CAE-DESIGN OF A VISCOELASTICITY-BASED MICRO-FOCUSER

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Microfluidics is a relatively recent field of fluid dynamics where fluids are made to flow in devices with micron length scales [1,2]. One of the main advantages as compared to macrosystems is the possibility to **analyze suspended particles** with characteristic size of the same order of channel dimensions (e.g., red blood cells, platelets, bacteria, tumor cells, etc.). In this context, **controlling particle trajectories** is in demand in many applications, including separation, sorting, counting, and detection [3].

Objective of the project

- **Flow-focusing:** technique allowing the alignment of particles along a streamline of the flow field [4-5] (Fig. 1).
- Several methods have been proposed: all of them use water as suspending medium but require complex apparati [4-5].
- What happens if the suspending fluid is **viscoelastic**, like a dilute aqueous polymer solution?

Aim: to use numerical simulations to design a geometrically simple flow-focuser by suspending the particles in a viscoelastic fluid

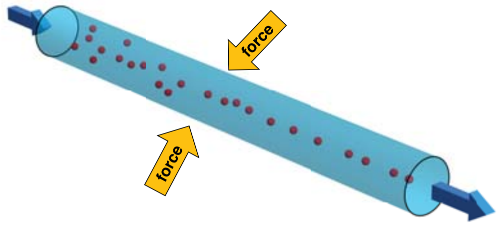


Fig. 1 – Flow-focusing mechanism: particles suspended in a fluid are randomly distributed in inflow; by applying some force, they aligns in outflow.

Problem formulation and numerical details

- Finite element simulations are used to solve the fluid dynamics of a system made by a **spherical particle** in a **viscoelastic fluid** flowing in a tube. A typical mesh is shown in Fig. 2.
- A realistic constitutive equation is adopted to model fluid viscoelasticity.

Governing equations

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

$$\nabla \cdot \boldsymbol{\sigma} = -\nabla p + \eta_s \nabla^2 \boldsymbol{u} + \nabla \cdot \boldsymbol{\tau} = \boldsymbol{0}$$

$$\lambda \overset{\nabla}{\boldsymbol{\tau}} + \frac{\alpha\lambda}{\eta_p} \boldsymbol{\tau} \cdot \boldsymbol{\tau} + \boldsymbol{\tau} = 2\eta_p \boldsymbol{D}$$

$$\boldsymbol{F} = \int_{\partial P(t)} \boldsymbol{\sigma} \cdot \boldsymbol{n} dS = 0$$

$$\boldsymbol{T} = \int_{\partial P(t)} (\boldsymbol{x} - \boldsymbol{X}) \times (\boldsymbol{\sigma} \cdot \boldsymbol{n})\, dS = 0$$

Boundary/initial conditions

$$\boldsymbol{u} = \boldsymbol{0} \quad \text{on } \Sigma_{\mathrm{w}}$$

$$Q \quad \text{on } \Sigma_{\mathrm{in}}$$

$$\textit{periodicity along } x$$

$$\textit{symmetry} \text{ on } \Sigma_{\mathrm{sym}}$$

$$\boldsymbol{u} = \boldsymbol{U}_{\mathrm{p}} + \boldsymbol{\omega} \times (\boldsymbol{x} - \boldsymbol{X}) \quad \text{on } \partial P(t)$$

$$\boldsymbol{\tau}|_{t=0} = \boldsymbol{\tau}_0$$

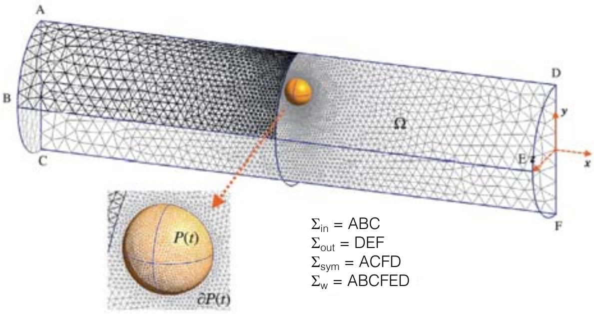


Fig. 2 – Computational domain used in the simulations. A spherical particle suspended in a viscoelastic fluid is placed along a cylindrical channel. A flow rate Q is imposed on Σ_{in}. Due to the symmetry, only one-half geometry is considered. The mesh on some boundaries is shown. The inset displays a zoom of the mesh on the particle surface P(t). The mesh is refined around the particle where the largest gradients are expected.

Results

- Fluid viscoelasticity leads to a phenomenon known as **particle migration** [6] (Fig. 3), i.e., the particle moves orthogonally to the main flow direction
- The migration direction depends on:
  - flow rate
  - channel and particle dimensions
  - fluid rheology
- The simulations show that the migration phenomenon is governed by a **single dimensionless parameter *Θ*** (Fig. 4)
- Experiments are carried out to validate the numerical results (Fig. 4)
  - very good **quantitative agreement**

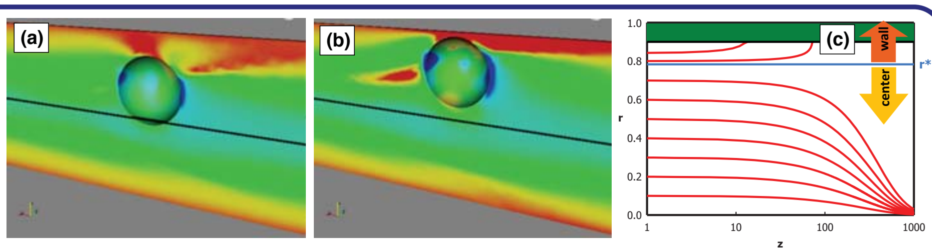
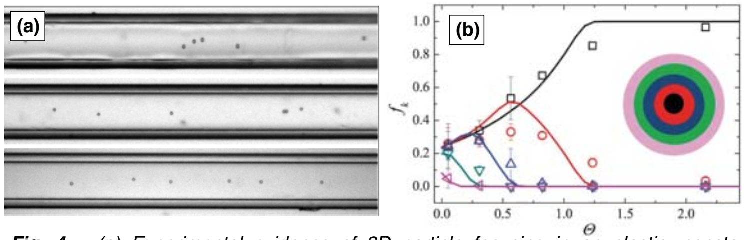


Fig. 3 – (a), (b) Distribution of the first normal stress difference ($N_1 = \sigma_{xx} - \sigma_{yy}$) for a particle migrating towards the centerline (a) and towards the wall (b). (c) Computed particle trajectories for different initial particle radial positions. Depending on the initial position, the particle can migrate to the center or the wall.



$$\Theta \propto \lambda\, Q\, L \frac{D_p^2}{D^6}$$

λ: fluid relaxation time
Q: flow rate
D_p: particle diameter
D: channel diameter
L: channel length

Fig. 4 – (a) Experimental evidence of 3D particle focusing in an elastic, constant viscosity fluid; the snapshots from top to bottom are taken at increasing distances from the channel inlet. (b) Measured (symbols) and computed (lines) fractions of particles in concentric regions of the channel cross-section as a function of the parameter Θ that accounts for the relevant fluid, flow and geometrical parameters.

Conclusions

- **Fluid viscoelasticity** promotes **flow-focusing** in a simple straight microchannel
- **Finite element simulations** have been performed to elucidate the migration phenomenon
- Numerical simulations allow to **design and optimize** a viscoelasticity-based **flow-focuser**

Numerical simulations are an essential tool for microfluidic applications

Relevant bibliography

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