Theoretical Studies of Flow-Induced Coalescence

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We study the dynamics of collision and film drainage that leads to coalescence of two drops in a flow. The objective is a comparison with experimental observations from our laboratory, which have been carried out using small Newtonian drops (20-40 micron), with and without surfactant, in a computer controlled four-roll mill. These measurements include detailed trajectories, the coalescence angle as a function of capillary number, viscosity ratio, drop size and the collision trajectory as specified by the offset at “large” separations. The four-roll mill allows two types of collisions: head-on collisions in which the drops stay in a head-on configuration until coalescence occurs; and glancing collisions in which the drops rotate around one another and either coalesce or are eventually separated by the flow. In the latter case, the critical parameter is the “critical capillary number” above which coalescence is not possible. In the case of head-on collisions for the range of parameters we have considered, the drops always coalesce eventually and the primary experimental measurement is then the “collision time”; namely the time from initial “contact” to coalescence. This provides an indication of the efficiency of the film drainage process.

Existing theory has mainly been carried out for capillary numbers that are in the range 0.1-0.01, which is significantly larger than the capillary numbers observed experimentally. As a consequence of this (at least in part), and possibly also inadequate resolution of the thin film geometry (especially for a fully 3D collision), the existing theories are only in partial agreement with our observations. It may be noted that the resolution problem is severe since the film thickness just prior to coalescence may be as small as 100 angstroms for a drop that is 40 microns in radius.

The present study is focused on theoretical studies of head-on collisions, but with a time-dependent force along the line of centers of the drops that varies with time in the same way that the force along line of centers varies with time in a “normal” glancing collision. Experiments carried out with the computer-controlled version of the 4-roll mill have demonstrated that the coalescence process in such a head-on collision is identical to that in the corresponding glancing collision for low capillary numbers. This includes even cases where it is observed that coalescence occurs after the force along the line of centers has changed sign (i.e. the external flow is pulling the drops apart at the point of coalescence). It is, of course, clear that the collision process for a glancing collision could be decomposed into a motion along the line of centers plus a rotation of the line of centers if the drops were not deformed (i.e. Ca=0). However, it is somewhat of a surprised that the same decomposition remains at least a very good approximation for small but nonzero capillary numbers where it is clear that deformation of the drop is an important part of the coalescence process.

Based on the experimental results mentioned in the preceding paragraph, we therefore focus on head-on collisions with a time-dependent force as mentioned previously. This focus on head-on collisions allows a much greater degree of spatial resolution than is possible in a fully 3D collision. Two types of theory are discussed: thin-film theory based on the asymptotic limit Ca<<1; and boundary integral calculations. The former follows closely the preceding theories of Davis and coworkers, but with several critical differences which follow from the asymptotic nature of the problem at low Ca (as well as the more accurate "retarded" version of the van der Waals force). The boundary integral calculations use a automatically generated mesh refinement to provide adequate resolution within the thin film. We find that the degree of resolution required is greater than has typically been applied in previous studies of the 3D collision process. With these changes, the theories agree in a number of respects with the experimental data. However, there are still some remaining puzzles and issues that we discuss at the end of the talk.