

Special Section on the Fluid Mechanics and Rheology of Nonlinear Materials at the Macro, Micro, and Nano Scale

This collection of selected papers are drawn from those presented at the IMECE 2004 in Anaheim, California at the Symposium “Rheology & Fluid Mechanics of Non-linear Materials,” “Advances in Processing Science,” and “Electric and Magnetic Phenomena in Micro and Nano-Scale Systems” sponsored by the Fluids Engineering Division and the Materials Division, as well as the Symposium on “Flows in Manufacturing Processes” held at the 4th JSME-FED (Japanese Society of Mechanical Engineers—Fluids Engineering Division of the ASME) joint meeting in Hawaii in July 2003. They represent excellent examples of cutting-edge multidisciplinary research.

This editorial is accompanied by an addendum, “Current Unanswered Questions and Future Directions.” I asked the authors in this special section to contribute their thoughts on yet unexplored issues they view as important in their respective areas, and they kindly obliged. I am grateful to those who decided to contribute. I learned the usefulness of the platform from my friend, the late Professor Lloyd Trefethen, who put together several very well received unanswered questions sessions during the meetings of the FED.

The symposia series centered on the theme of complex fluids developed as an interdivisional effort in the early nineties, and has been sustained primarily by the FED, the Materials Division and, in the early years, the Applied Mechanics Division, with organizing committees led by Dennis Siginer. Symposia focused on Electro-rheological Fluids, non-Newtonian and viscoelastic fluids, and industrial applications were held at every annual winter meeting of the ASME. A wider scope and a more encompassing recurring theme were embraced in the mid-nineties, and symposia on the “Rheology & Fluid Mechanics of Non-linear Materials” have been held every year since then without interruption. A second symposia series sponsored by the FED and the Materials Division addressing issues on “Electric and Magnetic Phenomena in Micro and Nano-Scale Systems,” of great interest to emerging technologies and to homeland security, was initiated early in this decade by Dennis Siginer and Boris Khusid. Two complementary symposia of interest to industry in materials processing and manufacturing, “Advances in Materials Processing Science” and “Flows in Manufacturing Processes,” have also been organized regularly for several years, the former held during IMECE and the latter during Summer Meetings of the FED.

This collection of papers opens with three contributions related to micro and nano scale problems. The first two are concerned with micro fabrication for the manipulation of nanoparticles using dielectrophoresis, and the third looks into optical finishing using magnetorheological jet polishing technology for a peak-to-valley surface accuracy of the order of 30 nm.

Riegelman et al. describe their research on the positioning of carbon nanotubes at predetermined locations with the use of dielectric forces and a fabrication technique to construct carbon nanotube based multiwalled fluidic devices. The technique combines dielectrophoretic trapping with photolithography.

James et al. present a novel separation device based on “dielectrophoretic gating” to discriminate between biological and non-

biological analytes captured in air samples. A technique for batch fabrication of self-sealed, surface micro-machined micro-channels equipped with dielectrophoretic gates is described. Setting the gates to a moderate voltage in the MHz-frequency range removes bacteria cells from a mixture containing non-biological particles.

Kordonski et al. present research on a new polishing technology, magnetorheological finishing (MRF). MRF can produce nanometer order surface accuracy and roughness and does not damage the material at the subsurface level, a major disadvantage of conventional “contact” polishing. However, high precision finishing requires a stable, relatively high-speed, low viscosity fluid jet which remains collimated and coherent before it impinges the surface to be polished.

The next group of papers is concerned with flow stability problems. The stability of the flow in the co-extrusion of multilayered sheets from a die is a major concern for product quality. Multilayered sheets are composite materials with specific physical properties. Any interfacial instability during the extrusion process will result in undesirable effects. The behavior of non-Newtonian fluids in curved pipes of non-circular shape is of great interest and has not received as yet the attention it deserves, in particular the Dean instability. Aspects of the Taylor-Couette flow fall in the same category. Although the elastic instability in Taylor-Couette flow has received a lot of attention recently, the important symmetry breaking effect of an obstruction on the flow relevant to horizontal oil drilling operations has not.

Rousset et al. study the influence of an interphase on the stability of the plane Poiseuille flow of two compatible polymers during the co-extrusion process. Each layer of these composite materials provides a specific end-use characteristic, such as optical, mechanical, or barrier properties. The authors successfully explain why stratified flows of compatible polymers are generally more stable than those of incompatible polymers.

