# VISCOUS EFFECTS IN PARTICULATES

Santamarina[1], J.C., Valdes[2], J.R., Palomino[1], A., Alvarellos[1,3], J.
*(1) Georgia Institute of Technology, (2) San Diego State University, (3) INTEVEP*

Abstract: Particulate materials are inherently multiphase. The solid phase includes the load-carrying granular skeleton and mobile particles. The fluid that fills the pores may be polar or non-polar, Newtonian or Maxwellian, and either single-phase or the mixture of non-miscible fluids. Fluids and viscous drag forces lead to unique phenomena in particulate materials, including the displacement of mobile particles and formation clogging, particle migration in asymmetric AC-electric fields, non unique contact angles, and the relative motion of non-miscible permeating fluids.

Key words: clogging, contact angle, particle drift, fluid drift

## 1. INTRODUCTION: PHENOMENA

Particulate materials are inherently porous, pervious, non-linear and non-elastic. Particle forces determine the mechanical properties of the granular skeleton, including its strength, stiffness and volume change.

The pore space is filled with a single fluid or mixed fluids. The presence of fluids alters interparticle forces, sustains various energy coupling mechanisms, changes all forms of conduction and diffusion properties, and gives rise to various linear and non-linear phenomena. Table 1 lists some of these processes.

The purpose of this study is to explore three fluid-related phenomena in particulate materials: fines migration and formation clogging, particle drift in AC-electric fields, and mixed fluid conditions. Processes are analyzed at the microscale.

*Table 1:* Some fluid-related effects in particulate media

| |
|---|
| *Hydrostatic (single-phase fluid)*<br>• Archimedes buoyancy<br>• Effective stress – established at the boundary<br>• Alters interparticle electrical forces (repulsion, van der Waals attraction, hydration) |
| *Constant hydraulic gradient (single-phase fluid)*<br>• Hagen-Poiseuille leading to Kozeny-Carman fluid flow<br>• Effective stress gradient due to viscous drag: volume and strength changes<br>• Coupled gradients: chemical, thermal, electrical<br>• Particle alignment. Fines migration. Relates to clogging, non-linear flow, sand production |
| *AC hydraulic gradient (single-phase fluid)*<br>• Particle alignment (relaxation) and fabric formation control<br>• Seismoelectric. In electrolytes: relative size and charge of cations and anions in pore fluid. In porous medium (even if water is de-ioninzed): particle size, surface charge, counterions size and charge<br>• Pressure diffusion<br>• Liquefaction - fluidization<br>• Terzaghi-Biot effects including slow P-wave. Frequency dependency of viscous forces.<br>• Resonance and relaxation. Dispersion-attenuation. Even at small strains, the presence of fluids increases attenuation more than 10 times, both in single and mixed fluid phase.(Kramers-Kroning)<br>• Strain-rate effects on strength and stiffness |
| *Asymmetric AC (DC=0) - Non-linear*<br>• Fluid displacement (single and multiphase)<br>• Preventing fingering and percolation in multiphase flow |
| *Mixed Fluid-phase*<br>• Young's contact angle. Fluid pressure: Laplace and Kelvin<br>• Capillary interparticle forces affect strength, stiffness and volume change (shrinkage)<br>• Changes in conduction and diffusion - Percolation and scaling. Residual saturation<br>• Mixed fluids exhibit Maxwellian behavior |
| *Viscous effects triggered by other gradients - Energy coupling*<br>• DC: electro-osmosis. AC: electro-seismic<br>• Particle alignment<br>• Asymmetric AC-field and particle drift<br>• Chemo-osmosis<br>• Thermal consolidation – Desiccation shrinkage<br>• DC: electro-osmosis. AC: electro-seismic |

## 2. PARAMETERS AND EQUATIONS

Salient mathematical expressions related to fluid flow are summarized in Table 2. The terminal sedimentation velocity is reached when the buoyant weight balances Stokes' viscous drag. Likewise, the Kozeny-Carman expression for flow rate in a pervious medium reflects the balance between the driving force and Poiseuille's drag. Viscous drag converts a hydraulic gradient into an effective stress gradient in the granular skeleton.

The fluid phase that fills the voids between particles can be multiphase, such as oil-and-water or water-and-air. Molecules at the interface between the two fluids experience asymmetric time-average van der Waals forces. This results in a curved interface that tends to decrease in surface area of the interface. The pressure difference between the two fluids *Du=u*$_1$- $u_2$ depends on the curvature of the interface characterized by radii $r_1$ and $r_2$, and the surface tension, $T_s$ (Table 2). In fluid-air interfaces, the vapor pressure is affected by the curvature of the air-water interface as expressed in Kelvin's equation (curvature affects solubility in liquid-liquid interfaces). Unique force equilibrium conditions also develop near the tripartite point where the interface between the two fluids approaches the solid surface of a particle. The resulting contact angle ? captures this interaction. Capillary raise reflects force equilibrium between weight and capillary pull.

