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Flow visualisation and modelling of solid soap extrusion

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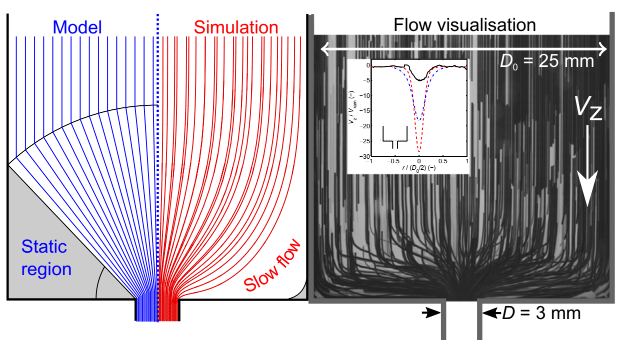
HIGHLIGHTS

- Solid soap ram extrusion was studied using three sets of tools of different size.
- Data were analysed using two standard models: fitting suggested good agreement.
- Flow visualisation of the extrusion revealed an unexpected velocity field.
- Fluid simulations with wall slip did not match the real or model velocity profiles.

GRAPHICAL ABSTRACT



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ABSTRACT

Ram extrusion of a solid granular soap was studied using three geometrically identical but differently-scaled extruders. The experimental design revealed deviation from the Benbow and Bridgwater (1993) extrusion model due to non-ideal, scale-dependent effects. Typically these effects, linked to the shear rate in the extruder, are absorbed into the model's material pseudo-properties. The data were able to be represented using the Basterfield et al. (2005) model for extrusion flow which does include a shear rate as a variable.

Flow visualisation in conjunction with fluid dynamics-based simulations showed, however, that the assumptions underlying the Basterfield et al. model are not appropriate for soap extrusion, despite the good agreement of the model with the experimental extrusion data. This highlights a need for care in interpretation of extrusion data, in that the limited information gathered about any given experiment, typically just the extrusion pressure, can lead to the generation of spurious parameters if the wrong model is applied.

1. Introduction

Extrusion is a net shape forming operation for the manufacture of objects with a constant cross section. The material to be formed is forced under pressure through an orifice or die with the desired shape, after which the rheological properties of the material cause it to retain its new geometry. Ram extrusion is a type of extrusion in which a moving piston or ram directly drives the material through the die while the material is constrained in a reservoir (the barrel).

The classes of extrudable materials are varied, ranging from liquid polymer melts, which rely on post-processing solidification and their high viscosity to retain the die shape; to metals such as aluminium which deform elasto-plastically when changing shape. This work is concerned with the ram extrusion of soft solids and visco-plastic fluids, such as gels, dense solid–liquid suspensions and pastes, which have applications in ceramic manufacturing, pharmaceuticals and foodstuffs, among other areas (Wilson and Rough, 2006).

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Nomenclature

Roman

A	Basterfield model conical parameter [–]
D	die diameter [m]
D_0	barrel diameter [m]
h	Herschel–Bulkley shear rate exponent [–]
k_{HB}	Herschel–Bulkley viscosity coefficient [Pa s^h]
L	die land length [m]
m	Benbow–Bridgwater exponent for velocity-dependent yield stress [–]
n	Navier slip exponent [–]
P_{ex}	extrusion pressure [Pa]
P_1	extrusion pressure component, deformation [Pa]
P_2	extrusion pressure component, die wall friction [Pa]
r	radial coordinate [m]
V_{ex}	extrudate velocity [m/s]
V_{ram}	ram velocity [m/s]
V_r	radial velocity [m/s]
V_z	axial velocity [m/s]
z	axial coordinate [m]

Greek

α	Benbow–Bridgwater velocity scale for yield stress [Pa/(m/s)^m]
β	Navier slip coefficient [Pa/(m/s)^n]
ϕ	angular coordinate [°]
θ	conical contraction half-angle [°]
σ_Y	Benbow–Bridgwater yield stress [Pa]
σ_0	Benbow–Bridgwater zero-velocity yield stress [Pa]
$\sigma_{Y,HB}$	Herschel–Bulkley yield stress [Pa]
τ_W	wall shear stress [Pa]
τ_0	wall slip yield stress [Pa]

Analysis of extrusion flow is complex, owing to a combination of the non-trivial contraction flow field, materials with strongly non-Newtonian rheology (particularly in extension) and the phenomenon of wall slip, which is especially prevalent in dense solid–liquid suspensions (Barnes, 1995). As a result, there is a gap in knowledge between theoretical models of extrusion and the issues encountered in real-world manufacture.

