점탄성을 가진 액적의 전기장에 의한 변형과 파괴

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Deformation and breakup of a viscoelastic droplet in an electric field

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Introduction

The understanding of liquid-liquid dispersions is very important since these phenomena may be encountered in various industrial operations. In these applications, the morphology of dispersed phase is a crucial factor to determine the efficiency of operation. Thus, in particular, the deformation and breakup of drop, dispersed in another immiscible fluid, by external force have been investigated intensively. One of the prominent applications of liquid-liquid dispersions is a blending of two immiscible polymers. It is well-known that the properties of polymer blend are largely influenced by its morphology, and by this reason, many researches concerned the evolution of morphology are available in literature. To modify the morphology of polymer blend efficiently, although in most part of studies about this topic have considered flow field, the external electric field may be recommended due to its easy manipulation of applying strength and direction.

In this study, we consider the effect of viscoelasticity on the deformation and stability of a drop suspended in an immiscible fluid under the action of a uniform electric field theoretically as well as experimentally. When the dispersed and the continuous phase have different and finite electrical properties, that is, neither of them is perfect dielectric nor perfect conducting material, the stress balance at the interface is not satisfied when the electric field is applied. As a result, fluid motions inside and outside drop are induced and the interface is deformed to match the tangential and normal components of stresses between two phases, respectively, and thus, the properties of interface and fluids such as viscoelasticity must be considered to elucidate the phenomena.

Theory

Unlike the Newtonian fluids, there have been relatively few theoretical investigations which pertain to electrohydrodynamic deformation and stability of non-Newtonian fluids. This is most likely a result of anticipated uncertainties in the selection of a reasonable constitutive model for non-Newtonian flows, as well as the obvious difficulty in solving the equations of motion after the choice has been made. In our opinion, however, for this type of problem it is sufficient to consider the influence of small instantaneous departures from Newtonian fluid behavior acting over a large time in at least a qualitative sense. It is worthwhile to note that the appropriate constitutive model for non-Newtonian flows which are nearly Newtonian is, well-known to be the second-order fluid provided the motion of fluids are both weak and slow in a rheological sense. A great deal of physical insight about *elastic effects* has been obtained by solving flow problems with the ordered-fluid models, although the ordered-fluids cannot describe the dependence of viscosity on the shear rate faithfully and the full range of time-dependent behavior[1]. With this assumption, the hydrodynamic stress may be written in familiar form

$$T^H = -PI + \tau_{(1)} + De\left[\tau_{(1)} \cdot \tau_{(1)} + \phi_1 \tau_{(2)}\right] + O\left(De^2\right) \tag{1}$$

and $\tau_{(n)}$ are Rivlin-Ericksen tensors given by

$$\left.\begin{aligned} \tau_{(1)} &= \nabla u + (\nabla u)^T \\ \tau_{(2)} &= \frac{\partial}{\partial t}\tau_{(1)} + u \cdot \nabla \tau_{(1)} + \tau_{(1)} \cdot (\nabla u)^T + \nabla u \cdot \tau_{(1)} \end{aligned}\right\} \tag{2}$$

In which, De and ϕ_1 are dimensionless parameters, defined as $De = a\left(E^\infty\right)^2\left(\Pi_1 + \Pi_2\right) / \mu_0^2$ and $\phi_1 = -\Pi_1 / 2\left(\Pi_1 + \Pi_2\right)$, where, Π_1 and Π_2 denote the first and second normal stress coefficient, respectively.

For the most problems, we cannot find exact analytical solutions so that we turn into a perturbation technique that can be used to develop solutions to flow problems for the retarded-motion expansion for small Deborah numbers, De. Inasmuch as the retarded-motion expansion is itself restricted to small De, no significant new limitations are imposed by the use of the perturbation procedure. In general, the problem formulated above is nonlinear, in spite of the fact that the governing equations are linear. The nonlinearity comes solely from the boundary conditions. Another difficulty inherent in this problem arises from the fact the interface location where the boundary conditions are applied is *a priori* unknown and must be determined as a part of the solution. In the present work, instead, we restrict our attention to the case of small deformations from the spherical shape, with the spherical shape being preserved by interfacial tension. Hence we can employ a purely analytical approach by considering the asymptotic limit $We \ll 1$. In this study, we proceed formally to the solution of our problem, via a double asymptotic expansion in We and De. Thus we let

$$1 \gg We, De \gg We^2, WeDe, De^2 \cdots$$

As a result, the magnitude of deviation from sphericity is expected to be $O(We)$. In the perturbation expansion which follows, we adopt the general procedures outlined by Leal[2], in which the velocity, kinematic and tangential stress conditions are satisfied at each order, and the deformation of the drop is then calculated using the normal stress condition.