Fellouah et al. investigate numerically the Dean instability of Newtonian, power-law, and yield stress fluids in curved ducts of rectangular cross-section with various aspect and curvature ratios. Curved channels are commonly encountered in turbomachinery and heat exchangers for heating or cooling systems because of the extended laminar flow regime and enhanced transverse mixing. The influence of the aspect ratio and the curvature ratio on Dean instability is investigated as well as the effect of the power law index and the Bingham number.

Loureiro et al. investigate the flow inside a horizontal annulus due to the inner cylinder rotation when the bottom of the annular space is partially blocked by a plate parallel to the axis of rotation, as is encountered in the drilling process of horizontal oil and gas wells. A major problem in this drilling technique is the efficient removal of the cuttings that settle and accumulate at the lower part of the annular gap. The objective of the research presented in the paper is to determine the influence of the partial obstruction on the flow structure in the gap for low rotational Reynolds numbers, both for Newtonian and power-law liquids.

Numerical computations with viscoelastic fluids suffer from the curse of high Weissenberg number limit. Numerical algorithms for

the solution of flow problems break down for reasons which are not yet well understood at values of the Weissenberg number larger than one depending on the type of flow. The source of the instability does not necessarily stem from the algorithm and/or may not be grid dependent, although that is a clear possibility, but it is rather related quite often to the constitutive structure. Hadamard-type instabilities as well as dissipative instabilities are the major deficiencies most constitutive equation formulations at the macro as well as micro level suffer. Over the years considerable progress has been made and the Weissenberg limit has been moved higher, but the problem is far from being completely solved and is still a burning issue in rheological fluid mechanics. Similar problems exist in numerical computation of dry granular flows and dispersed particle flows. The next two papers investigate computational issues with polymeric fluids and granular flows.

Feigl and Senaratne develop a micro-macro simulation algorithm capable of resolving multiple levels of description to calculate the flow of polymeric fluids. The calculation of the velocity and pressure fields is performed using standard finite element techniques, while the polymer stress is calculated from a microscopic-based rheological model using stochastic simulations.

The capability of the Lagrangian Molecular Dynamics simulation to track individual particles in dispersed particle and dry granular flows is limited by the computational expense. Continuum models remove this difficulty, but constitutive relations for fluid drag and solid drag are needed in the momentum equations of each particle phase to close the field equations. Gao et al. focus on particle-particle momentum transfer in a dry bidisperse granular mixture and perform molecular dynamics simulations of the mixture to characterize the solid drag.

The thread which connects the following five papers is the study of the effect of surfactants used as additives on the flow structure in various settings. Although surfactant solutions exhibit viscoelasticity, their behavior shows anomalous features and quite often deviates from the pattern of a closely associated class of fluids to that of dilute polymeric solutions. A class of motions which has attracted attention recently is the swirling flow of viscoelastic fluids driven from the bottom in cylindrical containers with either free surface or confined, in particular because of the vortex breakdown characteristics shaped by the elasticity of the solution and/or the use of the free surface shape to determine the constitutive constants of the fluid and characterize the fluid. Because surfactants do not degrade in shear as polymeric solutions do due to the stretching of long chains, it has long been advocated that they can be used in large-scale heating/cooling systems to save pumping energy through the considerable drag reduction they induce. Various aspects of these issues are explored in the next five papers.

In two complimentary papers on the swirling flow of viscoelastic fluids with free surface in cylindrical containers driven from the bottom, Wei et al. present a detailed experimental investigation of the structure of the flow and a numerical study. The motivation for these studies lies with the significant drag reducing ability in turbulent flow of very dilute surfactant solutions of the order of 70–80% with mass concentrations of only 30 and 75 ppm. In Part I the high Reynolds number swirling flow of water and a surfactant solution is experimentally investigated using a double-pulsed particle image velocimetry system. In Part II flow simulations in laminar regime are presented for both Newtonian

and viscoelastic solutions. The numerical simulations are run for laminar flow as viscoelastic large-eddy simulation (LES) turbulence models have not yet been developed for viscoelastic solutions. The tested Marker-and-Cell (MAC) method for Newtonian flow is extended to viscoelastic flow to track the free surface.

