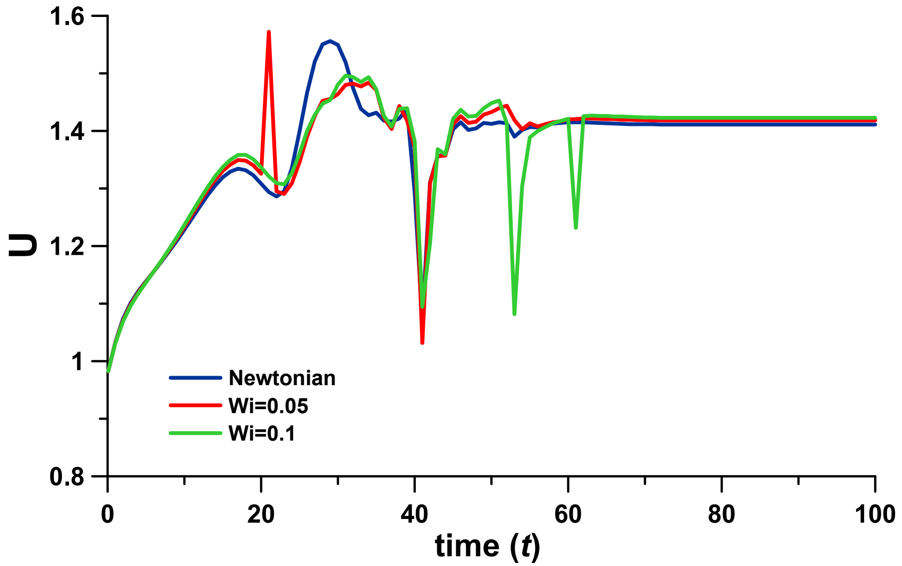
FENE-CR, *Dn* = 600, Wi=0.1, β= 0.1, L^2=100, θ = 150°, (*y*, *z*)= (0.87, 0.57)



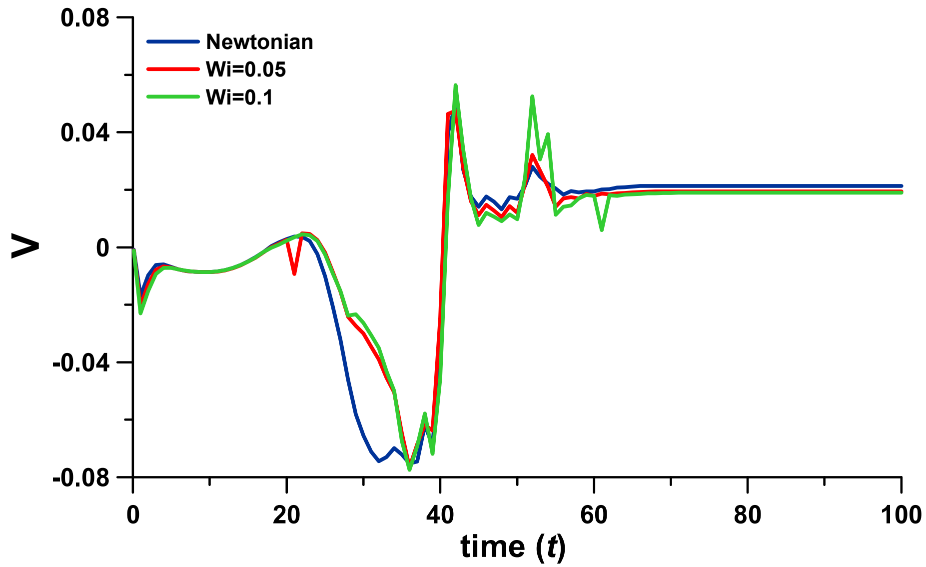


RESULTS – FENE-CR:

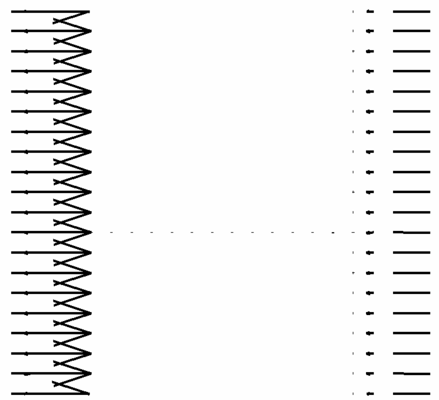
FENE-CR, Dn = 600, β= 0.1, L^2=100, θ = 150°, (y, z)= (0.87, 0.57)