Experimental

Purely elastic fluids, often referred to as "Boger fluids" or "second-order fluids", which exhibit elastic fluid response, e.g. normal stresses in shear flow, but a shear independent viscosity can be prepared by dissolving high molecular weight polyacrylamide in 0.1M NaCl aqueous solution [3]. These solutions are used for the drop phase. Newtonian silicone oils have different viscosity are used for the continuous phase. In order to consider the effect of non-Newtonian properties of continuous phase on the drop, we use another type of second-order fluid, namely, organic Boger fluid [4]. It can be prepared by dissolving polyisobutylene in a solvent which is composed of less viscous organic solvent and highly viscous one. Two flat copper plates, which are distanced by 3.5cm, are used for the electrodes. By using high voltage DC power supply, we can generate electric field about 6kV/cm in maximum. The deformed shape of drop is taken from lens-mounted CCD camera and recorded by VCR. The image of drop is captured by PC when necessary for the measurement of degree of deformation.

Results and Discussion

By utilizing the small deformation theory, the steady-state drop shape which is correct up to $O(We^2)$ can be obtained in terms of electrical Weber number, and consequently, the linear stability analysis for the steady-state drop shape can be performed. In Fig. 1, the effect of elasticity on the drop stability can be found shortly. The effect of non-Newtonian property is more appreciable when the viscosity of drop is much less than that of continuous phase. In this figure, R, S, and λ stand for the ratio of resistivity, permittivity, and zero shear viscosity, respectively. The parameter β represents a ratio of Deborah number for the two fluids, i.e.

$$\beta \equiv \left(\tilde{De} / De\right)\lambda \tag{3}$$

and, for moderate values of λ, both fluids thus contribute to the drop deformation if β is of $O(1)$. If β approaches zero or infinity, one of the fluids may be considered Newtonian and therefore produces no direct contribution to deformation at this order. When the drop is imposed in the uniaxial straining flow the drop becomes more stable by the influence of non-Newtonian property, and in contrast, when the drop is under the biaxial straining flow non-Newtonian property gives the drop reverse effect. The reason is that the $O(De)$ velocity field shows always biaxial straining flow. In actual, the $O(De)$ contribution to the drop deformation comes from solely the elastic property of fluid, and thus, it acts to restore the deformation resulted from electric field which produces uniaxial straining flow. In Fig. 2, the evolution of drop shape can be found. The degree of deformation of drop increases above its steady-state value, and then, decreases to steady-state shape by elastic force. From experiments, we confirm that the theory developed in this study is valid for the deformation of drop within the limit of relatively small deformation and stability analysis also present useful prediction for the critical point above which there exists no steady-state shape, qualitatively. The typical mode of drop breakup is tip-streaming, as shown in Fig. 3, if the Deborah number of drop is exceeded a certain critical point.

References

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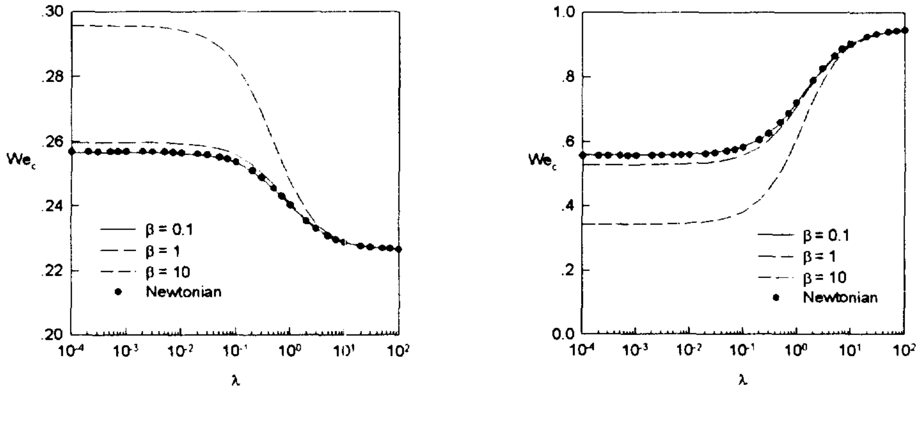

Fig. 1 Effect of non-Newtonian property of drop on the stability.
(a) R = 0.1, S = 1 (b) R = 1000, S = 1

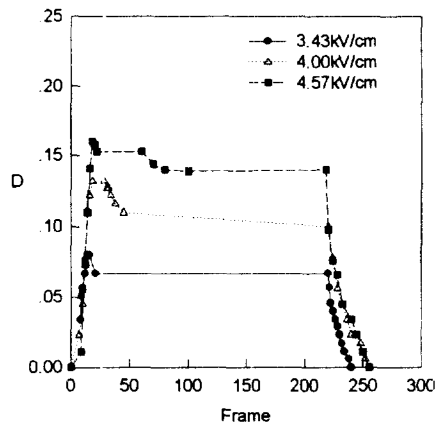

Fig. 2 The evolution of shape of polyacrylamide drop in polyisobutylene solution

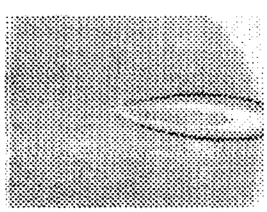

Fig. 3 Tip-streaming of aqueous polyacrylamide drop in silicone oil