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Measurement of the wall slip behaviour of a solid granular soap in ram extrusion

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ABSTRACT

The wall slip behaviour of a solid granular soap was investigated in the context of ram extrusion, with particular focus on determining the sensitivity of the wall shear stress to the pressure within the soap, as well as the slip velocity. Two novel slip measurement devices were used to infer the shear stress: a two stage extrusion die with inbuilt pressure gradient measurement; and a combined compression–translation assembly to measure the frictional force between the soap and the wall. Both devices provided differing measurements of the pressure sensitivity, and gave shear stress estimates in agreement with a Benbow and Bridgwater analysis of the extrusion behaviour, which cannot gauge pressure dependence.

The influence of the wall material on the slip and extrusion behaviour was also investigated, using three geometrically identical extruders constructed from polycarbonate, stainless steel and tungsten carbide. There was found to be a non-negligible relationship between wall material, wall surface roughness, and the Benbow–Bridgwater extrusion parameters, in which the wall shear stress was greatest against the smoothest, cemented tungsten carbide wall in contrast to a rougher stainless steel and rougher-still polycarbonate wall.

1. Introduction

The extrusion of dense solid–liquid suspensions is used as a net shape forming method for a wide range of products, from foodstuffs to machining tools [27]. A common feature of the flow of these materials is wall slip, and in particular apparent slip as described by Barnes [4]. True slip, in which the fluid molecules slide directly along the wall, is not typical of suspensions but has been noted in polymer melts [2].

Wall slip is often reported in studies of dense suspensions and related materials, e.g. Martin and Wilson [20], Kalyon [16] and Mitsoulis and Hatzikiriakos [21]. One mechanism for apparent slip in suspensions is the spontaneous reduction of the effective solids volume fraction adjacent to the wall, described in detail by Kalyon [16]. Owing to the strong relationship between the solids volume fraction and viscosity (e.g. Ref. 18), this layer of reduced viscosity acts as a lubricant between the stationary wall and the bulk flow giving the appearance of slip macroscopically.

Most measurements of slip in the literature are motivated by a need to quantify and subsequently remove it from rheological measurements. Mooney [22], Jastrzebski [15] and Yoshimura and Prud'Homme [28], among others, all describe experimental procedures for correction of capillary, Couette and parallel plate rheometry data from wall slip effects. As wall slip effectively enhances the flow of material within a channel, its occurrence manifests as a larger apparent shear rate than the true value. The degree of error does however scale with the size of the rheometer, and extrapolation to the no slip case is often made by testing a material using different gap sizes or channel diameters to obtain the true apparent viscosity curve. The above procedures are not always successful or appropriate for slip in dense suspensions, however, as noted by Martin and Wilson [20], and the modelling of such flows remains the subject of ongoing research.

Navier [23] was the first to propose a slip model based on tangential motion of fluid molecules in contact with a solid surface, relating the velocity of slip V_{slip} to the velocity gradient normal to the wall, as in Eq. (1) for a cylindrical coordinate system (r is the radial coordinate, V is the fluid velocity). The constant b has units of length and is referred to as the slip length; this can be interpreted geometrically as the distance into the wall at which the velocity profile would become zero.

$$b\frac{\mathrm{d}V}{\mathrm{d}r} = V_{slip} \quad (1)$$

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The Navier model is formulated for true slip as defined above, but it is also applicable to apparent slip systems where the velocity gradient of the bulk flow near the wall is used, rather than that of the low viscosity depleted layer which itself has a zero slip velocity. The Navier model is formulated for fluids of constant viscosity, though it can be extended by considering the relationship of the shear stress at the wall (τ_W) to the shear rate, as in Eq. (2), where η is the apparent viscosity.

$$\tau_W = \eta \frac{dV}{dr} = \frac{\eta}{b} V_{slip} = \beta V_{slip} \quad (2)$$

The parameter β is the slip coefficient and for a non-Newtonian fluid is a function of both the material and the slip behaviour. The relationship between τ_W and V_{slip} is sometimes found to be non-linear [14,26], and the Navier model can be extended as shown in Eq. (3) where n is the power-law exponent for the slip behaviour. This is justified by the likely non-Newtonian rheology of the depleted layer, particularly if the liquid binder itself is non-Newtonian.

$$\tau_W = \beta V_{slip}^n \quad (3)$$

The Navier slip condition can be viewed in contrast to the basic model of Coulombic solid–solid friction, in which the tangential stress is independent of sliding velocity but directly proportional to the normal stress. Benbow and Bridgwater [5] proposed two hybrid slip functions for paste flows based on the Navier model, incorporating pressure dependence in place of normal stress, given as Eqs. (4) and (5), where b_1 is a constant, μ is a friction coefficient and P is the pressure at the wall. These models were motivated by experimental data from extrusion of alumina pastes, though pressure-dependent slip has also been observed in molten polymer systems [13,24].

$$\tau_W = \tau_0 + \mu P + \beta V_{slip}^n \quad (4)$$

$$\tau_W = \tau_0 + b_1 P V_{slip}^n \quad (5)$$

Here, τ_0 is the stress required to initiate slip at the wall, sometimes referred to as a slip yield stress. It is analogous to the shear force required to initiate sliding at a solid–solid boundary represented by the static friction coefficient. In an apparent slip system a slip yield stress is logical as the lubricating layer forms primarily due to a shear rate gradient at the wall [19]. Starting from rest, the densely packed arrangement of particles close to the wall must be broken down before slip can initiate.

