MECHANICS OF PASTE FLOW IN RADIAL SCREEN EXTRUDERS

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ABSTRACT

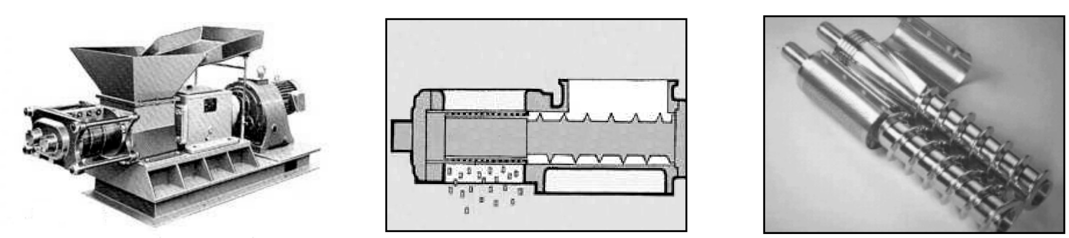
High solids volume particle-liquid mixtures, sometimes called pastes, often exhibit apparent yield stress behaviour and once formed, e.g. by extrusion, will retain their shape. Radial screen extruders have been developed for high flow rate, low mean pressure extrusion through multiple small diameter dies (< ~1.5 mm). The principles underlying the design and operation of these extruders are not well understood and consequently extruder efficiencies, throughput and reliability are often sub-optimal.

This paper reports results from an initial study of the flow mechanics of pastes in radial screen extruders. A novel experimental module, capable of investigating each flow component is described and results are presented for extrusion of a 0.56 volume fraction talc-based paste. The axial force on central frustum is determined by the conveying action, but the torque and normal stress on the screen are dominated by the nip flow created by the passage of the blade.

INTRODUCTION

A paste is a highly filled mixture of solid particles with a binding liquid phase. These materials are an example of 'soft solids', in that they are readily deformable, but possess an apparent yield stress and retain their shape after deformation. Pastes offer a method for generating high-density formed products with defined shape, often achieved by extrusion processes [1].

Radial screen extruders have many applications, in particular the manufacture of drug pellets and water dispersible granules. The extruder typically consists of two semi-cylindrical screens along each side of two counter rotating extruder heads, as shown in Figure 1. Each head consists of a truncated cone with three attached blades. A twin screw feeds paste into the space between the extruder heads and the screens. The relative motion between the screen and the blade causes the paste to be extruded through the screen in the vicinity of the blade. Compared to other technologies, radial screen extruders produce granules with medium density and hardness. Typically, screen hole diameters and flow rates range from 0.7 - 2.0 mm and 50 – 1000 kg/hr, respectively.



(*a*) Extruder unit (*b*) Elevation (*c*) Disassembled extruder

Figure 1. Images of a Fuji Paudal radial extruder

(Reproduced from Fuji Paudal promotional brochures, Fuji Paudal Co. Ltd., Osaka, Japan)

There is little information in the literature on mechanics and flow of pastes within these devices. Only the study by Shah *et al*. [2] has successfully attempted to measure the flow conditions within a screen extruder, but this was limited in its scope. To the authors' knowledge, no studies have been published which consider the flow pattern within a screen extruder. An understanding of the mechanics of paste flow is required to enable optimization of extruder design and selecting paste formulations to give even operability.

Figure 2 shows one half of a radial screen extruder and indicates four key process steps:

① Paste crumble drops from a hopper on to the feeder screws - see also Figure 1 (*a*, *b*).

② The frictional forces between the paste, the single flighted screw and the barrel force the paste along the barrel, as in other screw extruders. The constriction in flow area increases the stresses on the paste, resulting in paste compression and air expulsion.

③ The screw forces the paste to flow into and along the region between the screen and the frustum core/blades (the extruder head), aided to some extent by the core blades.

④ In the extruder head the stresses on the paste increase greatly as the blades pass by. Paste is extruded and the extrudate breaks off from the screen under gravity, falls and is collected.

