

Wall Slip Revisited-Analytical and Computational approaches for calculation Presented at the Nordic Rheology Conference Society, Helsinki, June 7-9, 1997

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ABSTRACT

Wall slip is an established rheological phenomena which has been historically neglected by instrument manufacturers for a variety of reasons. Whilst quantitative analysis of wall slip is rarely performed, exploitation of the phenomena often is, this paper revisits both historical and current approaches to the evaluation of wall slip and its relevance.

INTRODUCTION

Wall slip simply describes the loss of adhesion between a flowing material and the surface over which it is flowing. Wall slip is important for two reasons; firstly since most material production involves the flow of material through some die, the geometry of which is bounded by walls, to obtain the product, and secondly since most calculation assumes no loss of adhesion at the wall. The issue is further complicated when flow predictions are made using the no slip assumption on materials that do exhibit slip.

Wall slip can be encountered in materials processing either deliberately or unwittingly. In the former instance many extrusion operators regularly employ plasticisers (slip agents) to increase output for the same operating

pressure, or in the latter, wall slip can occur when a material phase separates to produce a lubricating sub-layer. In either case the zero wall velocity condition required for historical shear analysis is lost, and if correction is not made significant error induced.

Many materials naturally exhibit wall slip including, polymers, ceramics, rubbers and food stuffs. Due to their inherent multi-phase disposition, ceramics are particularly prone to phase separation; that is they may start out in a homogeneous post mix state, but on processing, separate into their constituent phases. In polymer systems slip can be induced deliberately in the form of plasticiser, as a processing aid, or inherently via the migration of low molecular weight species to the die walls.

MOONEY-THE HISTORICAL SLIP MODEL

Qualitative detection of wall slip can be easily achieved using a capillary rheometer. Fig. 1 shows the shear viscosity functions generated via a capillary rheometer with a high density polyethylene (HDPE) using a range of dissimilar die geometries. The three geometries chosen had diameters of 0.5, 0.75 and 1mm with lengths of 8, 12 and 16mm respectively.

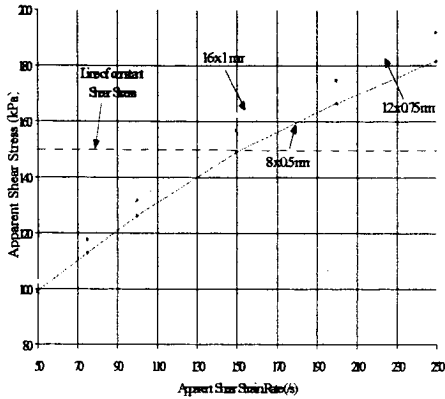


Figure 1. Capillary rheometer viscosity functions showing geometry dependence for an HDPE at 200°C.

One of the fundamental pre-requisites for making flow predictions from rheometer data is that the results are geometry independent; that is irrespective of the die geometry the same results should be obtained. Fig.1 shows the converse of this, in that when different die geometry is used different results are obtained and, whereas the viscosity functions should superimpose, they diverge. Consequently, if this data was used to predict flow behaviour, the predictions would be inaccurate. The reason for this divergence is wall slip, and in this case the slip is caused by migration of low molecular weight chains to the die wall.

Shear flow theory is based on the Poiseulle equations which state:

$$\text{Shear Stress, } \tau = \frac{r\Delta P}{2L} \quad (1)$$

$$\text{Apparent Shear rate, } \dot{\gamma}_a = \frac{4Q}{\pi r^3} \quad (2)$$

where; r is the capillary radius, Q the volumetric flow rate, ΔP the pressure drop and L the capillary length. In order to use these equations the velocity profile is assumed to be as shown in Fig.2, where it can be seen that velocity

rises from zero at the wall to some finite maximum value at the centre.