This work presents several measurements of the wall slip of a solid granular soap in the context of extrusion. While soap is not a solid–liquid suspension in the conventional sense, it does contain some moisture and acts as a lubricant under certain circumstances, being used as a base for lubricating greases. It is an interesting candidate for a material which could display either solid-like slip (normal stress-dependent, velocity-independent) or liquid-like slip as described above (normal stress-independent, velocity-dependent). Extrusion of soap materials has been studied previously, for example by Amarasinghe and Wilson [1], Domanti and Bridgwater [12], Kalyon et al. [17] and Barnes et al. [3], where soaps were found to be reproducible and reliable extrusion materials with behaviour conforming to the Benbow and Bridgwater [6] model for extrusion. It is important to distinguish between solid soap as studied here, consisting of pure stearates with minimal water content, from bar soaps or soaps containing fragrances or softeners (often oil-based), such as those studied by Kalyon et al. [17] and Barnes et al. [3], which have additional liquid content and as such flow more readily.

In particular, the present work seeks to determine whether the wall slip behaviour of soap is pressure dependent, as in Eqs. (4) or (5). Also tested is the effect of the wall itself on the slip behaviour. The wall material is of consequence to solid–solid friction measurements, where friction coefficients are always defined for a pair of materials, but has to the best of our knowledge not yet been studied in the context of dense suspensions or paste extrusion.

2. Materials and methods

A commercial solid granular soap was sourced to act as the test material (Dri-Pak Ltd., UK), which the manufacturer indicated was produced from a blend of sunflower and coconut oils with no additives, and as such is likely to contain only pure stearates, which are a solid lubricant. The soap consisted of flat, plate-like granules of typical size 5 mm with a translucent cream colour. The moisture content of the soap was determined by vacuum drying to be around 7.5 wt%. Further investigations into the extrusion behaviour of the soap can be found in Bryan et al. [9]. Differential scanning calorimetry of the material indicated a broad melting band beginning at approximately 45 °C which would manifest in a gradual softening of the soap material. All experiments were conducted in a temperature- and humidity-controlled laboratory at 23 °C and 50% R.H., though the extrusion tooling itself was not temperature controlled.

2.1. Standard extrusion protocol

The extrusion behaviour of the soap was classified using the Benbow and Bridgwater [6] approach, which relates the pressure required to extrude the material to aspects of the extruder geometry, a material yield stress (σ_Y) and a wall shear stress in the extrusion die (τ_W). In the current context the wall shear stress is of most interest as it can be interpreted in the context of the slip models presented previously, in particular Eq. (4) with zero pressure dependence (μ set to zero).

The ram extruder used was of the concentric cylinder, square-entry type (shown in Fig. 1) with barrel diameter 25 mm (D_0) and die diameter 3 mm (D). Dies of length (L) 16, 22, 28, 40, 52, and 58 mm were used. The maximum extrusion pressure attainable with the device was 120 MPa and the maximum ram velocity (V_{ram}) was 10 mm/s. The extrudate is assumed to undergo complete slip against the wall of the die at a velocity V_{ex}, the extrudate velocity, estimated by conservation of volumetric flow between the barrel and die ($V_{ex}D^2 = V_{ram}D_0^2$) assuming incompressibility of the material, which is standard practice in extrusion studies of this type. Details of the operation of the extruder can be found in Bryan et al. [10].

Three sets of extrusion tooling (barrels and dies) were fabricated from 316 stainless steel (SS), polycarbonate (PC) and cemented tungsten carbide (WC) in order to ascertain the effect of wall material on the slip behaviour (to be gauged through variation in τ_W). The surface finishes of each set could not be made equal owing to constraints on the manufacturing, although all cylindrical surfaces were reamed to achieve even finishes. To account for the differences in each surface, surface roughness measurements were taken using a stylus profilometer (Form Talysurf 120, Taylor Hobson Ltd., UK). A summary of R_a values (arithmetic average of absolute deviation) for the barrel walls is given in Table 1. The roughnesses of the dies could not be tested owing to the narrow diameters of the channels, and are assumed to be similar.

The surface roughness varies noticeably, with PC having the roughest surface (likely due to faster machining). The difference of nearly two orders of magnitude means that interpretation of the results from each extruder set must take into account both the wall material and the roughness, and it is not possible to decouple the