The material in the extruder experiences a wide range of stress and strain rate conditions, and it is not immediately clear which conditions will be dominant. Approximate operating condition ranges were calculated based on an extruder producing agrochemical granules. The typical axial velocity of paste at the entrance to the extruder might be 0.003 m/s, whereas a typical extrudate velocity might be 0.3 m/s. The ratio of outlet to inlet area, over the length of the frustum, is typically 3, and 5 for the flow out of the screen holes. The length to diameter ratio of a screen hole (effectively a die land) is approximately 1.

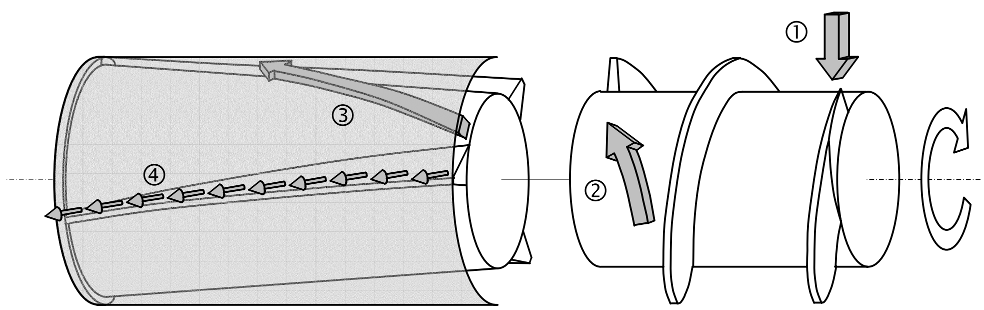


Figure 2. Exploded schematic of flow in one half of a twin-screw radial screen extruder

This paper presents a first-order model of the paste flow pattern within a radial screen extruder. A laboratory-scale test module based on this model was constructed which is capable of giving detailed measurements of extrusion forces.

FLOW PATTERNS

Flows in twin-screw extruders are complex [*e.g.* 3] so the model presented here is based on a single-screw analysis. Paste flow in the feeder screw has been modelled previously by Burbidge and Bridgwater [4]. The extruder head is similar to a three-flighted screw extruder which has a large screw helix angle, tapered channels and a perforated barrel. Burbidge and Bridgwater suggested that the whole channel volume in a paste screw extruder would be fully flooded, and that the paste flows as a plug along each channel. It is therefore appropriate to take plug flow along the channel between two blades as the starting point for a flow pattern.

Shah *et al.* [2] reported that a wave of high pressure preceded the blade as it passed across the screen. Thus the screen extrusion region might be taken to be immediately prior to the blade. The relative motion of the core and screen generates tangential shear stresses on the surfaces of the paste within the extruder channel, which force the paste into the nip between the screen and the blade. At the solid surfaces, migration of the liquid phase in the paste gives rise to a characteristic thin layer of rarefied suspension between the bulk of the paste and the surface. This layer typically shears at stresses lower than the apparent yield stress of the paste [1]. Therefore it might be reasonable to treat the tangential flow of paste into the nip as plug flow as well. Observation of twin screw extruders used with polymer melts [3] suggests that the two halves of the extruder head can be treaded separately, but with some interaction. At this point it is difficult to quantify this interaction, so it is arbitrarily set to zero.

Based on these insights a paste flow pattern over a cross-section of a twin-screen radial extruder is proposed in Figure 3. This flow pattern is based on the paste flowing as a plug both along the length of the extruder and as a plug towards the blade, slipping at both the screen and core surfaces.

This hypothesized flow pattern can be divided into two aspects of flow. Plug flow along the length of the extruder head, labelled ③ in Figure 2 and further illustrated in Figure 4 (*a*) feeds the extrusion through the screen. Flow into the nip between the blades and the screen, *i.e.* ④ in Figure 2; Figure 4 (*b*), leads to extrusion through the screen die holes.

