Classes of Interstitial Fluid Effects

We should observe at this point that there clearly several classes of interstitial fluid effects in the dynamics of granular flows. One class of interstitial fluid effect involves a global bulk motion of the interstitial fluid relative to the granular material; these flows are similar to the flow in a porous medium (though one that may be deforming). An example is the flow that is driven through a packed bed in the saltation flow regime of slurry flow in a pipe (see section (Nkd)). Because of a broad data base of porous media flows, these global flow effects tend to be easier to understand and model though they can still yield unexpected results. An interesting example of unexpected results is the flow in a vertical standpipe (Ginestra *et al.* 1980).

Subtler effects occur when there is no such global relative flow, but there are still interstitial fluid effects on the random particle motions and on the direct particle-particle interactions. One such effect is the transition from inertially-dominated to viscously-dominated shear flow originally investigated by Bagnold (1954) and characterized by a critical Bagnold number, a phenomena that must still occur despite the criticism of Bagnold's rheological results by Hunt *et al.*(2002). We note a similar transition has been observed to occur in hopper flows, where Zeininger and Brennen (1985) found that the onset of viscous interstitial fluid effects occurred at a consistent critical Bagnold number based on the extensional deformation rate rather than the shear rate.

Consequently, though most of these subtler interstitial fluid effects remain to be fully explored and understood, there are experimental results that provide some guidance, albeit contradictory at times. For example, Savage and McKeown (1983) and Hanes and Inman (1985) both report shear cell experiments with particles in water and find a transition from inertially-dominated flow to viscous-dominated flow. Though Hanes and Inman observed behavior similar to Bagnold's experiments, Savage and McKeown found substantial discrepancies.

Several efforts have been made to develop kinetic theory models that incorporate interstitial fluid effects. Tsao and Koch (1995) and Sangani *et al.*(1996) have explored theoretical kinetic theories and simulations in the limit of very small Reynolds number ($\rho_C \dot{\gamma} D^2/\mu_C \ll 1$) and moderate Stokes number ($m_p \dot{\gamma}/3\pi D \mu_C$ - note that if, as expected, V is given roughly by $\dot{\gamma} D$ then this is similar to the Stokes number, St, used in section (Npo)). They evaluate an additional contribution to Γ, the dissipation in equation (Npk1), due to the viscous effects of the interstitial fluid. This supplements the collisional contribution given by a relation similar to equation (Npk4). The problem is that flows with such Reynolds numbers and Stokes numbers are very rare. Very small Reynolds numbers and finite Stokes numbers require a large ratio of the particle density to the fluid density and therefore apply only to gas-solids suspensions. Gas-solids flows with very low Reynolds numbers are rare. Most dense suspension flows occur at higher Reynolds numbers where the interstitial fluid flow is complex and often turbulent. Consequently one must face the issues of the effect of the turbulent fluid motions on the particle motion and granular temperature and, conversely, the effect those particle motions have on the interstitial fluid turbulence. When there is substantial mean motion of the interstitial fluid through the granular material, as in a fluidized bed, that mean motion can cause considerable random motion of the particles coupled with substantial turbulence in the fluid. Zenit *et al.* (1997) have measured the granular temperature generated in such a flow; as expected this temperature is a strong function of the solids fraction, increasing from low levels at low solids fractions to a maximum and then decreasing again to zero at the maximum solids fraction, α_m (see section (Nqd)). The granular temperature is also a function of the density ratio, ρ_C/ρ_D. Interestingly, Zenit *et al.* find that the granular temperature sensed at the containing wall has two components, one due to direct particle-wall collisions and the other a radiative component generated by particle-particle collisions within the bulk of the bed.