Non-Newtonian fluid Interactions with Complex micro-swimmers

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Background

Fluid flow through microfluidic devices have been repeatedly studied and are in large part the manner in which research has been able to advance in terms of simulating non-newtonian flow and micro-swimmers. The aim of this study is to explore a valid representation of complex geometry 3 dimensional micro-swimmers and its interaction in a non-newtonian fluid. The following literary works have laid the groundwork for this study modeling the Eulerian and Lagrangian interaction in a variety of ways leading up to the development of more accurate simulations and application methods;

Reference	Swimmer Geometry	Fluid Dynamics
Computational Fluid Dynamic (John B. Bell)	2-dimensional swimmer shape	Groundbreaking as it is the first to discuss fluctuating hydrodynamics
Fluctuating Hydrodynamics (Y, Wang and P Atzberger)	Lagrangian represented geometry is a 2-dimensional circular micro swimmer	Stochastic hydrodynamics Eulerian portion modeled as a Newtonian fluid
Spatially Adaptive stochastic methods (P Plunkett)	Spherical 3-dimensional swimmer shape in channels with complex geometry	Fluctuating hydrodynamics modeled as a Newtonian fluid

Abstract

- Stochastic Eulerian Lagrangian Method refers to the interaction between Eulerian background fluid motion and embedded micro-swimmers. Stochastic Eulerian refers to the fluctuating Eulerian hydrodynamics and Lagrangian refers to the interaction between the motion of the fluid with the corresponding motion of micro-swimmers on the fluid.
- This research focuses on preliminary research regarding the Eulerian Lagrangian interaction of a non-newtonian fluid motion with embedded micro-swimmers and more realistic geometry and motion. Previous research in this field (CITE) assumed Newtonian fluids with circular two dimensional or simple geometry three dimensional micro-swimmers. These vary in applications and methodology.
- The current simulation and modeling system for non-newtonian droplets through microchannels is inadequate in realistically modeling subtleties in which outside forces such as meshless particles affect underlying flow. Microfluidic devices in conjunction with numerical simulations may be used to enable realistic modeling of multiphase flows.
- This has a wide range of applications including areas where visco-elastic drops can be modeled more accurately with the new numerical method of general non-newtonian droplets such as blood flow.

Methods

The mathematical model governing our equation is as follows

u is the fluid velocity, ρ is the density which can have large jumps at material interfaces, p is the pressure, and τ is a combination of the solvent stress tensor τ s and polymer stress tensor, τ p. μs is the solvent viscosity 1 which can have large jumps at material interfaces, D is the rate of deformation tensor, $2D = \nabla u + \nabla u^T$, and A is the configuration tensor. φm is the level set function for material m (m = 1, . . . , M) and is the sign distance to the m material. The Eulerian fluid motion is coupled to the prescribed Lagrangian swimmer motion by way of the no-slip condition, which is satisfied by all points x on the swimmer surface at time t.

(1) $$\nabla \cdot \vec{u} = 0$$

(2) $$\frac{\partial(\rho\vec{u})}{\partial t} + \nabla \cdot (\rho\vec{u}\vec{u}^T) = \nabla \cdot (-p\boldsymbol{I} + \boldsymbol{\tau})$$

(3) $$\boldsymbol{\tau} = \boldsymbol{\tau}_s + \boldsymbol{\tau}_p$$

(4) $$\boldsymbol{\tau}_s = 2\mu_s \boldsymbol{D} = \mu_s(\nabla\vec{u} + \nabla\vec{u}^T)$$

(5) $$\boldsymbol{\tau}_p = \frac{\mu_p \boldsymbol{f}s(\boldsymbol{A})}{\lambda}$$

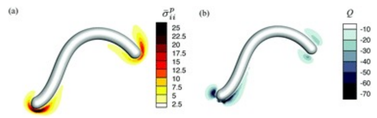
(6) $$\overset{\nabla}{\boldsymbol{A}} \equiv \frac{\partial \boldsymbol{A}}{\partial t} + \nabla \cdot (\vec{u}\boldsymbol{A}) - \boldsymbol{A} \cdot \nabla\vec{u} - (\nabla\vec{u})^T \cdot \boldsymbol{A} = -\frac{f_R(\boldsymbol{A})}{\lambda}$$