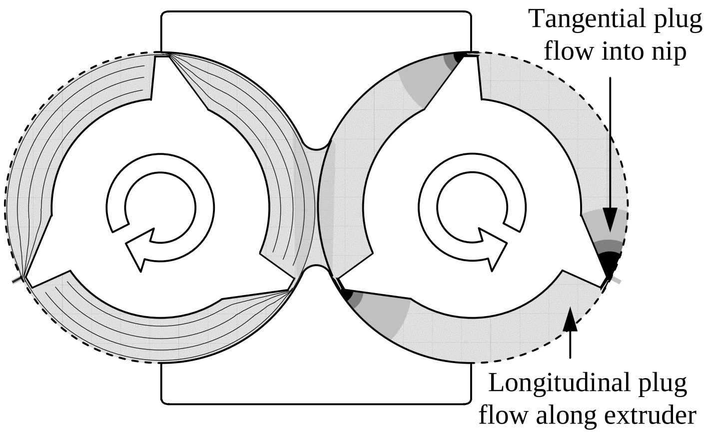
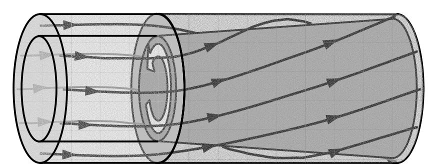
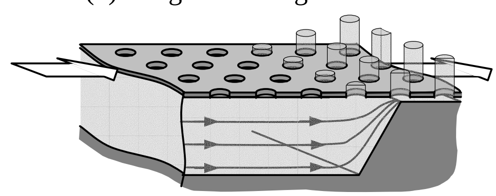


Figure 3. Proposed paste flow pattern over a cross-section of a radial screen extruder

On left: streamlines of flow relative to core.
On right: distribution of strain rate, darker = larger.