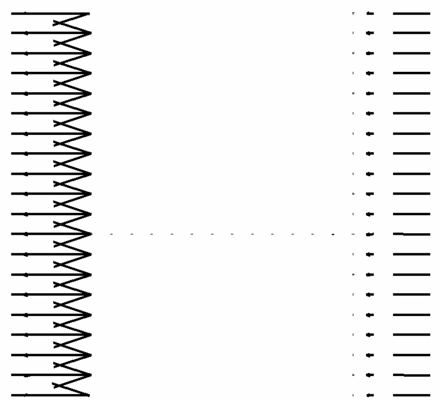
Effect of elasticity (Wi)



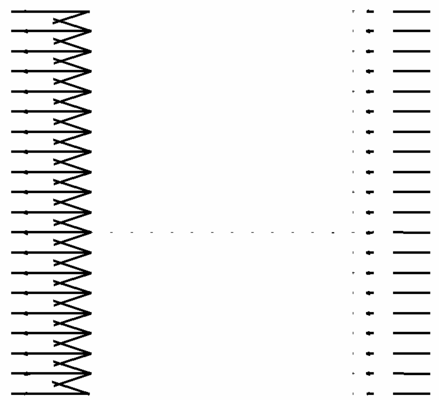
RESULTS – FENE-CR:



Wi= 0.2

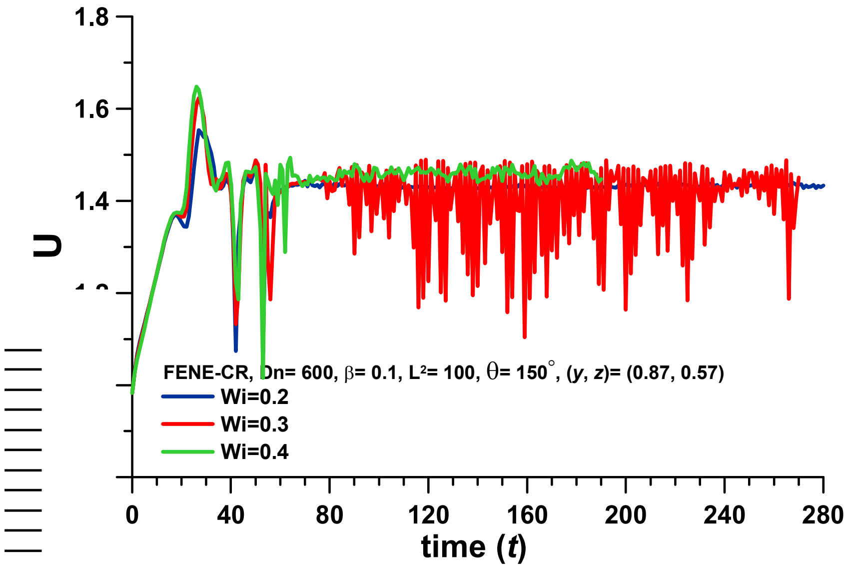


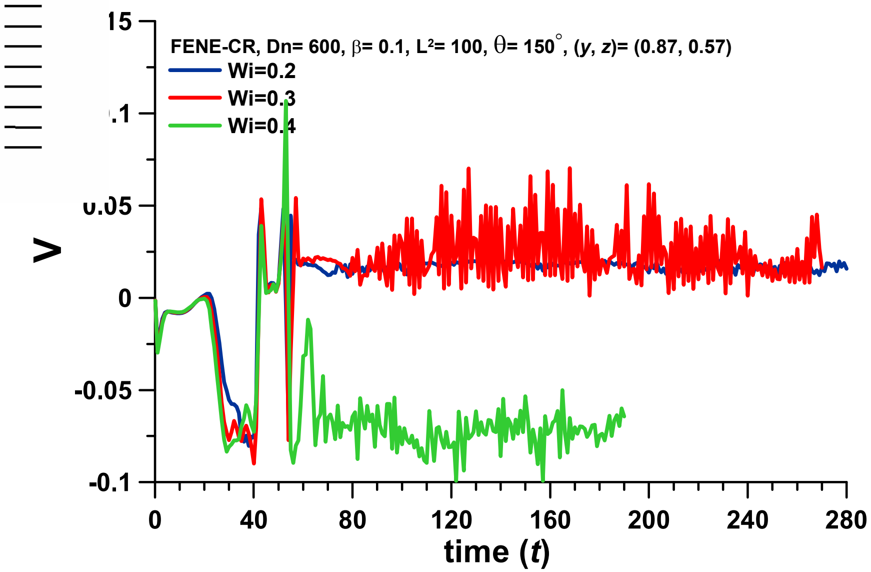
Wi= 0.3



Wi= 0.4

Effect of elasticity (*Wi*)

