LOCOMOTION OF A VISCOUS DROP, INDUCED BY THE INTERNAL SECRETION: BOUNDARY EFFECTS

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Summary A theoretical model for the locomotion of the drop induced by the internal secretion of a surfactant is presented. The effect of nearby solid walls or non-deformable liquid-liquid interfaces on the motion has been studied. Cases of plane and spherical boundaries. The dependence of the drop migration velocity on the location of the source and on the separation distance between the drop and the outer boundary as well as on the physical parameters of the system is reported. The dynamics of the drop is studied in the cases of a fixed location of the source inside the drop, and in the case when it passively moves with the internal circulation.

INTRODUCTION

Many modern industrial applications involve drops motion in liquid matrix accompanied by heat or mass transfer between the phases. These include, e.g. direct heat exchange or liquid-liquid extraction. Exchange of active species with an ambient media is one of the most characteristic features of living biological bodies as well. Most of the theoretical studies of such processes were based so far on the assumption of a uniform concentration/temperature inside the drops. This assumption does not hold in the case when a dissolved substance is secreted from some internal source within a drop, e.g. an encapsulated smaller drop in the course of technological processes involving compound drops or from certain organelles in a living cell. For an off-center location of the internal source, the diffusive mass transfer results in a non-uniform distribution of surfactant along the outer surface that, in turn, results in interfacial stress variation that ultimately induce a surface motion and the locomotion of the drop.

We present here a theoretical study of the motion of a drop due to the internal secretion of a surface-active substance. In our model we consider a viscous drop that contains another smaller droplet or a point source of a surface-active substance. The system is embedded in an immiscible viscous fluid that is either unbounded or confined by plane or or within spherical boundaries. A brief description and preliminary results for the motion of a complex drop in unbounded media can be found in Nir & Lavrenteva (2003). In the present work we report a detailed study of the locomotion of drops for a variety of physical parameters. We consider the motion in an unbounded liquid as well as more relevant cases when the flow domains are confined by boundaries of various physical nature. The cases of solid-liquid and liquid-liquid boundaries with various boundary conditions for the concentration are studied. The dependence of the drop migration velocity on the location of the source and on the separation distance between the drop and the outer boundary as well as on the physical parameters is reported. The focus of the study is on the case of a locomotion induced solely by the Marangoni effect. For completeness, the combined action of buoyancy and Marangoni effect is also considered.

PROBLEM DEFINITION AND METHOD OF SOLUTION

Consider a spherical drop containing a source of a soluble weak surfactant, which is submerged into an immiscible viscous fluid. The outer fluid is either unbounded or confined by a flat or spherical boundary. Three different types of outer boundary are considered: solid wall, free surface and liquid-liquid interface, as well as two different types of boundary conditions for the concentration at these boundaries: zero mass flux or given uniform concentration. All physical properties of the fluids are assumed to be constant except for the interfacial tensions, which are assumed to depend on the surface concentration. At the outset, we introduce dimensionless variables based on the size of the larger drop and the physical properties of the ambient fluid. The system is governed by the following set of dimensionless parameters: Reynolds number, Peclet number, two capillary numbers, the Bond number, the ratios of physical characteristics of the phases (viscosity, diffusivity), and the geometry of the system. When the drop moves under the action of gravity force, numbers characterizing the relative influence of gravity and Marangoni effect are also considered.

For simplicity, we consider the cases when inertia, convective transport and deformation effects can be neglected. i.e. Reynolds, Peclet and the capillary numbers are assumed to be zero. Under these conditions the quasi-steady approximation is valid, i.e. the concentration and velocity fields can be somewhat decoupled and found from stationary equations (Laplace and Stokes, respectively). The problems remain coupled only through the dependence of interfacial stress conditions on the variation of surfactant concentration at the surface.

The velocity and pressure fields in each phase satisfy the quasi-stationary Stokes equations with the following boundary conditions: The fluid is at rest at infinity. No-slip conditions are imposed on solid walls. The velocity field is continuous across drops interface, while the drops do not deform. The difference of tangential stresses at the interfaces is balanced by the gradient of the surface tension. The problem definition is complemented by the balance of the forces acting on each of the drops from which the dynamics is extracted, and by the equations for temporal evolution of the positions of the drop and the internal source. The latter may be either fixed within the drop or passively migrate with the internal circulation.

The above problem is solved for axisymmetric configurations using conformal mapping techniques. In this procedure we first calculate the concentration distribution and the Stokes stream function from which the force on the drop can be obtained as a sum of Marangoni force, Stokes drug and buoyancy. Balancing these forces provides an equation on the drop's migration velocity that is used to advance the geometry of the system.

RESULTS OF CALCULATIONS AND CONCLUSIONS

The dependence of the drop migration velocity on the location of the source and on the separation distance between the drop and the outer boundary as well as on the physical parameters of the system is reported. The various flow patterns are described The dynamics of the drop is studied for the cases of the fixed location of the source inside the drop and in the case, when it passively moves with the internal circulation.

For the case of a motion in an unbounded fluid, the internal source was modeled as a smaller droplet with a uniform concentration of a surfactant. Our computations revealed that the internal secretion from the inner droplet induces locomotion of the compound viscous drop and that the flow generated by the interface of the large drop causes the migration of the internal droplet in the same direction. In general it was found that the velocity of the inner droplet exceeds that of the large drop. With the passage of time, the droplet approaches the interface of the drop and the eccentricity of the system is increased. When the distance between the centers increases, the relative velocity first grows, but as the droplet approaches to the interface, its relative motion is retarded by the strong viscous resistance. At the limiting configuration of the touching droplets the aggregate will move with a constant velocity. When the dimension of the inner droplet is much less than that of the large one, it is natural to model it by a point mass source with a given strength. This model is adopted for the computation of the drops locomotion is confined domains.

The combined effect of the buoyancy and spontaneous Marangoni motion is studied as well. It is shown that a rich variety of interaction patterns may occur, which exhibits separation of flow in the outer fluid and within the large drop. In some particular cases both drops remain suspended motionless in the laboratory reference frame with the fluid circulating in a steady manner. A pair of drops may have several equilibrium positions, with one or two of them being stable.

The presence of nearby boundaries normally increase the hydrodynamic resistance and, thus, fluid flow near the boundary has lower velocity as compared to those in unbounded medium for the same external forcing. On the other hand, for the surface induced flow, a nearby boundary affects the concentration at the drops surface and hence the Marangoni flow. Our calculations revealed that the boundary with constant concentration has a repulsive effect on the drop, while an insulated boundary tends to attract a drop. For a large separation distance, the motion of the drop is similar to that in an unbounded fluid, while for smaller separations it is considerably retarded and, in some cases, can be even reverted.

The effect of liquid-liquid and liquid-gas interface on the hydrodynamic resistance of a nearby particle is much weaker than that of the solid wall. On the other hand, a Marangoni flow is induced on such an interface as well as on the surface of the drop itself. This effect is shown to be quite strong being able to change the flow pattern and the direction of the drops migration.

The dynamics of the drop is calculated for a fixed location of the course inside the drop as well as when it passively moves with the internal circulation for all the types of external boundaries mentioned above.

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