(7)

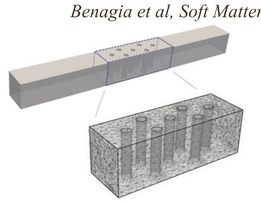
(8) $$\frac{\partial \phi_m}{\partial t} + \vec{u} \cdot \nabla\phi_m = 0 \quad m = 1, \ldots, M$$

Literature review establishing a potential improvement on current state of the art → Development of new numerical algorithm with better stability properties → Validation and verification of computational results → Potential biomedical applications of the new algorithm

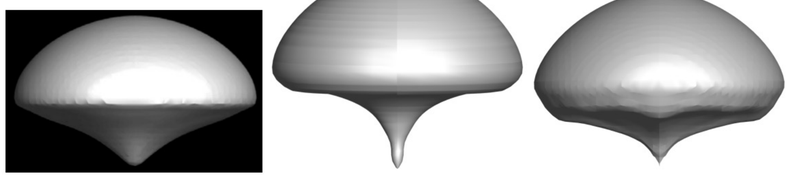
Results



Benagia et al, Soft Matter, 2019



Spatially Adaptive Complex Geometry



Analysis of Previous Results and Simulations:

In Fig. 1, the literary work presented with comparable methodology with differences in geometry of the micro-swimmer representative of the alternate application of the simulation.

In Fig. 2, this paper contains simple spherical geometry micro swimmers through microchannels that have cylindrical columns representative of the potential applications of the simulations.

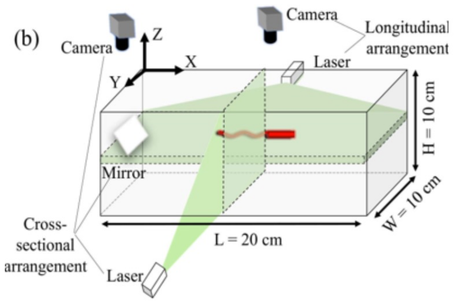


Fig. 2

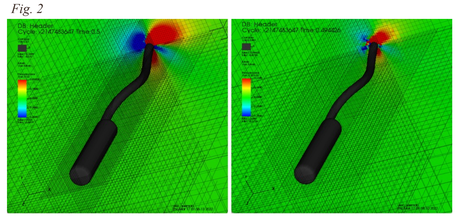


Fig. 3

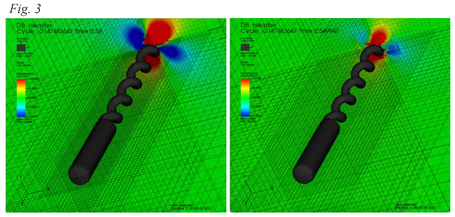


Figure 1: Comparison between staggered and non-staggered algorithms for a gas bubble rising in a non-Newtonian fluid; from left to right: (a) collocated results 3D, (b) staggered results, 3D axis-symmetric, at time t = 0.434, (c) staggered results, 3D, quarter domain simulation at time t = 0.472.

Purcell's swimming scallop

In physics, the scallop theorem states that a swimmer that exhibits time-symmetric motion cannot achieve net displacement in a low Reynolds number Newtonian fluid environment, i.e. a fluid that is highly viscous. It is important to note that no movement would be observed in a Newtonian fluid.

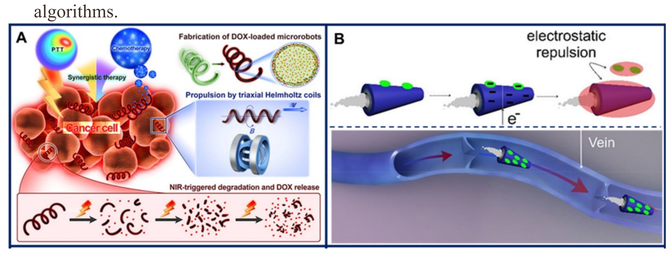
Two types of results are presented in this report: (A) verification results, and (B) validation results.