(*a*) Plug flow along extruder

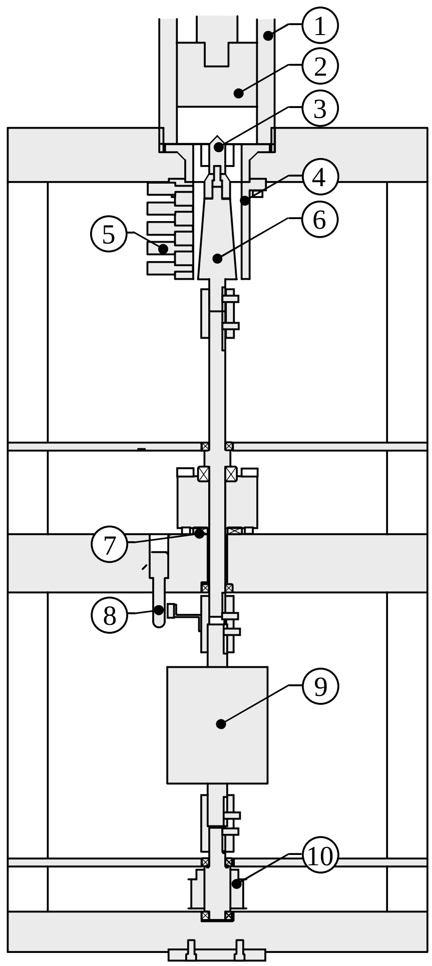


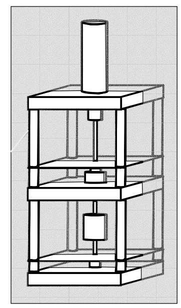
(*b*) Flow into nip and through screen

Figure 4. Components of paste flow in a radial screen extruder

EXPERIMENTAL STUDIES : ROTATING CORE MODULE

Two extruder modules have been developed for detailed investigation of the paste flow modes in a radial screen extruder. Both modules were designed for use within a strain frame, configured to act as a ram/feed system. The rotating core module, shown in Figure 5, was designed to allow a variety of interchangeable cores (6) to be rotated within a screen (4). The core was driven by a motor via a pulley (10). A speedometer (8) measured the rotation speed. Paste in the barrel (1) was driven by the piston (2) to feed the extrusion region with annular plug flow, simulating the screw extruder feed ② in Figure 2. An array of normal stress (pressure) transducers (5) measured the radial stress profile along the length of the screen. Further transducers allowed the axial force on the core (7) and the spindle torque (9) to be measured simultaneously. A wide range of flow conditions could be investigated with this module, but the relatively large size of the pressure transducers (diameter 4 mm) limited the resolution of the radial stress profile measured in the nip between the screen and blade. The second module was developed to provide detailed measurement of the stress profile of a plug flow of paste into a nip, but is not presented further here. Detailed descriptions of the apparatus and experiments are given in [5]. Experiments were performed using a talc-based paste (solids volume fraction = 0.56) which has been described previously [6].





Item	Description
1	Barrel
2	Piston
3	Die arrangement
4	Screen
5	Pressure transducers
6	Rotating core
7	Force transducer
8	Speedometer
9	Torque transducer
10	Pulley

0 100
scale mm

Figure 5. Cross section through rotating core module
Shaded areas denote area where module has been sectioned.

RESULTS AND DISUSSION

Figure 6 shows a sample set of results from the rotating core module. A blank screen (*i.e.* no perforations) of length 50 mm and diameter 30.8 mm was used with a parallel sided core of diameter 25 mm. A single longitudinal blade was attached to the core such that the nip angle formed with the screen was 45°. The gap between the blade and screen, and the blade tip length, were both 0.6 mm. The core was rotated at a speed of 200 rpm and the paste forced to flow at a rate of 3900 mm^3/s.

Figure 6 (*a*) shows increase in axial piston stress over the initial part of the experiment as paste was compacted in the barrel and made to fill the extrusion region. After a slight peak, the stress reached a steady value. The axial force and torque data (Figure 6 (*b*) and (*c*) respectively) are consistent, with no change evident until the paste contacted the core.

The radial stress response in Figure 6 (*d*) shows a cyclic pattern, corresponding to the rotation of the core. Data recorded over fifteen periods was averaged and plotted as mean radial screen stress profiles in Figure 6 (*e*). A clear difference exists between the transducer upstream of the core, giving a weak variation in stress, and the four transducers downstream, which showed a distinct peak as the blade passed. The increase in stress before the peak was more gradual than the decay afterwards. The middle third of the period was approximately steady. The magnitude of the peak stress was greatest at the start of the core, and decreased along its length. Figure 6 (*f*) shows that this decrease was almost linear, whereas the mean steady state stress decreased rapidly at first before levelling off. The difference in magnitude between these two stresses confirmed that extrusion is more likely to be determined by the blade/nip action.

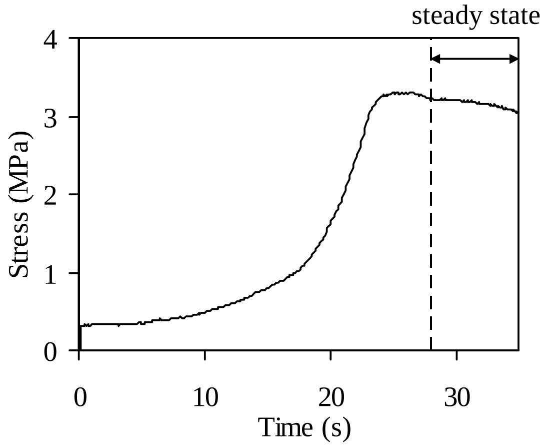
Series of experiments were conducted to assess the effect of different process and design parameters on operating conditions in an extruder, over a range of process variables and dimensionless geometries comparable to those used industrially. The action of the nip formed between the blade and the screen was isolated somewhat by only considering cylindrical cores with a single, longitudinal blade. The experiments were further restricted to the blank screen case (*i.e.* no perforations). Figures 7 and 8 show a selection of experimental results for different nip angles, θ, and ratios of screen to channel velocity, v_s/v_c

Figures 7 (*a*) and (*b*) show the variation of the axial force on the core and the core torque, respectively, with the velocity ratio v_s/v_c. Both appeared to decrease as v_s/v_c increased, and as v_c decreased. Figures 7 (*c*) and (*d*) show the effect of nip angle θ on the force and torque. Both parameters appeared to be independent of the nip angle. In other experiments, the axial force showed no dependence on dimensionless blade gap, δ/D_s, whilst the torque generally increased slightly as δ/D_s was reduced.