No Wall Slip

Wall Slip

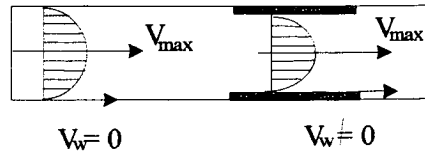


Figure 2. Velocity profiles - zero and finite wall velocities.

Once slip is established the wall velocity is no longer zero but assumes some finite value, any subsequent shear flow calculations now become geometry dependent.

Mooney¹ is historically quoted as presenting the first model to quantify slip. The model exploits the geometry dependence caused by slip and expresses the apparent wall shear rate, $\dot{\gamma}_a$ as a function of both wall shear stress, τ_w , and slip velocity, V_w . The principal assumption made by Mooney is that the slip velocity is only dependent on the shear stress; the model simplifies to:

$$\dot{\gamma}_a = \frac{4V_w}{r} + \dot{\gamma}_{true} \quad (3)$$

Thus on plotting shear rate vs $1/r$ at constant shear stress, the slope is equal to four times the slip velocity and the intercept is equal to the true shear rate corrected for slip, $\dot{\gamma}_{true}$. This is repeated for a range of shear stresses in order to produce a plot of V_w vs τ_w . In order to eliminate any possible dependence on length, L the procedure is performed using dies of equal length to diameter ratio.

EXPERIMENTAL

The work conducted for this paper is restricted to polymers, specifically HDPE. Fig.1 shows the geometry dependence encountered on characterising with a Rosand Rh7-2 capillary rheometer, it is

believed that migration of low molecular weight chains to the die wall are creating the lubricating sub-layer responsible for slip. On application of the Mooney model the slip velocity is calculated as a function of shear stress, the resulting V_w vs τ_w plot can be seen in Fig. 3.

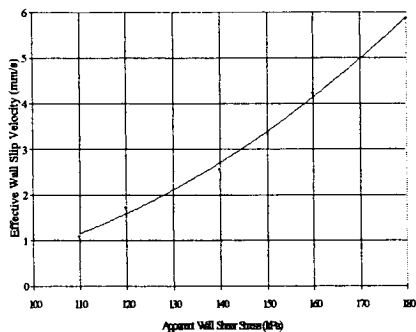


Figure 3. Slip velocity vs shear stress for HDPE at 200°C via Mooney.

HISTORICAL DIFFICULTIES WITH MOONEY.

The Mooney model has been extensively used since 1931 to quantify wall slip in many materials, examples of which using capillary geometry have been reported, amongst others, by Lupton and Register², Blyler and Hart³, and Worth et al.⁴. One of the main weaknesses encountered when using Mooney is that it is often possible, when using highly filled suspensions, to achieve negative true shear rates. These negative true shear rates are often accompanied by very high slip velocities, so high in fact as to exceed that of the mean velocity of the fluid, which is physically impossible in pressure driven flow. In order to overcome these problems several workers have suggested modifications to Mooney. Geiger⁵ suggested that a local flow gap modification be introduced to Mooney when the above phenomena were observed leading to the slip velocity

being calculated from a plot of $\log \dot{\gamma}_a$ vs $\frac{1}{r}$. In a similar approach Weigrefe⁶ suggested a flow gap modification to produce slip velocity from a plot of $\dot{\gamma}_a$ vs $\frac{1}{r^2}$. Having encountered

the same behaviour in butadiene styrene rubbers, Mourniac⁷ et al. also suggested a modified approach to account for local geometry effects. Other workers providing modifications include; Hatzikiriakos⁸, Lau and Schowalter⁹ and Hill et al.¹⁰.

It may be that the Mooney model is simply too basic for characterising some materials, particularly highly filled, multi-phase suspensions, and that more sophisticated models will have to be developed. However it is also evident from the work presented in this paper that Mooney may be used with some confidence in some of the more homogeneous polymer systems.

