RHEOLOGY AND MULTIPHASE FLOW IN CONGESTED AMMONIA-WATER-ICE SLURRIES.

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Introduction: Some aspects of the rheological behaviour of ammonia-water-ice slurries have been investigated by Kargel et al. [1] over a range of temperatures and compositions relevant to the icy satellites. However, a proper quantification of the rheology and flow behaviour of fluid-particle suspensions remains a major theoretical and experimental challenge. This complex, multiphysics problem is somewhat difficult to generalize, as many mechanisms occur simultaneously and interdependently. Suspension rheology is particularly relevant in this respect due to its strong influence on the style of flow and emplacement of cryomagmas both internally and at the surface [2].

This study is concerned with estimates of flow rheology at high crystal loads (ϕ > 50%), well above the experimental range investigated in [1]. Such materials are referred to in the micromechanics literature as congested [3], and magmas during their latter stages of flow, where cooling and crystallisation dominate, provide excellent natural examples.

Multiphase flow: Cryomagmas, along with their silicate counterparts, are prime examples of flows that involve the transport of solids, gases (and other fluids) by a separate carrier phase. Such flows are called multiphase, and have attracted much recent attention due to their important range of engineering applications [4]. Where the number density of the dispersed phase is large, the influence of particles on the fluid motion becomes significant and must be taken into account in any explanation of the bulk behaviour of the mixture. Numerical techniques for simulating multiphase flow require that computation of particle and fluid trajectories are done simultaneously and iteratively, are still in a relatively unadvanced state [5]. Further complications arise due to the interactions between particles and walls, and when phase changes take place in the carrier fluid.

*Flow Rheology***:** Equations describing first and second-order order corrections to an infinite mixture with a Newtonian fluid viscosity (μ), and spherical particles of equal size *d* comprising a solids volume fraction (ϕ), are well known, but valid strictly only for dilute suspensions where the grain packing is isotropic [6]. Inevitably a number of problems follow from this simplification, one of the more serious being that in narrow channels, particles are forced to come very close together so that particle-particle interactions become dominant. A measure of this is given by the Bagnold number. This has led to the important observation that for all cases where a shear gradient exists in densely packed suspensions (ϕ > 0.3), a migration effect takes place [7].

Lubrication limit. Rather than attempt third-order (and higher) corrections to the viscosity term as extrapolated from dilute suspensions, a more sensible way to proceed might be to tackle the problem by deriving formulations for the effective viscosity of densely packed suspensions directly. One approach that holds promise is based on the lubrication limit concept of particle interactions [8]. This limit dominates when the surface contact distance between two particles (*h*) is << *d*. An approximate expression linking the ratio *d/h* to the solidosity (ϕ > 0.2) is:

$$\frac{d}{h} = \frac{(1-\phi)^3}{6\phi(2-\phi)} \qquad (1)$$

with the derived estimate of the effective viscosity (ς)

$$\varsigma = \frac{6\mu\phi(2-\phi)}{(1-\phi)^3}\,. \qquad (2)$$

Application to congested ammonia-water-ice slurries: Using eqn. 2 it is possible to make some preliminary statements about the rheology of an initially densely packed suspension that have bearing on the flow rates of cryomagmas. Fig. 1 is a plot showing the changing effective viscosity of the mixture as a function of melt viscosity and particle content (solidosity). The melt viscosity of the continuous phase, an ammonia-water liquid (NH_3 c. 21-35%) over the temperature interval 40 < 10^4 K/T < 60, varies from ~ 10^{-3} to 10 Pa s [1]. From eqn. 2, the order of magnitude increase in effective viscosity with increasing solids content and melt viscosity ranges from 0.02 Pa s (ϕ = 0.4) to 7 x 10^3 Pa s (ϕ = 0.8). The estimated effective viscosity of a congested slurry with a 20% porosity where the liquid phase is at the ammonia water-ice peritectic (T = 176.2, μ ~ 4 Pa s [1] is c. 10^3 Pa s.