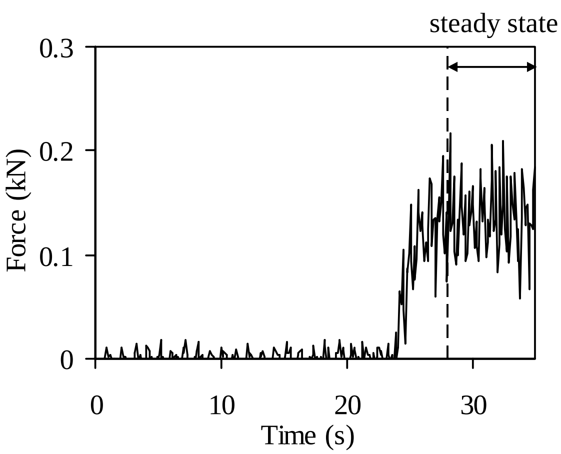
The profile of peak radial stress against position along screen, x, in Figure 6 (*f*) showed a linear decrease towards an exit value. This trend was quantified by linear regression over the fractional length, x/L, and expressed as a gradient and an exit stress. Two factors might contribute to the profile; *a*) a stress associated with flow into the nip – perhaps constant along the length of the extruder, and *b*) a stress associated with longitudinal flow along the channel – perhaps of constant gradient (for the cylindrical core) and zero at the exit.

Figures 8 (*a*) and (*b*) show the variation of the stress profile gradient and exit stress with the ratio of screen to channel velocity. The gradient appeared to decrease as v_s/v_c increased and as v_c decreased; the exit stress did not display any sensitivity to these parameters. Figures 8 (*c*) and (*d*) show the variation of the gradient and exit stress with nip angle. Again, neither parameter exhibits any dependence on the nip angle. The radial stress gradient showed no dependence on dimensionless blade gap, while the exit stress generally increased slightly as δ/D_s was reduced.

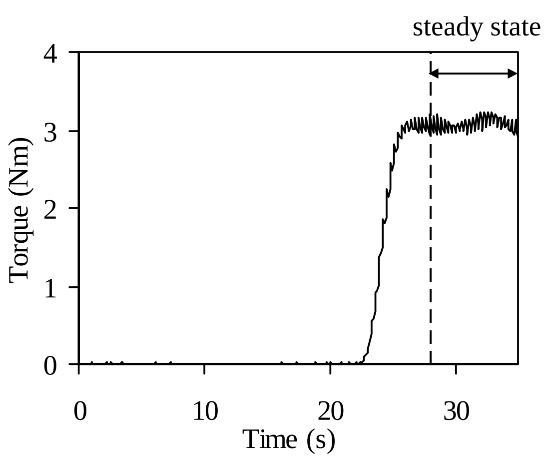
The extrusion flow has been modelled [5] as a soft solid material using the Benbow-Bridgwater approach [1] and the flow pattern described here. There is insufficient space to report the model in this paper: in general, it predicts the trends observed in these experiments. The notable exception is the response to changes in the velocity ratio v_s/v_c. For example, the model suggests that the torque should increase with v_s/v_c (at constant v_c) whereas Figure 7 (*b*) indicates that it may decrease. Slight eccentricity of the rotating core (< 10 μm) may have prevented full contact between the core and paste, which might account for this disparity.