In a related paper Itoh et al. investigate the steady confined swirling flow of viscoelastic fluids in cylindrical containers using laser Doppler velocimetry. Prominent among the findings in the paper is the decrease in the azimuthal velocity with increasing Weissenberg number at any aspect ratio tested. Experimental data is compared to the numerical predictions based on the Giesekus and power-law models, both of which can fairly well describe the retardation in the azimuthal velocity in the range of small Weissenberg numbers.

Watanabe et al. use the laser-induced fluorescence (LIF) technique for visualization of the formation of Taylor vortices in the gap between two coaxial cylinders. The nonlinear test fluids are drag-reducing polymeric solutions in various concentrations and surfactant solutions. Experimental observations show that Taylor cells form in polymer solutions but not in surfactant solutions with viscoelastic properties, a puzzle which needs further investigation.

Munekata et al. experimentally investigate by two-dimensional laser Doppler anemometry the effect of drag-reducing surfactants in swirling pipe flow. The considerable drag-reducing ability of surfactants when used as additives to a Newtonian fluid is well known in straight, non-swirling pipe flow, but in most industrial applications pipes are not straight. Swirl decay, vortex type, and turbulence intensity are discussed and compared with the swirling flow of water.

The last two papers in this collection cover industrially important flows in the blow molding film manufacturing process, the rimming flow on the inside of a horizontal cylinder which presents a rich variety of fluid mechanics phenomena and flow between coaxial cylinders driven by an axial pressure gradient as well as the rotation of the inner cylinder.

Fomin and Hashida present an asymptotic analysis of the coating of shear-thinning non-Newtonian fluids on the inner surface of a hollow rotating horizontal cylinder, and derive the runoff condition. The solution for the film thickness is continuous if the runoff condition is satisfied with subcritical, critical, and supercritical flow regimes.

Woo et al. present an experimental study of the fully developed laminar and transitional vortex flow, and in particular of the skin friction coefficient of Newtonian and shear-thinning fluids in a concentric annulus driven by the rotating inner cylinder and the axial pressure gradient. The study is motivated by the importance in engineering applications of flows in annular passages with a rotating inner wall such as bearings, rotating-tube exchangers and, especially, mud flow in the case of slim hole drilling of oil wells.

In closing I would like to express my deepest appreciation to the Editor of JFE, Professor Joe Katz, for his leadership and for the opportunity to include this special section among the pages of this Journal. I would like to again thank the numerous anonymous reviewers and the authors who made this special section possible.

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Unraveling the Behavior of Liquids at the Nanoscale

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The behavior of liquids under extreme confinement is of interest from both the scientific and the technological points of view. Advances in nanotechnology have facilitated the fabrication of devices in which conduits and pores have hydraulic diameters as small as a few nanometers. Conduits and pores with nanoscale dimensions are also ubiquitous in nature. Since the dimensions of these flow conduits are much smaller than those commonly encountered in many engineering applications and the conduits are characterized by very large surface area to volume ratios (on the order of $10^8 \text{ m}^2/\text{m}^3$), one wonders whether highly confined liquids behave differently than their macroscopic counterparts. Some of the relevant questions are: (1) At what length scale does the continuum approximation break down? (2) Is the nonslip boundary condition applicable at very small scales? How do fluid/solid molecular interactions affect slip? (3) Are surface phenomena that are typically ignored in larger conduits important in their small-size counterparts? (4) How are fluid phase change equilibrium and dynamics affected by the presence of surfaces and interfaces at ultrafine length scales? To answer some of these questions, our research group is conducting fluid flow experiments in conduits consisting of carbon nanotubes. Carbon nanotubes are a convenient material with which to work for several reasons. First, carbon nanotubes can be fabricated with diameters ranging from a fraction of a nanometer to several hundred nanometers, allowing one to conduct experiments with various tube sizes. Second, the tube's surface properties can be modified with heat and/or chemical treatments to facilitate behaviors ranging from hydrophilic to hydrophobic, allowing one to probe the effect of surface properties on the liquids' behaviors. Indeed, there is growing experimental evidence that liquids flowing on hydrophobic surfaces exhibit slip. See Ref. [1] for a recent review. Third, the tubes' walls are sufficiently thin to be transparent to light [2] and electrons [3–6]. Moreover, the tubes can contain high-pressure fluids for an extended time even in the vacuum environment of the electron microscope [3,4].

