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Direct numerical simulation of two-phase flow: Flow patterns and rheology of particle suspensions

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Melt flow in porous media has received much attention because melting and melt migration play dominant roles in heat and mass budget of the Earth. Whilst some aspects of melt migration processes are known, the physics of the processes remain a matter of discussion. A major source of uncertainty in classical two-phase flow models is that the transfer of momentum between the solid and melt phase is characterized by a single macroscopic parameter, i.e., the matrix permeability. Here we eliminate this uncertainty by constructing a microscopic 2D model of two-phase flow in which we solve the Stokes equations directly on the spatial scale of the individual pores.

To characterize the mechanical behaviour of the two-phase systems as a function of material parameters and melt fraction our initial condition is a layer with homogeneously distributed high viscosity grains and interstitial melt overlying a layer of pure melt. The model evolution from this condition indicates that for moderate to large melt fractions particle interactions are significant and result in macroscopic Rayleigh-Taylor instabilities. On the basis of this observation, we derive an expression for the effective viscosity in a particle suspension system assuming strong interactions. Viscosities predicted by this expression are in good agreement with directly computed effective viscosities for Newtonian and non-Newtonian melt and matrix rheologies. For extremely large melt fraction a different mechanical mode is observed, in which individual grains sink independently (Stokes-suspension mode). A simple analytical theory is developed that successfully predicts the transition between the Stokes-suspension (sinking particles) and Rayleigh-Taylor mode (interacting particles). This treatment predicts an abrupt reduction in the effective viscosity of non-Newtonian two phase media at melt fractions of 10-30 %, as has been observed experimentally. Under the assumption of linear viscous melt, experimental studies indicate that melt-solid systems behave non-linearly for moderate to higher strain rates. In contrast, the numerical results show that such systems only behave non-linearly if the melt has non-Newtonian rheology irrespective of the rheology of the solid, a result that motivates us to re-examine the assumption of linear viscous melt rheology in the analysis of experimental results.