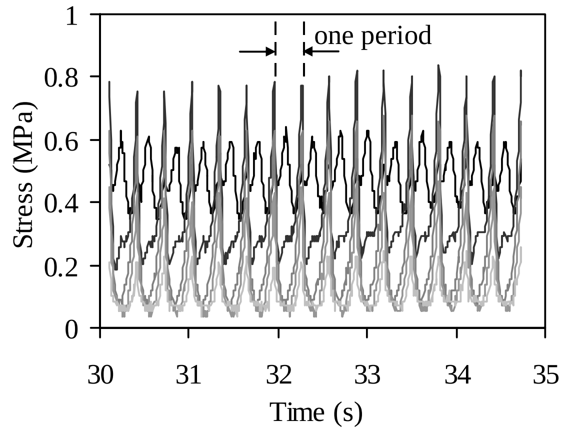
(*a*) Mean axial stress on piston against time



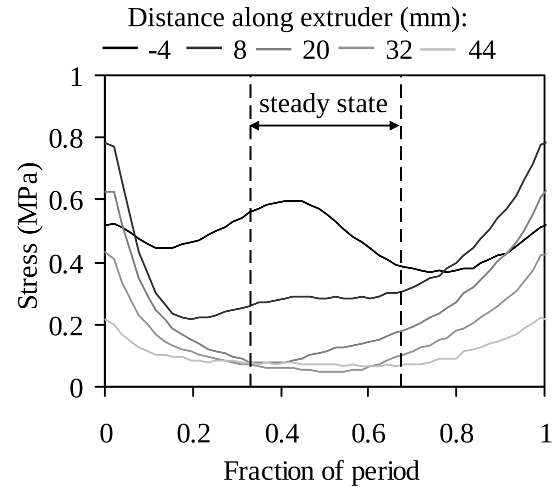
(*b*) Axial force on core against time



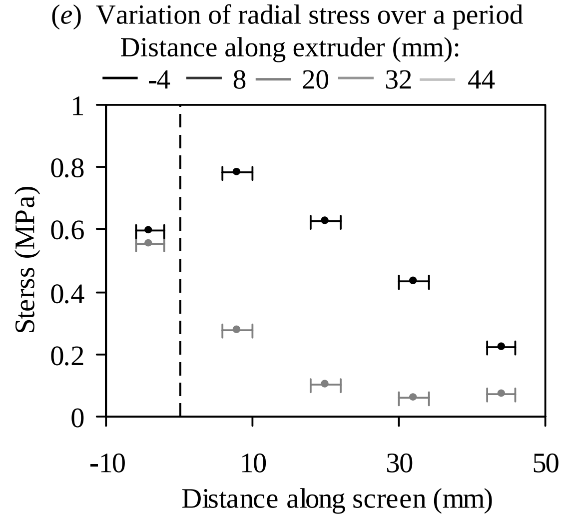
(*c*) Spindle torque against time



(*d*) Variation of radial stress on screen



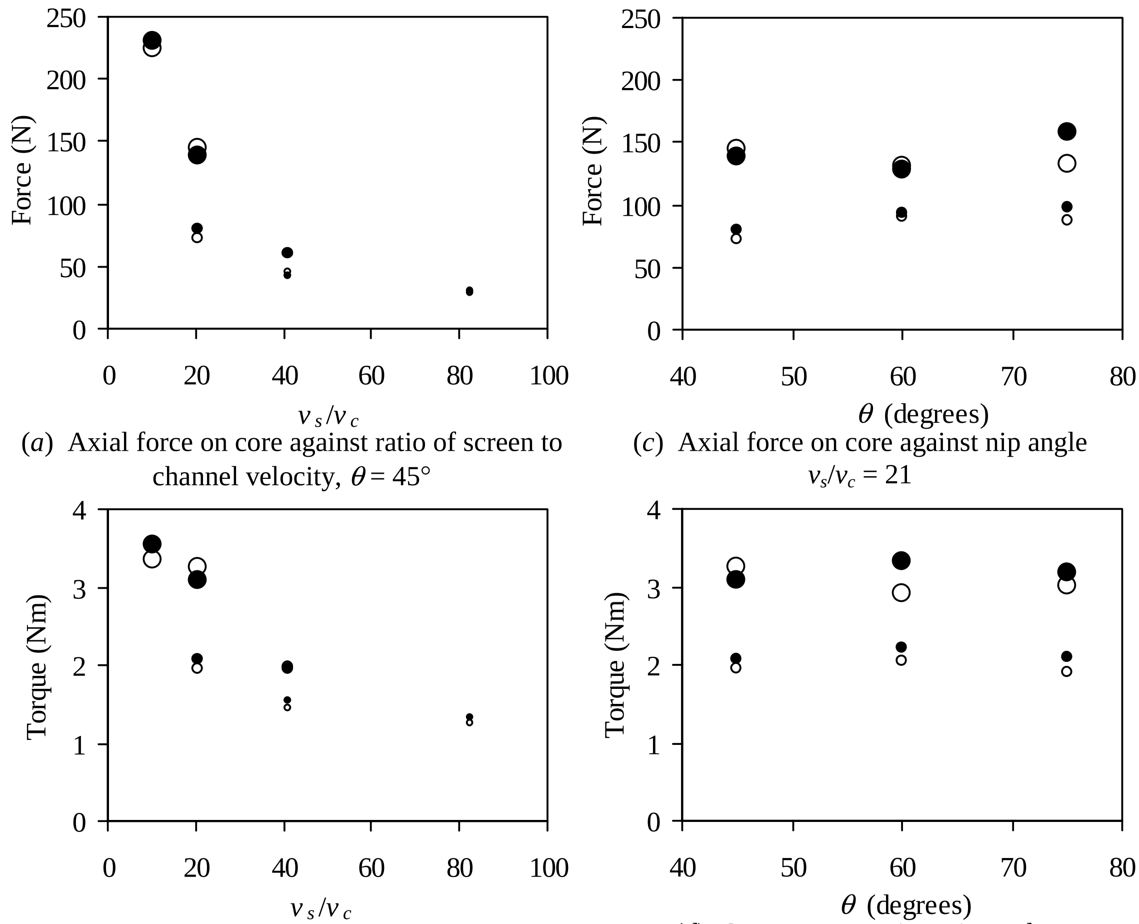
(*e*) Variation of radial stress over a period



(*f*) Radial stress on screen along the screen
Error bars show width of transducers.
Peak stress: ● Mean steady state stress: ●

Figure 6. Sample results from the rotating core module

Single blade creating a nip angle with the screen, $\theta = 45°$ and rotating at 200 rpm.
Screen diameter, D_s = 30.8 mm, length, L = 50 mm. Cylindrical core diameter, D_{core} = 25 mm.
