ELASTO-INERTIAL FOCUSING MECHANISMS OF PARTICLES IN SHEAR-THINNING VISCOELASTIC FLUID IN RECTANGULAR MICROCHANNELS

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ABSTRACT

In this work, full 3-D numerical simulations are performed to study the combined effects of elastic and inertial forces along the Y and Z-midline of the channel. Ultimately, simulation results are compared and matched with experimental fluorescent streak images of the focusing of particles under the same parametric conditions. We reported that shear-gradient (F_{SG}), N_2-induced secondary flow transversal drag (F_{SF}), and elastic (F_{EL}) lift are the main forces responsible for the focusing of particles in the elasto-inertial regime.

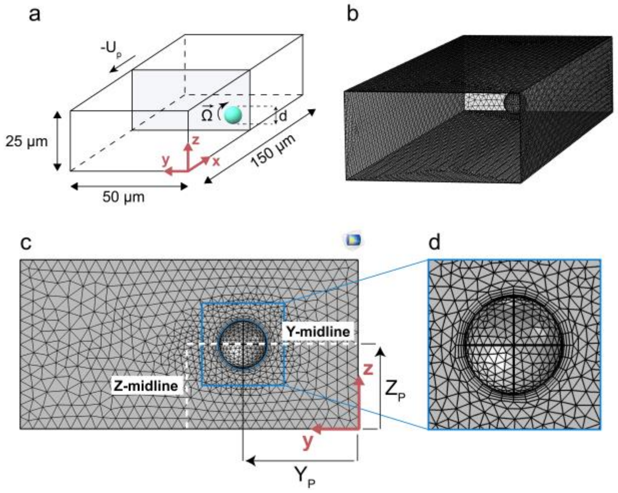
KEYWORDS: Viscoelastic focusing, particle separation, shear-thinning

INTRODUCTION

Due to increased global concern over clinical research and public healthcare over the past few years, microfluidic-based bioparticle sorting and separation has gained substantial attention as the first step in most diagnostic and therapeutic procedures [1]. Although a number of studies have focused on the applications and mechanics of the elasto-inertial focusing [2, 3], lack of combined numerical and experimental investigation, specifically at higher Wi numbers (Wi is a dimensionless number that measures the ratio of elastic to viscous forces) leads to incomplete understanding of the focusing mechanics due to challenges of achieving convergence for $\mathrm{Wi} > 3$. Herein, we numerically and experimentally study the focusing mechanisms at $\mathrm{Wi} = 3.6$ and $\mathrm{Wi} = 18$ and explore the effects of particle size, shear-thinning and N_2-induced secondary flow on the migration and focusing of 4 and 7 µm particles.

METHODS

COMSOL Multiphysics 5.6® is used to solve the momentum and mass conservation equations inside the microchannel. Simulation domain consists of a rectangular duct with the particle present as a spherical hole**.** Model schematics, mesh configuration details and viscoelastic phenomenon due to first and second normal stress differences (N_1 and N_2) in a Giesekus fluid are presented in **Fig. 1.** *Giesekus* constitutive equation with $\alpha = 0.2$ is used to accurately capture shear-thinning behavior of the fluid: $\lambda \mathrm{T_e} + \left(1 + \frac{\alpha\lambda}{\mu_p}\mathrm{T_e}\right)\mathrm{T_e} = 2\mu_p \mathrm{S}$, where $\mathrm{T_e}$ denotes the extra elastic stress and S is the strain rate tensor. λ and μ_p are the relaxation time and polymer part of the viscosity of the fluid, and α is the mobility factor. Note that the extent of shear-thinning behavior of the fluid can be fine-tuned by adjusting the α constant in the *Giesekus* model, with pronounced shear-thinning behavior at higher alpha values.



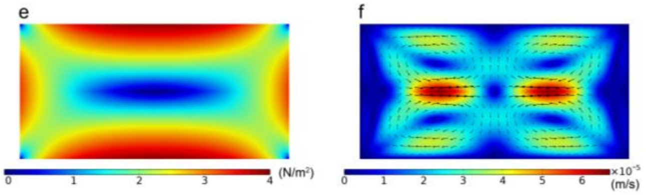


Fig 1. Model schematics, mesh configuration, and viscoelastic phenomenon in *Giesekus* fluid. (a) Simulation box with the channel walls moving with the speed of $-U_p$ while the particle has angular velocity vector of Ω. (b) Domain mesh (c) cross-section mesh and (d) Finer mesh on the particle surface and boundary layer mesh surrounding the particle. (e) N_1 distribution, (f) N_2-induced secondary flow formation in the cross-section of the channel.