*Table 2*. Important relations related to fluid flow in granular media

| | |
|---|---|
| $\mathrm{Re} = \dfrac{\rho_{fl} dV}{\eta}$ | Reynold's number. Ratio between inertial and viscous forces |
| $F_{drag} = 3\pi\, d\eta\, V$ | Stoke's viscous drag on spherical particle (diameter d, fluid velocity V). Applies to Re<~1 |
| $F_{drag} = 8\pi\, L\eta\, V$ | Poiseuille drag against cylindrical tube (diameter d, fluid velocity V. Turbulence Re>~2000 |
| $u_e = \dfrac{\varepsilon_0 \varepsilon_r \zeta}{\eta} E$ | Smoluchowski's electrophoretic particle velocity $u_e$ in an electric field E as a function of the the zeta potential $\xi$ |
| $\Delta u = T_s\left(\dfrac{1}{r_1}+\dfrac{1}{r_2}\right) = -\dfrac{\rho_{fl} RT}{M} \ln \dfrac{P}{P_o}$ | Laplace-Kelvin equation. Difference in fluid pressure ?u across two-fluid interface. Related to surface tension $T_s$ and the curvature radii $r_1$ and $r_2$. It is also related to the vapor pressure P |
| $\cos\theta = \dfrac{h_c \rho_{fl} g}{4T_s} d$ | Contact angle related to capillary rise $h_c$ |

Notation: fluid viscosity ?≅0.001 N·s.m$^{-2}$ for water at 20°C; $P_0$: normal vapor pressure at the free liquid; P: vapor pressure at the curved interface; T: abs. temperature; R=8.31 N·m/mol·K; M: liquid molecular weight; $\rho_{fl}$: liquid density; surface tension $T_s$=0.0727 N/m (water-air at 20 °C); $?_{fl}$: fluid mass density; $\varepsilon_o$ permittivity of free space, $\varepsilon_r$ fluid relative permittivity.

## 3. FLOW AND FINES MIGRATION - CLOGGING

The transport of mobile particles within the porous network is called fines migration and is governed by particle-level forces and geometrical constraints. In some cases, migrating fines are retained at pore throats, clog the porous network and produce a severe decrease in permeability. Fines migration and clogging are relevant in multiple fields ranging from biological filters to petroleum recovery. Fines mobilization, retardation, and bridging cause and radial clogging. Each of these mechanisms are briefly discussed next (the research is documented in Valdes 2002).

*Mobilization.* Fluid drag can yield particle detachment and mobilization. Mobilization depends on the balance among participating particle-level forces (weight and electrical), the magnitudes of which are controlled by particle size, and electrochemical fluid characteristics.

*Retardation.* A mobilized particle inherently falls behind the moving fluid since the drag force experienced by the particle is proportional to the relative velocity. Hydrodynamic conditions around the tortuous geometry of the pore space, gravity, inertial effects, high flow velocity and collisions enhance retardation. Retardation increases the local concentration of particles near pore throats.

*Bridging.* Migratory particles can be retained at pore throats that are larger than the diameter of a single particle by forming bridges. However, bridge formation requires the simultaneous arrival of a sufficient number of particles. Therefore, retardation is required for bridging.

*Radial Clogging.* Radial flow towards a well (Figure 1), implies a radial velocity field that permits gravity retardation in the far field and causes inertial retardation in the near field. The interplay between these retardation mechanisms renders a non-homogeneous ring-like clogging pattern at a characteristic distance that depends on the interplay between the participating phenomena described above and the hydrodynamic regime.

*Figure 1.* Clogging ring formation in experimental radial flow system.

## 4. DRIFT IN ASYMETRIC AC-ELECTRIC FIELD

Electrophoresis is the motion of charged particles relative to the electrolyte in response to an applied DC-electric field: the field causes a shift in the particle's counterion cloud, the counterion-diminished end of the particle attracts other counterions from the bulk fluid, counterions from the displaced cloud diffuse out into the bulk fluid, and particle migrates. The particle velocity is predicted by the Smoluchowski equation.

