ACCUMULATION OF PARTICLES AT AN ADVANCING MENISCUS: VISCOUS MISCIBLE FINGERING IN THE CONVERGING PARALLEL PLATE GEOMETRY

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When two parallel circular plates with a known volume of a pure viscous fluid placed in between them approach each other (Figure 1), the radius of the propagating fluid front R increases such that R^8 is linear in time t in the lubrication limit, neglecting the effects of surface tension.

$$R^8 = R_0^8 + \frac{8MgV_0^2}{3\pi^3\mu}t \tag{1}$$

Here R_0 is the initial radius, M is the mass of the top plate, g is the acceleration due to gravity, V_0 is the volume of the suspension charged into the geometry before the experiment and μ is the viscosity of the fluid.

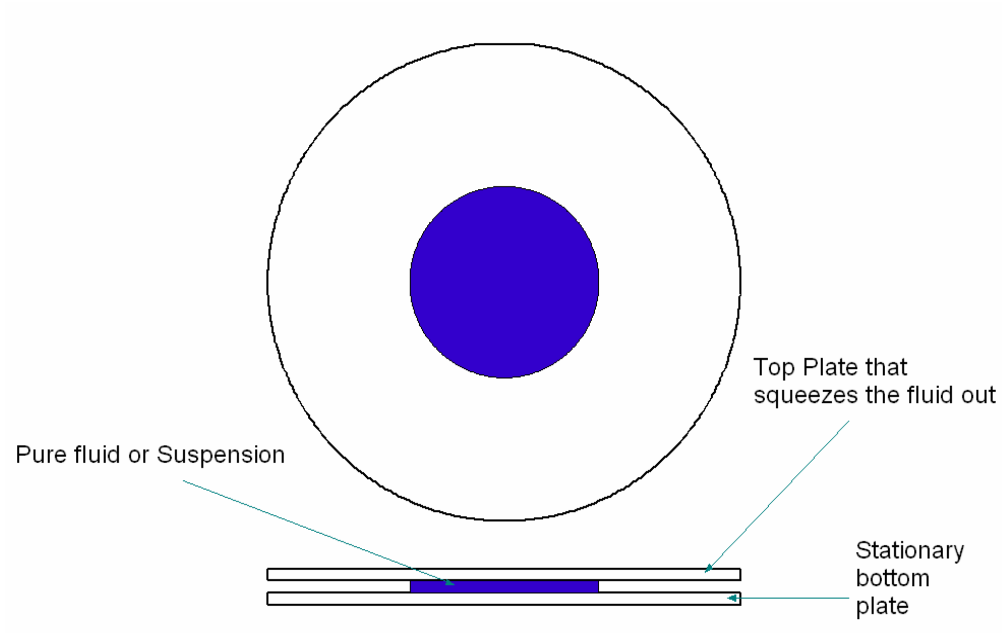

Figure 1. The converging parallel plate geometry

However, when the experiment is repeated with a suspension of rigid particles instead of the pure viscous fluid, the behavior deviates from the R^8 v/s t relationship after following it for a short period of time (Figure 2). This deviation in the R^8 v/s t relationship is followed by appearance of fingers at the propagating suspension interface (Figure 3). In this paper, we characterize the meniscus fingering phenomenon for suspension flow in the converging parallel plate geometry on the basis of the shear induced migration phenomenon.

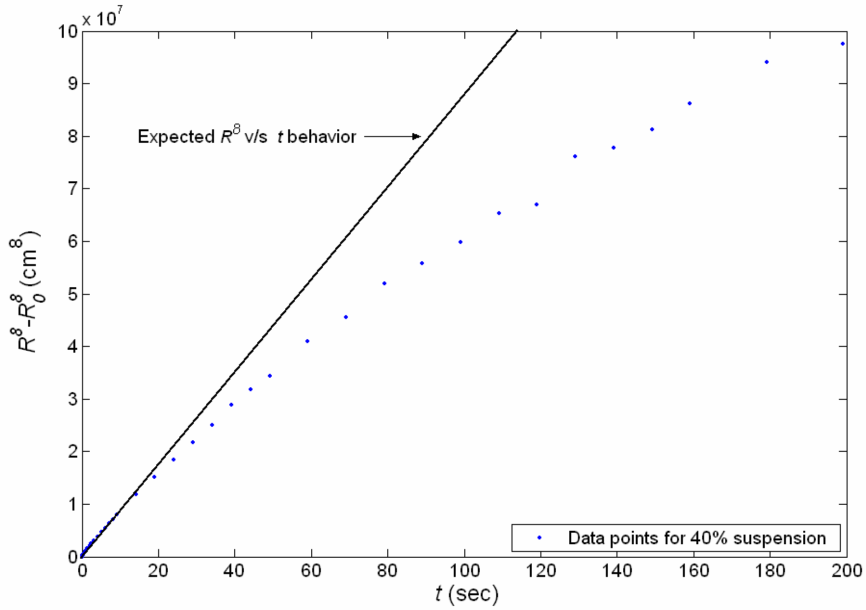

Figure 2. A plot of the radius of the propagating fluid front R raised to the eighth power with time for a 40% suspension of 100 μm glass spheres in glycerin.