One of the obstacles encountered when studying nanoscale phenomena is the limited resolution of visible light. Fortunately, given the relatively small wavelengths of electrons, scanning and/or transmission electron microscopy allows one to visualize phenomena at sub-nanometer length scales. Hence, electron microscopy holds great promise for the study of liquid behavior at the nanoscale. Unfortunately, however, conventional electron microscopy requires vacuum conditions, and, in the past this has precluded its use for the study of volatile fluids. With present day technology, at best, one can operate with environmental chambers that allow the introduction of humid gases. This shortcoming of electron microscopes can be alleviated by fully encapsulating the fluids in sufficiently small containers that facilitate electron transmission through them. Indeed, our group has demonstrated the feasibility of observing and thermally actuating liquids confined in nanotubes with both transmission and scanning electron microscopy [3–7] (see Fig. 1). To make additional progress and enable controlled experiments with well-characterized fluids in an elec-

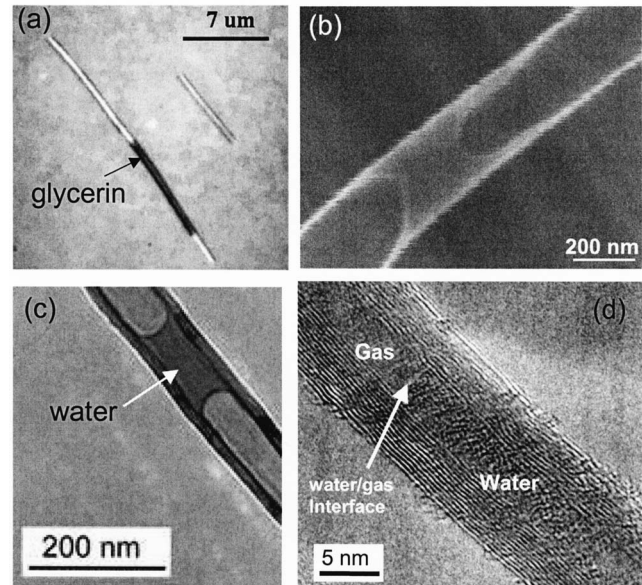


Fig. 1 Micrographs showing glycerin (a) and water (b)–(d) inside carbon nanotubes. The tubes shown in (a) and (b) were fabricated with chemical vapor deposition in alumina templates. The tubes in (c) and (d) were hydrothermally produced. (a) Optical micrograph of glycerin inside an open CVD-grown nanotube. (b) Environmental SEM image of water inside a nanotube similar to the one shown in (a). (c) TEM image of water inside a hydrothermally-produced, sealed carbon nanotube. (d) TEM micrographs of a fluid inside a multi-wall, hydrothermally-produced, sealed carbon nanotube.

tron microscope, it is necessary to construct nanotube-based devices that allow for the deliberate introduction and removal of well-characterized liquids in the vacuum environment of the electron microscope's chamber. The construction of and preliminary experiments with such a device, made utilizing hybrid fabrication technology, are described in this issue [8]. This hybrid technology utilizes dielectrophoresis, a phenomenon that involves interesting fluid mechanics all by itself, for the controlled positioning of nanotubes at predetermined locations, and photolithography and microfabrication for the construction of functional devices.

Although the use of electron microscopy to study the behavior of liquids at the nanoscale appears to be promising, there are also potential hurdles. Through ionization, radiolysis, and heating, the electron beam may alter the liquid and the tube's surface properties [5,6]. Additionally, the electron microscope data may require sophisticated interpretation. To partially address some of these issues, we are comparing optical and electron microscope images

of liquid flow in tubes of diameters in the range that allows both optical and electron imaging (Figs. 1(a) and 1(b)).