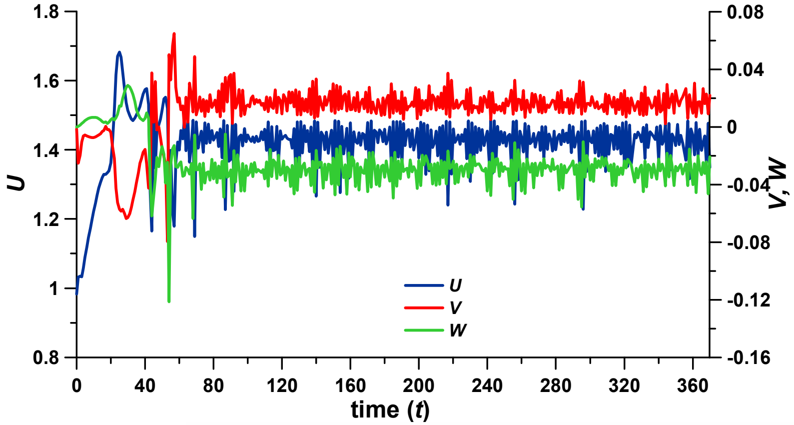


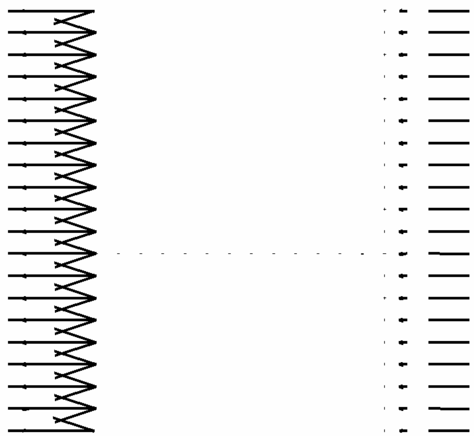


RESULTS – FENE-CR:

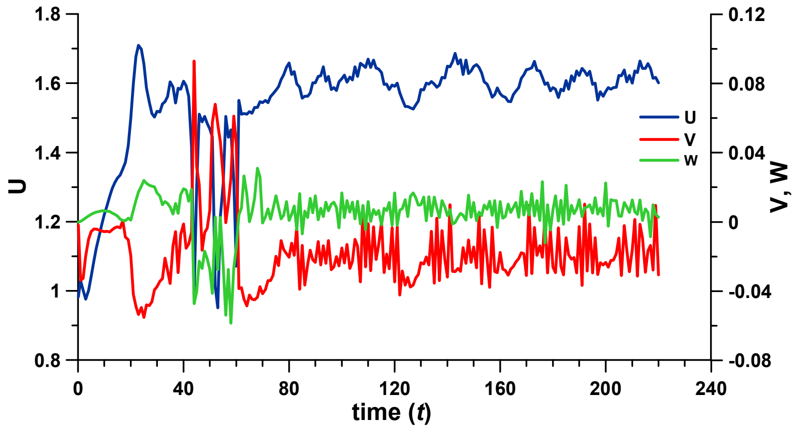
FENE-CR, Dn = 600, Wi= 2.0, L^2=100, θ = 150°(y, z)= (0.87, 0.57)

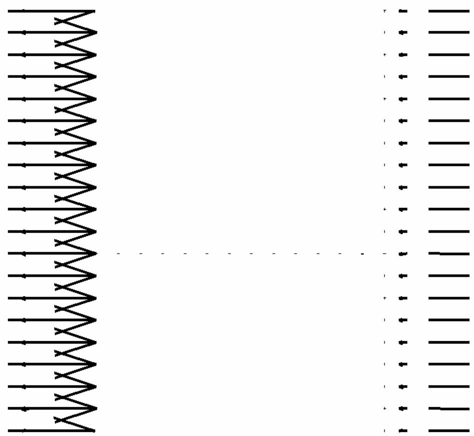
β= 0.5





β= 0.1





Conclusions

- Time dependent viscoelastic fluid flows:
  - exhibit steady, periodic and chaotic solutions, for increasing Wi.
  - undergo into a chaotic solution faster as $\beta \rightarrow 0$

Future Work

- Build diagram:
  - with the distribution of the unsteady solutions for viscoelastic fluids (FENE models);
  - of multiple solutions for viscoelastic fluids (FENE models) – by adding perturbation (ex: pulsating/oscillatory flow)

ACKNOWLEDGMENTS

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