As is shown in the two comparison Figures, 2 and 3, we have qualitative agreement between the previous collocated algorithm and the present staggered grid algorithm. Whereas the distribution of Q11 is in agreement, there is disagreement in the magnitude of Q11.

We attribute this disagreement to the following: (a) the translational velocity was different between the collocated simulations and the staggered grid simulations, (b) the treatment of the boundary conditions where the non-Newtonian liquid interacts with the dynamic helical swimmer is different between the two formulations, and (c) (perhaps the biggest reason for the difference) the recent staggered grid swimmer results implemented more aggressive adaptive mesh refinement which has the benefit of more efficient use of available computer resources, but at the cost of less accuracy on the coarse parts of the computational domain.

Conclusions and Applications

A new staggered grid numerical method has been developed for simulating the Eulerian-Lagrangian interaction of a "Helical Micro-swimmer" with the surrounding Non-Newtonian fluid. In comparing the present (novel) staggered grid numerical method for non-Newtonian multi-phase, multi-fluid flow with the previous model; it has been found to pertain no significant benefits to the stability as compared to the non-staggered algorithms.



Recent examples of micro-swimmers developed for the delivery of chemotherapeutic agents. (A) Spirulina-based magnetic helical micro-swimmers loaded with doxorubicin (DOX). The micro-swimmers were shown to fight cancer in vitro by synergistic photothermal effects and DOX release upon near infrared-triggered degradation. Figure reproduced from [71], © 2019 American Chemical Society. (B) Top: Mechanism of the electrochemical release of DOX from a bismuth/nickel/platinum tubular micro-swimmer upon applying a negative potential (−1 V). Drug release is attributed to an increase in the negative repulsive charge in the system. Bottom: Micro-swimmer navigation inside a vein. Figure reproduced from [75], © 2019 American Chemical Society

References

Binagia, J. P., Guido, C. J., & Shaqfeh, E. S. (2019). Three-dimensional simulations of undulatory and amoeboid swimmers in viscoelastic fluids. Soft Matter, 15(24), 4836–4855. https://doi.org/10.1039/c8sm02518e

Bell, John B., et al. "Computational Fluctuating Fluid Dynamics." *ESAIM: Mathematical Modelling and Numerical Analysis*, vol. 44, no. 5, 2010, pp. 1085–1105., doi:10.1051/m2an/2010053.

Burgner, J., Swaney, P. J., Lathrop, R. A., Weaver, K. D., & Webster, R. J. (2013). Debulking from within: A robotic steerable cannula for intracerebral hemorrhage evacuation. *IEEE Transactions on Biomedical Engineering*, *60*(9), 2567–2575. https://doi.org/10.1109/tbme.2013.2260860

Plunkett, P., Hu, J., Siefert, C., & Atzberger, P. J. (2014). Spatially adaptive stochastic methods for fluid–structure interactions subject to thermal fluctuations in domains with complex geometries. *Journal of Computational Physics*, *277*, 121–137. https://doi.org/10.1016/j.jcp.2014.07.051

R;, B. A. I. T. (2020). *Recent advances in Microswimmers for Biomedical Applications*. Micromachines. Retrieved March 16, 2022, from https://pubmed.ncbi.nlm.nih.gov/33261101/

Wang, Y., Lei, H., & Atzberger, P. J. (2017). Fluctuating hydrodynamic methods for fluid-structure interactions in confined channel geometries. *Applied Mathematics and Mechanics*, *39*(1), 125–152. https://doi.org/10.1007/s10483-018-2253-8

Rhie, C. M., and Chow, W.-L. Numerical study of the turbulent flow past an airfoil with trailing edge separation. AIAA journal 21, 11 (1983), 1525–1532

Ohta, M., Furukawa, T., Yoshida, Y., and Sussman, M. A three-dimensional numerical study on the dynamics and deformation of a bubble rising in a hybrid carreau and fene-cr modeled polymeric liquid. Journal of Non-Newtonian Fluid Mechanics 265 (2019), 66–78.

Wang, Y., Lei, H., and Atzberger, P. J. Fluctuating hydrodynamic methods for fluid-structure interactions in confined channel geometries. Applied Mathematics and Mechanics 39, 1 (2018), 125–152.

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