Gap between blade and screen, δ = 0.6 mm. Length of blade tip, $L_{bl.}$ = 0.6 mm.



(*a*) Axial force on core against ratio of screen to channel velocity, $\theta = 45°$

(*c*) Axial force on core against nip angle $v_s/v_c = 21$

(*b*) Core torque against ratio of screen to channel velocity, $\theta = 45°$

(*d*) Core torque against nip angle $v_s/v_c = 21$

Figure 7. Effect of geometry and operating conditions on core torque and axial force

v_s/v_c = ratio of (screen velocity relative to core) to (mean paste velocity along channel).

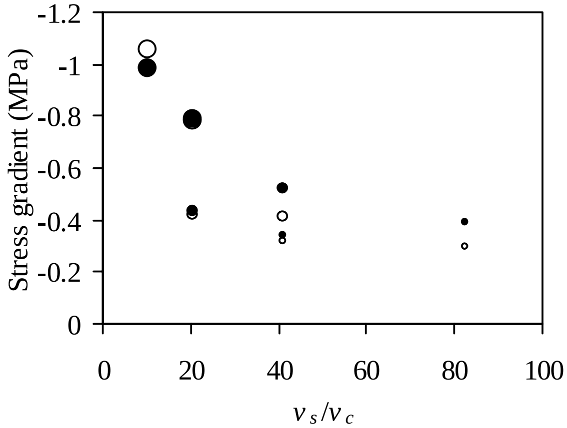
$D_{core}/D_s = 0.81$. $L_{bl.}/D_s = 0.019$

Mean velocity of paste along channel = v_c (m/s):	δ/D_s: 0.019	0.032
0.0036	• (small filled)	∘ (small open)
0.0078	● (medium filled)	○ (medium open)
0.016	⬤ (large filled)	◯ (large open)

