Nanoscale Modeling of Flow of Macromolecules Through Microfluidic Devices

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PROJECT OVERVIEW

Microfluidic devices are rapidly finding an increasing number of applications in biology, chemistry, and medicine, to name a few. These devices rely on the ability to control the flow and transport of fluids and macromolecules through micron and nanometer scale geometries. As the ability to manipulate and process materials at the nanometer level advances, so will the demand to make *a priori* predictions of macromolecular behavior in flow processes on this scale. In the area of complex fluids, DNA and carbon nanotube solutions are particular technologically interesting examples, spanning the range from very flexible to stiff molecules.

The rational design of microfluidic devices requires theoretical and computational tools that span this range, accounting for the different phenomena that dominate. In the proposed work, a large-scale computational approach is adopted to model the transport of fluids containing macromolecules through microdevices of arbitrary geometry. One overall goal of the proposed work is to develop efficient methods for molecular scale simulation of: (1) large, flexible molecules in flow, fully accounting for hydrodynamic, excluded volume and electrostatic interactions; (2) assemblages of semiflexible polymers, accounting for the interparticle interactions that often dominate the behavior in flow; (3) hydrodynamic interaction effects on dynamics of chain molecules near solid surfaces; (4) coupling of nanoscale Brownian dynamics simulations and continuum fluid mechanics simulations for self-consistent solution of complex flow problems.

Our overall objective is therefore to develop a general, multiscale computational fluid dynamics formalism in which microstructural, nanoscale simulations of arbitrary systems are seamlessly and efficiently integrated into full-scale flow simulations for design of microfluidic processes. As part of our effort we intend to acquire the fundamentals for subsequent development of a general nanoscale process simulator, akin to the ones currently in use for design of large-scale industrial process design. In this project, these technical advances will be applied to improve the understanding of polyelectrolytes in flow; to study the flow of DNA solutions through microchannels and near surfaces; to study the interaction between flow and nanoscale microstructure in geometries characteristic of microfluidic devices.

In the initial stages of this project, we have concentrated our attention on the efficient treatment of hydrodynamic interactions in dilute macromolecule solutions. The computational demands of hydrodynamic-interaction calculations scale with the third power of the molecular weight of the macromolecule. Simulations that take hydrodynamic interactions into account are computationally prohibitive, and have therefore been limited to very small molecules. Unfortunately, neglecting such interactions in flow calculations leads to incorrect scaling of transport properties with molecular weight.

We have now developed a computational formalism that reduces the computational demands of hydrodynamic calculations significantly, and we have applied it to develop a predictive model for the flow behavior of dilute solutions of DNA. The predictions of the model have been verified by careful comparison to available experimental data. We have shown that neglecting hydrodynamic interactions can lead to incorrect descriptions of the transient behavior of DNA solutions, particularly for large molecules. Overall, our model is able to capture the dynamic behavior of DNA in dilute solutions with good accuracy.

Our next step is to consider how hydrodynamic interactions are mediated by the presence of a confining surface. This next stage of our work will require that we develop a formalism to include hydrodynamic effects in stochastic (Brownian) calculations. Such formalism will necessarily have to be highly efficient and will have to exhibit a favorable dependence on molecular weight. After completing this section of the project, we will proceed to examine in a systematic manner the effects of confinement and molecular flexibility on the rheological properties of dilute and semi-dilute solutions of macromolecules.

We have also started to implement a multi-scale algorithm for combined Brownian-continuum hydrodynamic simulations. Recent developments in computational fluid dynamics and microstructural simulation techniques, as well as dramatic increases in computing power, have made conceivable the simulation of flows of microstructurally complex materials in complex geometries, without invoking closure approximantion, directly from coarse-grained models of the microstructure, such as those outlined above.

The basic idea of the approach is simple: at each time step the continuum equations of conservation of mass and momentum are solved via finite elements, self-consistently with microstructural (e.g. Brownian dynamics) simulations for the microstructure at each point in the flow. The central problem with constructing an Eulerian (fixed mesh) scheme for microstructural simulations in complex flows is how to ``communicate'' the microstructural information from point to point along pathlines in the flow. A straightforward approach addresses this problem by solving a convection equation in physical space for each trajectory of the microstructural simulation. Since good statistics require large ensembles -- 1000 trajectories is not unusual -- this is an expensive process. The fundamental idea underlying our approach is that distribution functions can be accurately characterized by far fewer than 1000 pieces of information. In particular, we dramatically streamline this “communication” step by choosing a small number of key properties of the microstructural distribution function, and modifying the microstructure

to reflect the convection of those properties. The current methodology determines, via a linear least squares calculation, the smallest correction to the microstructure that conserves these properties. If the properties are chosen appropriately, this scheme represents a convergent approximation of the exact problem. We have demonstrated the viability of this approach and using it, have performed the first studies of a full chain model (rather than a dumbbell model) in a nontrivial flow field.

Ongoing developments in this multiscale simulation approach include:

- implementation in a full scale viscoelastic flow code for arbitrary chain models (including semiflexibility and fluctuating hydrodynamics near surfaces).

- analysis of how the choice of convected properties affects the performance of the method. The recently developed GENERIC formalism for nonequilibrium thermodynamic modeling of microstructure may provide guidance here.

- incorporation of diffusive fluxes of microstructure. In polymer solutions, variations in stress can drive diffusion even in the absence of concentration gradients This fact may be of crucial importance for the performance of microfluidic bioseparation processes, but our current theoretical understanding of the phenomenon is primitive Furthermore, we have found that concentration variations driven by Brownian motion can, during flow, be much larger near boundaries than in bulk solutions. Since essentially all the fluid in a microfluidic system is near a boundary, this effect may also be important in understanding microfluidic bioseparations.