Apparent wall slip in visco-plastic flow of food fluids

Peter J. Martin[1]*, Alasdair Walker[2], Baha Ehlweg[3], Y.M. John Chew[3], D. Ian Wilson[3]

[1]School of Chemical Engineering & Analytical Science, University of Manchester, UK
[2]Department of Engineering Science, University of Oxford, UK
[3]Department of Chemical Engineering, University of Cambridge, UK

1. Wall slip: the problem

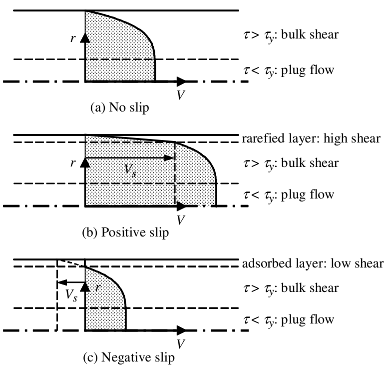


Fig. 1: Schematic of slip effects in capillary flow profiles[1]

Many foods suspensions display visco-plastic behaviour and exhibit apparent wall slip. Assuming wall slip is often useful, and the limits to its application are not known but can cause serious errors when interpreting data from rheological measurements.

Mooney's classical technique of accounting for apparent wall slip often fails, and untested variants to account for non-standard cases (*e.g.* that by Jastrzebski) have prospered[1].

$$\frac{4Q}{\pi R^3} = \frac{4}{R}V_s + \frac{4}{\tau_w^{\,3}}\int_{\tau_y}^{\tau_w} f^{-1}(\tau)\tau^2 \,\mathrm{d}\tau$$

We present a detailed evaluation of the apparent wall slip of two important visco-plastic foods, namely ice cream and a potato starch paste.

Ram extrusion was performed on a potato starch suspension using glass capillaries and high speed imaging to measure slip and for comparison with variants to Mooney's analysis. Capillary flow data sets for a commercial ice cream were provided by an industrial collaborator: pressure drops were measured across a 2 m long tube with i.d. varying from 0.10-0.48 m.

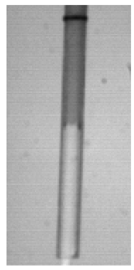


Fig. 2: Stained potato starch illustrates apparent wall slip during flow along a glass capillary

2. Ice cream: 'industrial rheology'

Initial analysis of the ice cream data sets[3] using classical Mooney analysis indicated that significant slip effects were present. The bulk constitutive behaviour could be modelled as a power law fluid, *viz.* $\tau = K\dot{\gamma}^n$ with n ~ 0.5.

Ice cream is a viscous and temperature sensitive material: viscous dissipation at the wall could cause sufficient heating to reduce the viscosity of the fluid near the wall and therefore generate apparent slip.

The fortuitous result, that n ~ 0.5, allowed us to evaluate the likely effect of viscous heating on the industrial test system using the semi-analytical model of Bird[2] for adiabatic flow of a power law fluid along a tube.

Figure 3 shows that the change in wall temperature can be significant, confirming that 'apparent slip' could be the result of viscous heating.

The flow along the industrial test unit was modelled using the FEM package COMSOL Multiphysics, including viscous dissipation and temperature dependent K.

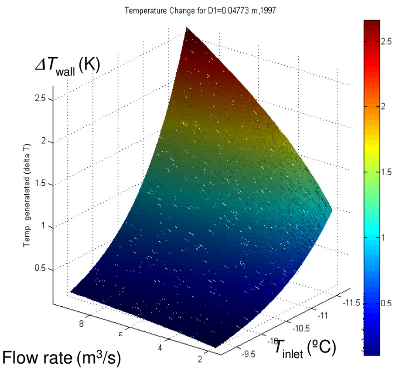


Fig. 3: Predicted temperature rise in industrial pipe rheometer for conditions employed in tests

The semi-analytical model indicated data likely to be subject to some viscous heating effects, assigned as ΔT > 0.1 K (see Figure 4): the plot shows that nearly all data at lower temperatures were subject to viscous heating effects.