When a low frequency AC electric field is imposed, the particle does not migrate but oscillates around its mean position and platy particles may become optimally aligned with the field. At high frequencies, neither particle shift nor alignment takes place. However, translational movement of dispersed particles can be attained in an asymmetric AC field (without a DC component). The observed drift is attributed to the velocity-dependent viscous drag force in relation to double layer polarization as sketched in Figure 2; for reference, bacteria swim at 0.02-1 mm/s (the research is documented in Palomino 2003).

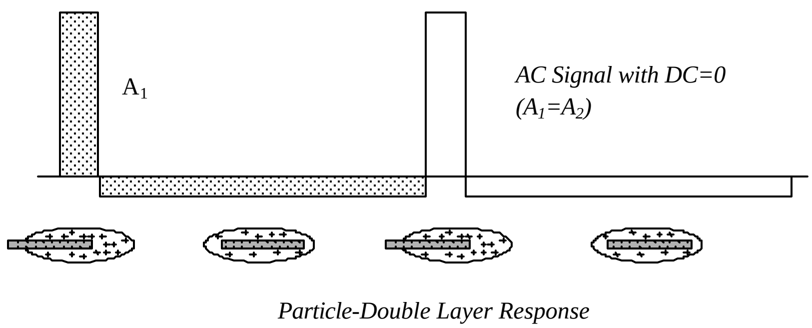


*Figure 2.* Particle drift in asymmetric AC field (no DC component).

The field frequency ω must be low enough such that ionic concentrations and hydrodynamic fields may adjust to changes in the electric field E. A beat function made of two superimposed harmonics with a phase shift may be conveniently used for these tests.

## 5. MIXED FLUID PHASE

Most fluids in engineering are Newtonian. However, fluids such as petroleum and blood are Maxwellian, that is, the stress tensor is not only a function of the strain rate but also a function of strain itself; the relaxation time in Maxwellian fluids is the ratio between the fluid viscosity and its stiffness.

Capillary forces in mixed fluid phase conditions are inversely proportional to the curvature of the interface. Therefore, menisci introduce elasticity, and mixtures of two Newtonian fluids exhibit global Maxwellian response (details on this research can be found in Alvarellos 2003).

This behavior is experimentally demonstrated with a capillary tube partially filled with a water droplet. The tube is tilted at an angle *b* smaller than the critical angle that causes unstable displacement. Then, a harmonic excitation is applied to the tube in the axial direction. For each frequency, the amplitude of the vibration is increased until the water droplet becomes unstable and flows in the capillary. Data in Figure 3 show a minimum required tube velocity between 40 and 50 Hz. This behavior indicates resonance of the visco-elastic system (the ratio of the relaxation time and characteristic time for pure viscous effect is larger than 11.64).

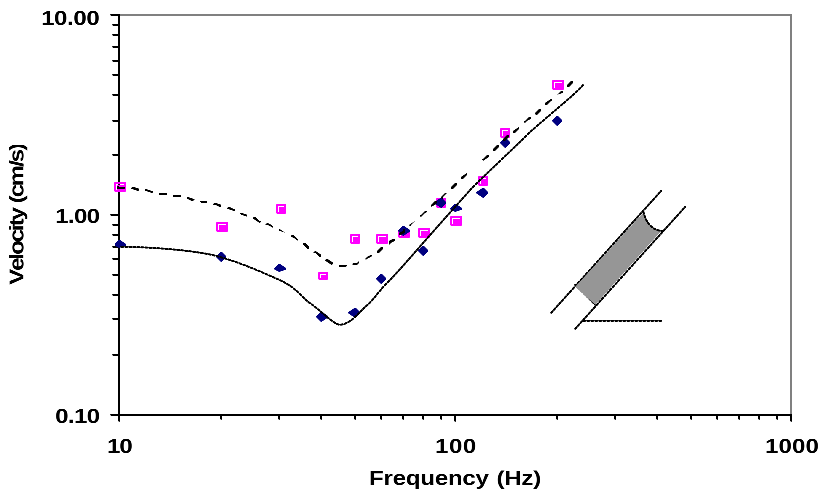


Figure 3. Liquid stability in a tilted capillary tube.

**ACKNOWLEDGEMENTS**. NSF, PDVSA, Goizueta Foundation.

## REFERENCES

Alvarellos, J. (2003), Fundamental Study of Capillary Phenomena in Porous Media, Ph.D. Dissertation, Georgia Tech, Atlanta, Georgia.

Palomino, A.M. (2003), Fabric formation and Control in Fine Grained Soils, Ph.D. Dissertation, Georgia Tech, Atlanta, Georgia.

Valdes, J. R. (2002), Fines Migration and Formation Damage - Microscale Studies, Ph.D. Dissertation, Georgia Tech, Atlanta, Georgia.