It is well known that when a suspension of particles is drawn through simple geometries such as tubes and rectangular slots, the suspended particles accumulate behind the advancing meniscus. The phenomenon of shear induced migration causes the particles in the high-shear stress regions near the wall to migrate to the low-shear stress regions near the center of the geometry. Since the fluid streamlines at the center have higher velocities than the fluid streamlines near the walls, there is a net convection of particles towards the meniscus, resulting in the packing of particles at the meniscus. The accumulation phenomenon thus causes a concentration gradient, and therefore a sharp viscosity gradient to be set up at the meniscus, due to the highly non linear relationship of viscosity with concentration. A tube, which has a single length scale in its cross section, is stable to viscous miscible fingering caused by such viscosity gradients and simply displays a continuously growing packed layer of particles at the meniscus after the induction length is achieved. However, geometries like the rectangular slot and converging parallel plates which have more than one length scale in their cross-sections are susceptible to the viscous miscible fingering phenomenon. For radial source flow, the induction radius R_c required to observe a packed layer of particles at the interface scales as b^3/a^2 from shear-induced migration, where b is the spacing between the plates and a is particle radius. However, for squeezing flow between two parallel plates, the gap width b is a function of time. In this case, the induction radius R_c can be shown to obey the following scaling:

$$R_c^7 \sim V_0^3/a^2 \qquad (2)$$

This induction length scaling was verified from experiments (Figure 4). The wavelength of the instability is a complex function of the concentration, the particle radius a and the initial volume V_0. In the long wavelength limit, the instability can be analyzed as a three-fluid problem: a suspension of volume average concentration ϕ_0, a packed meniscus layer and air. For short wavelengths, shear-induced diffusion renders the interface stable and therefore the dispersion relationship for this instability shows a maximum. For appropriate concentrations and particle to gap-width ratios, the maximum growth rate is positive and therefore represents the most-dangerous wavenumber for the problem.

Figure 3. An image of the suspension/air interface rendered unstable by viscous miscible fingering. A 40% suspension of 100 μm glass spheres in glycerin was used in the experiment

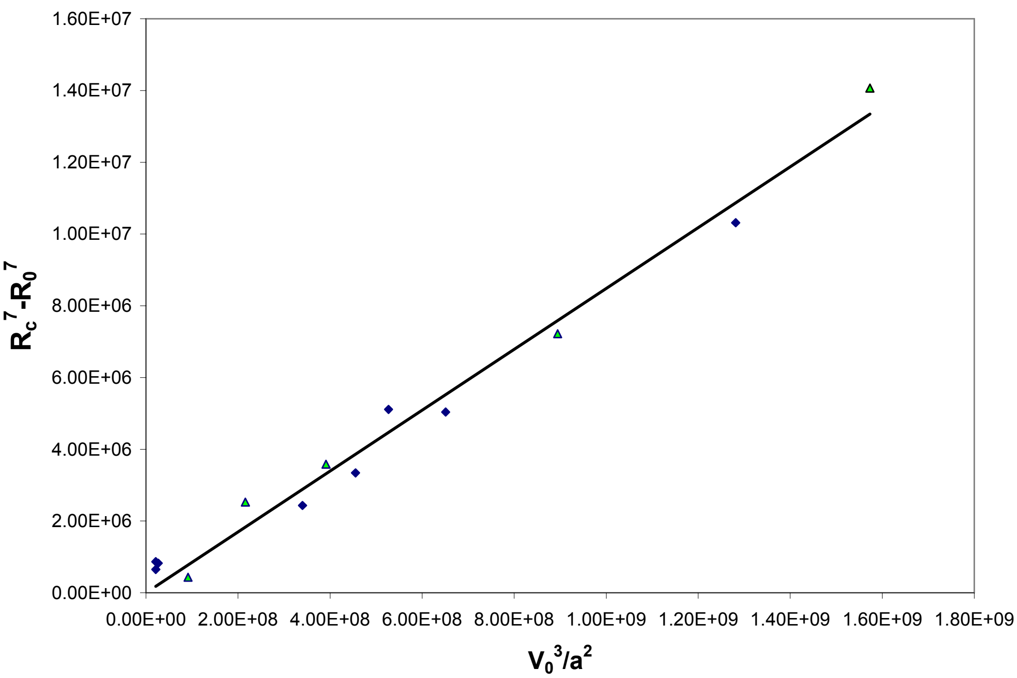

Figure 4. The induction radius R_c as a function of the scaling V_0^3/a^2 for a 40% suspension of rigid spheres: ▲– 50 μm particles, ◆– 100 μm particles. R_0 is the initial radius in each experiment.