Dynamics of Viscoelastic Fluid Displacement Flows: Influence of Polymer Concentration and Chain Architecture

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The free surface displacement flow of viscoelastic fluids is an important problem that finds application in a variety of industrial applications, such as enhanced oil recovery, gas assisted injection molding and coating of thin films. In particular, coating flows, i.e., flows where surfaces of solid substrates are coated with polymeric films, has attracted tremendous interest as they are susceptible to purely elastic free surface instabilities under creeping flow conditions [1,2]. Hence, understanding the interfacial flow dynamics of viscoelastic free surface displacement flows is not only of fundamental importance, but also of practical interest. However, the majority of the prior studies on interfacial dynamics of displacement flows have focused their attention on Newtonian fluids.

It is only recently that robust simulation tools have been developed for viscoelastic free surface displacement flows [3,4,5]. Specifically numerical simulations has been performed by Lee et al. [3] and Pasquali et al. [4] to examine the effect of viscoelasticity on the dynamics of coating flows of dilute polymeric solutions. Both studies were mainly concerned with the slot coating flow under steady state conditions and have shown formation of a stress boundary layer in the capillary transition region that significantly influences the interface dynamics. Furthermore, Lee et al. examined the flow dynamics of an air bubble penetrating through a viscoelastic fluid in a Hele-Shaw cell type of flow and found similar results in terms of formation of a thin stress boundary layer near the interface.

KEY RESULTS

We have extended the work of Lee et al. on dilute polymeric solutions to a much broader range of Ca, Wi and Bo numbers [5]. We find that there exist two clearly defined flow regimes. In the absence of gravity, a recirculation flow at low Ca (Ca<1.0), and a bypass flow at high Ca (Ca>1.0), are observed. The recirculation flow is characterized by the presence of a recirculation region, and an interfacial stagnation point, in addition to the stagnation point at the bubble tip, while in the bypass flow, all the fluid elements flow past the air bubble and the flow contains a single stagnation point at the bubble tip. In the recirculation region, we observe the formation of elastic normal stress boundary layers in the capillary transition region, an increase in the film thickness and an increase in the compression of the bubble free surface in the capillary transition region, with increasing elasticity. In addition, a phenomenon of 'meniscus invasion' (i.e., the tip of the bubble is drawn into the fluid as a sharp point) is observed when the normal stresses in the stress boundary layer get large enough. For the bypass flow, in addition to the normal stress boundary layer in the capillary transition region, we observe an additional stress boundary layer near the bubble tip. As Wi is increased, there is a film thickening effect and increased compression of the bubble free surface in the capillary transition region, however, the stresses in the bypass flow never get large enough for the meniscus invasion phenomenon to occur. In addition, we have also studied the effect of gravity on both flows. We observe that the presence of gravity in the recirculation flow results in a film thinning effect and an increase in the normal stresses in the capillary transition region, while in the bypass flow, addition of even a small amount of gravity introduces a recirculation pattern. Furthermore, in case of the recirculation flow, we have also qualitatively studied the effect of channel divergence on the flow dynamics, and shown that by increasing divergence, both film thickening and formation of the normal stress boundary layer is delayed to a higher Wi. However, the film thickness normalized with the maximum normal stress in the stress boundary layer collapses onto a single universal curve, indicating that the film thickening is driven by the maximum normal stress in the stress boundary layer in the capillary transition region, i.e., a local phenomenon.

Hence, in order to determine whether the film thickness can be estimated by specific fluid material properties and the dynamics of the localized normal stress boundary layer in the capillary transition region, we have examined the effect of concentration and chain architecture on the flow dynamics. In order to accomplish this, we employ a variety of realistic constitutive equations to model dilute and concentrated polymeric solutions, as well as, linear and branched polymeric melts. Specifically, we extend the dilute solution computations to incorporate the FENE-P model [6], employ the Giesekus model [6,7] for concentrated solutions, and the Extended Pom-Pom (XPP) model [8] for linear and branched polymer melts. Our study indicates that regardless of polymer concentration and chain architecture, the flow is characterized by a recirculation pattern at low Ca (i.e., Ca<1.0) and by a bypass pattern at high Ca (Ca>1.0). The amount of compression of the bubble free surface in the capillary transition region, the film thickening and the magnitude of the stress in the normal stress boundary layer are all observed to be functions of polymer concentration and chain architecture, and are largest for the most extensional hardening fluids and reduce with decreasing extensional hardening or increasing shear thinning. We show that the film thickness is determined by two competing factors, normal stress gradients in the flow direction (that depend on the normal stress in the stress boundary layer in the capillary transition region) and shear stress gradients in the gap direction (near the solid surface). In case of the recirculation flow, we show that for the dilute solutions and the linear polymer melts, that display extensional hardening behavior, the film thickness scales with the maximum normal stress in the stress boundary layer. For the concentrated solutions and branched polymer melts, that do not display any significant extensional hardening behavior, but are shear thinning, the film thickness is determined by the viscous drag felt by the fluid elements and scales with the shear viscosity based on the wall shear rate. Furthermore, we show that it is possible to estimate the magnitude of the normal stress in the stress boundary layer in the capillary transition region based on information obtained from the behavior of the fluid under planar extensional flow and the flow kinematics of the actual free surface displacement flow. In case of the bypass flow, the film thickness depends on the normal stresses formed at both the bubble tip and the capillary transition region, and consequently a scaling analysis based on the interfacial dynamics in the capillary transition region breaks down.

We also examine the effect of elasticity on the stability characteristics of the free surface in both the recirculation and the bypass flow by examining the major forces at the bubble tip. We find three major competing forces, viscous normal stresses, accumulation of polymeric normal stresses near the central stagnation line and a pressure drop across the interface. We illustrate how elasticity destabilizes the flow by altering the stress balance at the interface. Furthermore, by conducting a linear stability study of a model planar stagnation viscoelastic free surface displacement flow, utilizing the Oldroyd-B model, we show that elastic destabilization of the flow occurs due to the alteration of the isotropic pressure distribution at the free surface by the elastic normal stress boundary layer localized near the stagnation point [9].

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