Disperse Phase Separation and Dispersion

In order to determine the limits of a disperse phase flow regime, it is necessary to identify the dominant processes enhancing separation and those causing dispersion. By far the most common process causing phase separation is due to the difference in the densities of the phases and the mechanisms are therefore functions of the ratio of the density of the disperse phase to that of the continuous phase, ρ_D/ρ_C. Then the buoyancy forces caused either by gravity or, in a non-uniform or turbulent flow by the Lagrangian fluid accelerations will create a relative velocity between the phases whose magnitude will be denoted by W_p. Using the analysis of section (Nej), we can conclude that the ratio W_p/U (where U is a typical velocity of the mean flow) is a function only of the Reynolds number, $Re = 2UR/\nu_C$, and the parameters X and Y defined by equations (Nej3) and (Nej4). The particle size, R, and the streamwise extent of the flow, ℓ, both occur in the dimensionless parameters Re, X, and Y. For low velocity flows in which $U^2/\ell \ll g$, ℓ is replaced by g/U^2 and hence a Froude number, gR/U^2, rather than R/ℓ appears in the parameter X. This then establishes a velocity, W_p, that characterizes the relative motion and therefore the phase separation due to density differences.

As an aside we note that there are some fluid mechanical phenomena that can cause phase separation even in the absence of a density difference. For example, Ho and Leal (1974) explored the migration of neutrally buoyant particles in shear flows at low Reynolds numbers. These effects are usually sufficiently weak compared with those due to density differences that they can be neglected in many applications.

In a quiescent multiphase mixture the primary mechanism of phase separation is sedimentation (see section (Nsh)) though more localized separation can also occur as a result of the inhomogeneity instability described in section (Njn). In flowing mixtures the mechanisms are more complex and, in most applications, are controlled by a balance between the buoyancy/gravity forces and the hydrodynamic forces. In high Reynolds number, turbulent flows, the turbulence can cause either dispersion or segregation. Segregation can occur when the relaxation time for the particle or bubble is comparable with the typical time of the turbulent fluid motions. When $\rho_D/\rho_C \gg 1$ as for example with solid particles suspended in a gas, the particles are centrifuged out of the more intense turbulent eddies and collect in the shear zones in between

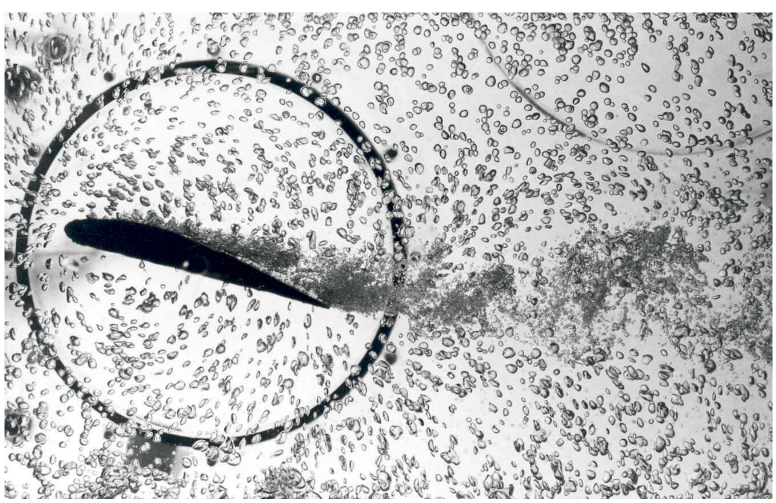

Figure 1: Bubbly flow around a NACA 4412 hydrofoil (10cm chord) at an angle of attack; flow is from left to right. From the work of Ohashi *et al.*, reproduced with the author's permission.

(see for example, Squires and Eaton 1990, Elghobashi and Truesdell 1993). On the other hand when $\rho_D/\rho_C \ll 1$ as for example with bubbles in a liquid, the bubbles tend to collect in regions of low pressure such as in the wake of a body or in the centers of vortices (see for example Pan and Banerjee 1997). We previously included a photograph (section (Nca)) showing heavier particles centrifuged out of vortices in a turbulent channel flow. Here, as a counterpoint, we include the photograph, figure 1, from Ohashi *et al.* (1990) showing the flow of a bubbly mixture around a hydrofoil. Note the region of higher void fraction (more than four times the upstream void fraction according to the measurements) in the wake on the suction side of the foil. This accumulation of bubbles on the suction side of a foil or pump blade has importance consequences for performance as discussed in section (Njh).

Counteracting the above separation processes are dispersion processes. In many engineering contexts the principal dispersion is caused by the turbulent or other unsteady motions in the continuous phase. Figure 1 also illustrates this process for the concentrated regions of high void fraction in the wake are dispersed as they are carried downstream. The shear created by unsteady velocities can also cause either fission or fusion of the disperse phase bubbles, drops, or particles, but we shall delay discussion of this additional complexity until the next section. For the present it is only necessary to characterize the mixing motions in the continuous phase by a typical velocity, W_t. Then the degree of separation of the phases will clearly be influenced by the relative magnitudes of W_p and W_t, or specifically by the ratio W_p/W_t. Disperse flow will occur when $W_p/W_t \ll 1$ and separated flow when $W_p/W_t \gg 1$. The corresponding flow pattern boundary should be given by some value of W_p/W_t of order unity. For example, in slurry flows in a horizontal pipeline, Thomas (1962) suggested a value of W_p/W_t of 0.2 based on his data.