Flow velocities and segregation: The new estimates of effective viscosities can in principle be used to place order of magnitude constraints on flow velocities of congested ammonia-water-ice slurries in dykes. However, the problem requires some knowledge of the pressure gradients available to drive the flow. Estimates of cryomagma properties on Europa suggest that the slurries can be either positively or negatively buoyant, depending upon factors such as initial melt composition and bulk differentiation of the crust [9]. These parameters are not currently well known for any icy planet in the solar system. However, for illustrative purposes, Fig. 2. shows a plot of the predicted cryomagma flow velocities for a pure liquid and cryomagma slurry in a 1 metre-wide dyke for a density contrast of 50-150 kg/m^3 [9]. The gravity field (1.3 m/s^2) is typical of the icy moons. The maximum average flow velocity (u) for crystal-free pertiectic NH_3-H_2O melt is c. 4 m/s. Mean cryomagma flow velocities range from a maximum of 0.23 m/s to 2 x 10^{-3} m/s for highly congested magma (ς = 0.8, $\Delta\rho$ = 50 kg/m^3). Slurry flow in a confined channel at high crystal loads is problematic. However, a migration effect is expected during shear arising from fluctuations in particle velocity. This tends to keep the margins of the flow relatively free of particles, thus lubricating the congested central plug. For relevant theory that captures both the solidosity and granular temperature fields due to velocity fluctuations in sheared suspensions see [e.g. 7,10].

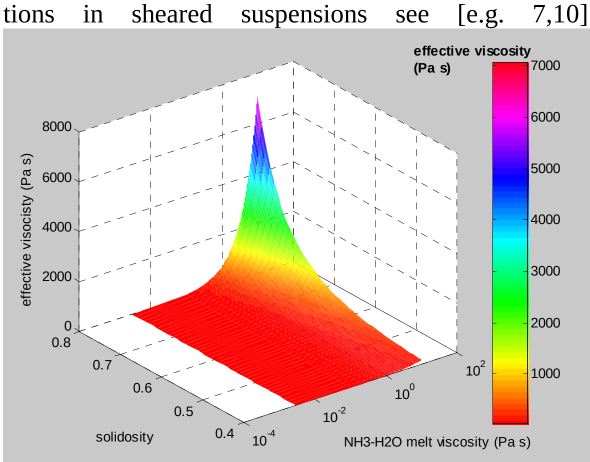

Fig. 1. Plot showing estimated range in effective viscosity for ammonia-water-ice slurries (melt viscosities from [1]).

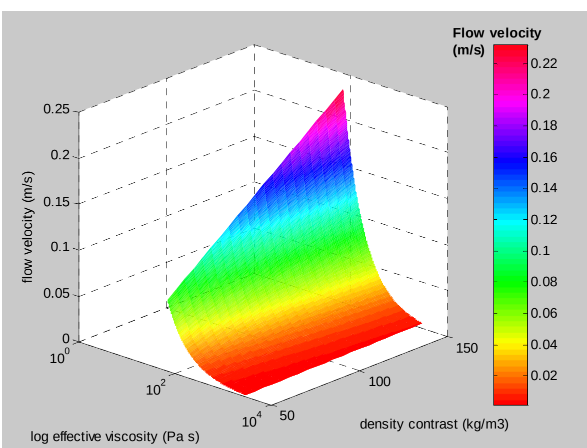

Fig: 2. Plot showing estimated range in flow velocities for congested cryomagmas (40-80% solids).

Shear-enhanced melt extraction: Should the eutectic melt phase mass density equal or exceed that of the solid residue, upwards transport of cryomagmas due to buoyancy forces is not possible. Stress corrosion and the generation of fluid-filed cracks during tidal flexing are potential alternative transport mechanisms [9]. Another is shear-induced dilatancy in the ice matrix. Arguably the low temperatures in the outer solar system make the viscous behaviour unlikely on short timescales, so ice might behave as a granular material over the timescale of tidal loading (hours to days). This would open up a way of extracting melt from its solid matrix by a sucking action caused by fluctuating pressure gradients. The driving force is the externally imposed shear strain rate. Detailed equations setting out the theory of shear-enhanced melt extraction due to dilatancy are given in [11]. While the application was focused on silicate magmas, this purely mechanical model is equally suited to multiphase flow in low temperature systems. More information on the rheological properties of ice would help in this respect [e.g. 12].

Implications: Curious structural features and changes in albedo on Ganymede (also Titan) may reflect successive emplacement of darker (particle-rich) and lighter (melt dominated) cryomagmas [13], implying segregation mechanisms at work. Flow segregation during cryomagma ascent to form an axial slurry, followed by extraction of lower viscosity melt from the congested mush by shear might be one way of achieving some of the observed surface texturing. This hybrid model of density-driven flow followed by shearing of a densely packed suspension may be tidally driven, resulting in episodic transitions between slurry flow (gravity-driven) and strain rate assisted flow of an efficiently segregated pure melt phase. This and other multiphase flow behaviour including impact fluidization of cryomagma slurries, is the subject of ongoing theoretical investigations.

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