The filtered data set were used to estimate the flow curve and this was then used in the simulation. The apparent viscosity was calculated from the estimated pipe pressure drop (as in the experiments). The Figure shows that the high shear rate deviation is due to viscous dissipation.

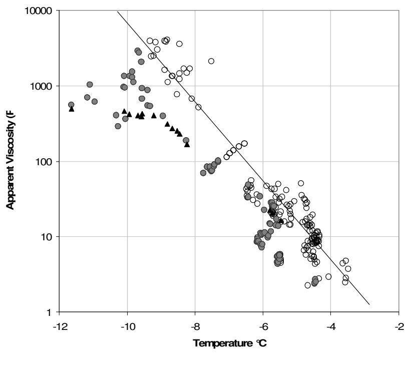
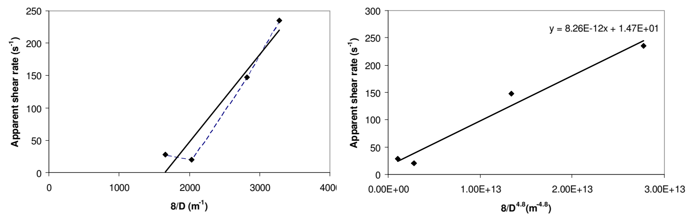


Fig. 4: Filtered data. Open circles – cases where ΔT < 0.1 K; solid circles - ΔT > 0.1 K; triangles – apparent viscosity predicted for highest shear rate cases employed in experiments.

3. Potato starch

Ram extrusion was performed on a potato starch suspension using glass capillaries and high speed imaging to measure slip and for comparison with variants to Mooney's analysis. The Mooney plots constructed were unviable; they were not linear trends passing through or above the origin on the ordinate axis. Following the approach of Jastrzebski[4] the index of the diameter term associated with slip was varied to find a viable fit; a value of m = 3.8 was found to be suitable. Figure 5 illustrates the transformation of the data.

$$\frac{32Q}{\pi D^3} = \frac{8}{D^{m+1}}\frac{\tau_w}{\beta_f} + \frac{4}{\tau_w^3}\int_{\tau_0}^{\tau_w}\left(\frac{\tau-\tau_0}{K}\right)^{\frac{1}{\lambda}}\tau^2 d\tau$$



(a) Classic construction (b) Construction following Jastrzebski

Fig. 5: Mooney plots for τ_w = 1300Pa.

High speed imaging of the colour marked paste enabled direct measurement of the apparent slip velocities. For the first time slip velocities found following Jastrzebski's approach can be compared with directly measured values. Figure 6 compares the fraction of flow due to apparent wall slip for the two measurements, where a value of one indicates plug flow.

Direct measurement of slip by imaging showed the slip fraction to increase with wall shear stress and reduce with diameter. Jastrzebski's analysis both grossly over- and under-estimated the slip fraction and showed no consistent trends.

These results indicate that deviations away from Mooney's classic analysis, based on an assumed relationship between wall slip and wall curvature, yield grossly inaccurate and unrealistic interpretations of the flows.

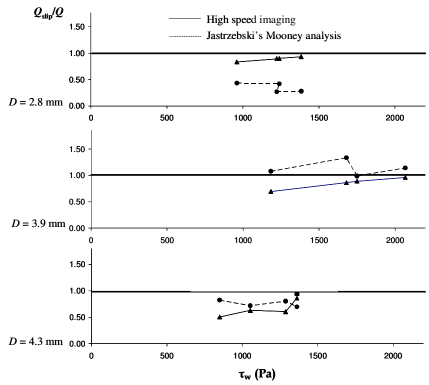


Fig. 6: Fraction of flow due to wall slip measured by imaging and Jastrzebski's Mooney analysis for different capillary diameters

References

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***Contact: Peter Martin (p.martin@manchester.ac.uk)**

4. Conclusions

This paper shows that variants which follow Jastrzebski's modification to Mooney's analysis of wall slip give incorrect results when assessed against directly measured data. Alternative physical models are illustrated for the example of ice cream which describe the true development of slip layers. A variety of fluid specific apparent slip mechanisms may exist which lead to non-compliance of the classic Mooney analysis – but which do not validate the use of Jastrzebski's modification.