A popular model for ram extrusion of such materials is that of Benbow and Bridgwater (1993), Eq. (1a). The model, proposed by Ovenston and Benbow (1968), and later advanced by Benbow (1971) and Benbow et al. (1987), describes the extrusion pressure P_{ex}, which is the force applied to the material divided by the contact area of the ram, as a function of the extrusion geometry and rate, these being defined in Fig. 1 for a cylindrical extruder. The type of extruder shown is known as a square-entry device as the angle between the barrel wall and the surface of the die is 90°; an alternative style of extruder is a conical-entry device (not shown) where the die is tapered and the angle at this corner is greater than 90°.

The contributions to P_{ex} for the square-entry case according to the model are the pressure required to effect the change in cross-sectional area from the barrel to the die (P_1) and the pressure to overcome friction between the die walls and the material (P_2). Material both upstream and downstream of the die is assumed to be in plug flow, with the ram velocity (V_{ram}) being related to

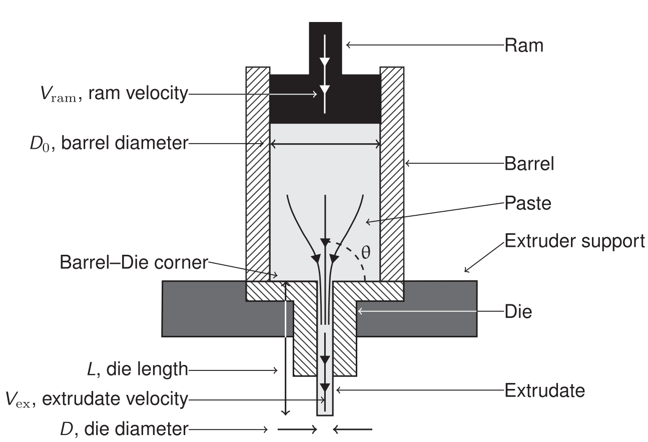

Fig. 1. Schematic diagram of a vertical, concentric cylinder ram extruder with a square-entry geometry.

the extrudate velocity in the die (V_{ex}) by conservation of volume, i.e. $D_0^2 V_{ram} = D^2 V_{ex}$.

$$P_{ex} = \underbrace{2\sigma_Y \ln\frac{D_0}{D}}_{P_1} + \underbrace{4\tau_W \frac{L}{D}}_{P_2} \tag{1a}$$

$$= 2(\sigma_0 + \alpha V_{ex}^m)\ln\frac{D_0}{D} + 4(\tau_0 + \beta V_{ex}^n)\frac{L}{D} \tag{1b}$$

While the P_1 contribution is derived from an assumption of ideal work on a perfectly plastic material (with yield stress σ_Y), real extrusion materials are more complex. Experimental observations caused Benbow and Bridgwater to account for non-ideal work using the modified yield stress expression $\sigma_0 + \alpha V_{ex}^m$, as in Eq. (1b). Here σ_0 is an 'ideal' static yield stress, α is a velocity multiplier for additional yield strength and m is a velocity exponent.

The P_2 contribution is the result of a force balance on the paste which experiences a shear stress from the die wall (τ_W). This was again extended based on experimental observations (Eq. (1b)) to include a rate-dependent wall shear stress $(\tau_0 + \beta V_{ex}^n)$, with a 'slip yield stress' τ_0 and an additional multiplier and exponent β and n. This form of wall shear stress is similar to the slip law attributed to Navier (1823), with an extension to non-linearity and allowance for cessation of wall slip below a certain stress.

An alternative P_1 expression was provided by Basterfield et al. (2005), Eqs. (2a) and (2b), which is based on an analysis of a material exhibiting Herschel–Bulkley rheology. The analysis assumes a conically converging flow of material into the die, forming a conical flow zone with half-angle θ measured from the centreline (also defined in Fig. 1 for the square-entry case). This type of model is referred to in the literature as a 'radial flow' model, examples being Snelling and Lontz (1960) and Ariawan et al. (2002), among others, as the flow converges radially to a point just inside the die entrance.

$$P_1 = 2\sigma_{Y,HB}\ln\frac{D_0}{D} + Ak_{HB}\left(\frac{2V_{ex}}{D}\right)^h\left[1 - \left(\frac{D}{D_0}\right)^{3h}\right] \tag{2a}$$

$$A = \frac{2}{3h}[\sin\theta(1+\cos\theta)]^h \tag{2b}$$

A conical flow field is assumed to develop either due to the use of a conical-entry extruder as described earlier, or in the square-entry case due to material at the barrel–die corners being stagnant and unyielded, forming static regions which emulate a conical wall. A further assumption of the model is that this wall is frictionless, which is required to permit the derivation of this one dimensional result.