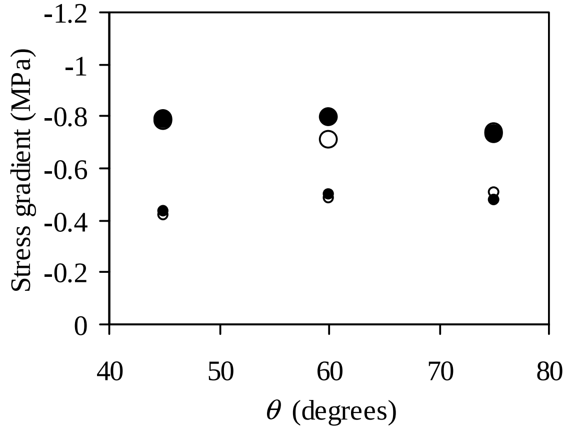
CONCLUDING REMARKS

An analysis of the flow pattern inside a radial screen extruder has been presented and a novel apparatus, capable of giving quantitative measurements of the different forces associated with the flow, has been commissioned. Stress cycling on the screen has been confirmed as being due to passage of the blade (and nip flow), while stress distributions have been measured. The force and torque on the core, along with the radial stress distributions (and magnitudes) are strongly affected by the paste flow rate and the core rotational speed. The core torque and the stress distributions are affected by the gap between the blade and the screen. The system is not noticeably dependent on the nip angle.

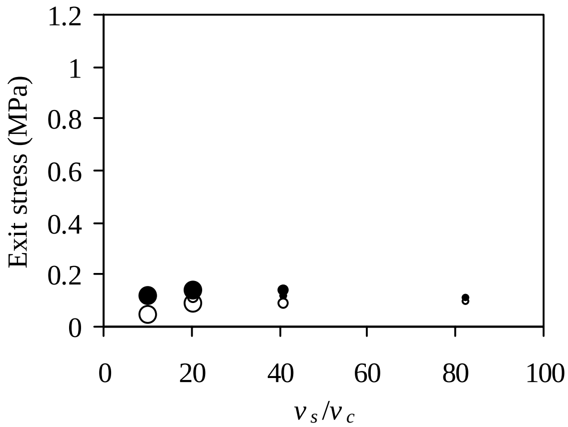
The dependence of the torque on the relative screen velocity was contrary to that expected. Associated modelling work will be reported in detail in a subsequent paper along with a detailed consideration of the results.



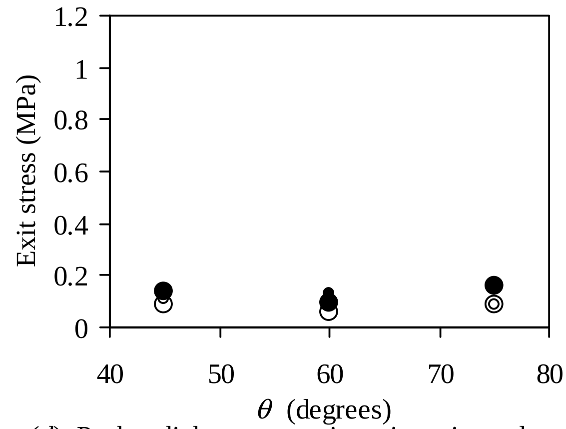
(a) Peak radial stress profile gradient against ratio of screen to channel velocity, $\theta = 45°$



(c) Peak radial stress profile gradient against nip angle, $v_s/v_c = 21$



(b) Peak radial stress at exit against ratio of screen



(d) Peak radial stress at exit against nip angle $v_s/v_c = 21$

Figure 8. Effect of geometry and operating conditions on peak radial stress profile

Symbols and notation are as in Figure 7.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge support from Syngenta and the Engineering and Physical Sciences Research Council (UK). PJM gratefully acknowledges the award of an ICI and a Travel Grant from the IChemE Particle Technology Subject Group.

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