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Modeling and Computational Simulation of Viscoelastic Flows

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An important goal in viscoelastic fluid mechanics is to understand the relationship between a flow process, the flow-induced microstructure of the fluid, and the rheology of the fluid. Achieving this goal requires theoretical modeling, computational simulations, and experiments. On the modeling side, the development of accurate stress-strain models for rheologically complex fluids remains a challenge. Advances in this area require the development and investigation of models which incorporate structural information on the fluid. For polymer solutions and melts, this translates into molecular-based modeling involving, for example, reptation theory and/or network theory. It is vital to continue these efforts. It is equally important to investigate other suitable modeling approaches for these fluids and for emulsions and polymer blends. In particular, more attention should be given to the GENERIC thermodynamical approach which allows the derivation of a complete set of evolution equations for a defined set of state variables, includ-

ing structural variables. A second challenge is the development and implementation of accurate, efficient, stable, and robust numerical algorithms for solving flow problems involving these models in engineering applications. Micro-macro simulations of polymeric flow involve the coupling of the conservation equations from continuum mechanics with a molecular-based rheological model. While perhaps out of its infancy, this multiscale simulation approach needs much more development and theoretical analysis. Efficient numerical algorithms are also needed for solving the very large, coupled, nonlinear systems of equations which the GENERIC modeling approach typically produces in inhomogeneous flows. Furthermore, it is important to increase the use of these simulations as a model validation tool, including the comparison of simulation results, e.g., velocity and stress fields, with experimental data.

Research in Rimming Flows

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The problem of rotational flow on the inner wall (rimming flow) and on the outer wall (coating flow) of a hollow horizontal cylinder is of interest due to its wide range of applications in industry. Both coating and rimming flows are shaped by the same forces, exhibit similar hydrodynamic effects, and are described by the same governing equations. In both configurations flow exhibits a surprisingly rich variety of phenomena, including various instabilities and pattern formations. Due to the complexity of the problem previous investigations were focused only on the analysis of the isothermal flows of Newtonian fluids with constant physical properties. However, real polymeric solutes used in rotational molding and coating technology are chemically very complex strongly nonlinear substances and, therefore, are non-Newtonian (shear-thinning and shear-thickening, viscoplastic and viscoelastic) and heterogeneous (multi-component) reactive fluids. Thermophysical properties of these fluids are strongly temperature-

dependent. To the best of our knowledge, the impact of important factors such as chemical reactions and temperature variation on the flow regime has not been discussed in the literature related to rimming flows.

Elimination of instabilities and determination of a criterion for flow stability of reacting nonlinear polymeric solute to obtain a continuous and smooth coating film on the wall of the cylinder are of major concern for the engineer-practitioner. Therefore, there is a need in the near future for attention to be focused on the following issues: (i) assessment of the effect of the nonlinear properties of the liquid polymer on the flow regime and flow instabilities; (ii) derivation of the stability criteria for non-Newtonian fluids; (iii) analysis of the effect of chemical reactions, temperature, and concentration variations in the solute on the stability of the rimming flow.

A Puzzling Pattern in Taylor-Couette Flow

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The flow pattern for a Newtonian fluid between two coaxial cylinders changes to Taylor-Couette flow from rotational Couette flow with increasing rotational speed of the inner cylinder. This flow field is ideal for research into the transition process from laminar to turbulent flow because it is slower than other flow systems and the instabilities are well understood. Thus, much theoretical and experimental research on the transition process using this flow field has been carried out for Newtonian fluids since Taylor's work. However, there are comparatively few studies on the flow of non-Newtonian fluids.

Flow visualization results for polymer solutions show that Görtler vortices of half the number of Taylor cells occur in the gap between coaxial cylinders when Taylor vortex flow in the primary mode is formed [1]. However, for 50 and 100 ppm surfactant

solutions Taylor vortices are not apparent and Görtler vortices collapse. Thus, the following questions naturally arise: Why is it that surfactant solutions do not form Taylor cells in the stale Taylor-Couette flow, whereas dilute polymer solutions do so, even though both are viscoelastic? What is the crucial difference between polymeric and surfactant solutions in constitutive formulation and physical properties to result in this behavior? What are the consequences concerning the Weissenberg assumption for the shear flow of surfactant solutions?

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Research in Optical Finishing Technology

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Conformal (or freeform) and steep concave optics are important classes of optics that are difficult to finish using conventional techniques due to mechanical interferences and steep local slopes. It has been demonstrated that impingement of a magnetically stabilized, collimated jet of MR fluid provides an ideal tool for finishing such challenging shapes. Existing theoretical work is focused on the modeling of the flow in the impingement zone. In

numerous experiments with different process parameters (jet velocities, nozzle diameters, and fluid viscosity) it was shown that material removal in the polishing spot closely correlates with the computed rate of work done at the surface by the fluid. Future optimization of the technology requires theoretical considerations to model the mechanism of jet stabilization.