RESULTS AND DISCUSSION

In order to predict focusing position of particle and explore combined effects of inertia and elasticity on the focusing patterns, elastic, inertial, and total force curves were plotted along the Y-midline of the channel **[Fig. 2(a-f)]**. At Wi = 3.6, F_{EL} and F_{SF} push the particles towards the channel center. At higher flowrates, pronounced F_{SG} alongside with F_{EL} will cause particle migration away from the channel center, leading to focusing positions at Y_P = 17, and Y_P = 14 for the 7 and 4 µm particles, respectively. Top and side view fluorescent streak images of the focusing position of the same two particle sizes support our simulation results **[Fig. 2(g,h)]**. Lastly, we showed that the predicted focusing position can be a strong function of the mobility factor in the Giesekus equation, i.e. the extent of shear-thinning behavior of the fluid **[Fig. 2(i)]**. Particles are shown to focus closer to the channel center when $\alpha = 0.4$, and no focusing is predicted when $\alpha = 0.1$.

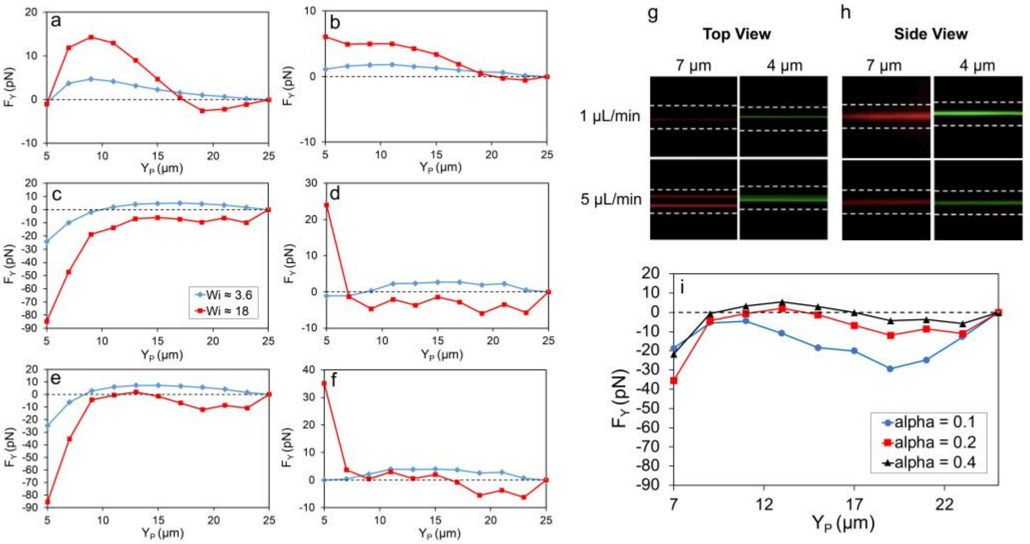


Fig 2. Simulation and experimental results of the forces and focusing positions. (a,b) Elastic, (c,d) Inertial, (e,f) Total force curves for the 7 (left) and 4 µm (right) particles. (g) Top, and (h) side view fluorescent streak images of the focusing position of particles at 1 & 5 µL/min (Wi = 3.6, and 18, respectively). (i) Effects of the mobility factor on the correct prediction of focusing position of the 7µm particle at Wi = 18.

CONCLUSION

We reported that elasto-inertial focusing of particles in rectangular microchannels is achieved by the interplay of F_{SG}, F_{SF}, F_{EL} lift forces. Additionally, our results suggest that the correct prediction of focusing patterns along the Y-midline of the channel is directly affected by the appropriate estimation of rheological properties of the fluid, specifically the extent of shear-thinning behavior. We believe that our results can enhance the existing knowledge on the mechanics of elasto-inertial focusing and pave the way for easier and more accurate design of microfluidic sorting and separation devices.

ACKNOWLEDGEMENTS

This is a project supported by industrial partner Genus titled "Precise Cellular Alignment and Positioning in Viscoelastic-Inertial Flows" through NSF Center for Advanced Design and Manufacturing of Integrated Microfluidics (CADMIM).

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