COMPARISON WITH COMPUTATIONAL METHODS

The objective of this paper is to examine the useful application of the simple Mooney model for wall slip in its original form. For these purposes the results presented here have been generated using a capillary rheometer for HDPE. The results have also been restricted to those showing representative Mooney slip velocities and positive corrected shear rates. In order to give some feel for confidence, the slipping material must be compared to a datum material or condition which is known not to slip. Mourniac et al., achieved this by using a slit die with a *non-slip* epoxy surface, in which results for dissimilar geometry showed no dependence.

In this work the assumption has been made that at very large diameters the slip component is minimal, thus a no slip

viscosity function can be extrapolated from those showing geometry dependence. A commercially available simulation software package (Compuplast Viscofit and Polycad) has then been used to assign Mooney obtained slip velocity values to the software generated die walls in order to predict the measured shear stresses and pressures; the evidence of applicability being if the measured results equal those predicted by the software.

Fig. 4 shows the modelled viscosity functions, via a Carreau model in Viscofit, for the rheometer data presented in Fig 1.

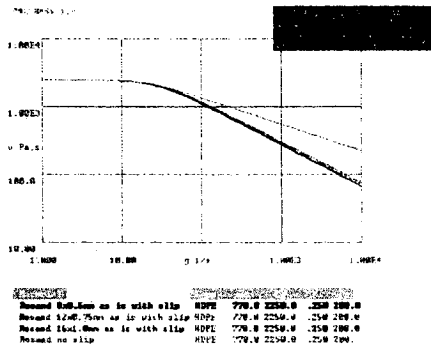


Figure 4. Software modelled viscosity functions.

The no slip function has been modelled by extrapolation to a die radius of $r=10\text{mm}$ from a plot of viscosity vs r , again using the results of Fig. 1. It can be seen in the above figure that the die geometries where slip is believed to occur have lower viscosity values over the test shear rate range than that of the no slip function, which is exactly the desired response on employing plasticisers. The 0.5mm diameter die geometry was then generated in the Polycad simulation software with the viscosity function of the no slip condition. The maximum slip velocity of 5.8mm/s obtained via Mooney was then

assigned to the die walls (see Fig.5) in order that the predicted shear stresses and pressures be compared to those actually measured using the 0.5mm diameter die.

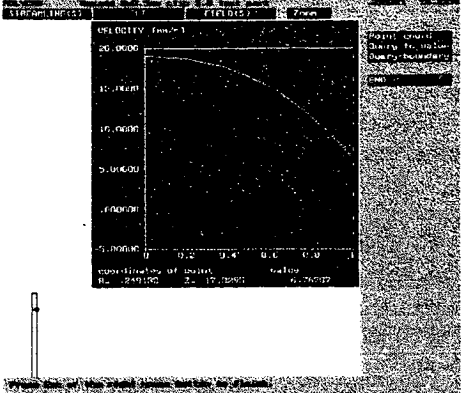


Figure 5. 0.5mm diameter die geometry with Mooney calculated slip velocity.

Figs. 6&7 show the predicted pressure and stress fields respectively. It can be seen that the predicted shear stress rises from zero at the wall to a maximum value at the die centre line as expected. The predicted shear stress is 175.3Kpa and is clearly very close to the actual of 180Kpa. The predicted maximum pressure is 11.6Mpa and is again very close to that of the actual pressure of 11.1Mpa.

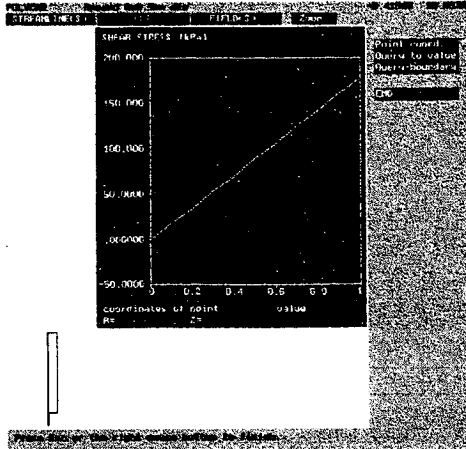


Figure 6. Predicted shear stress field.

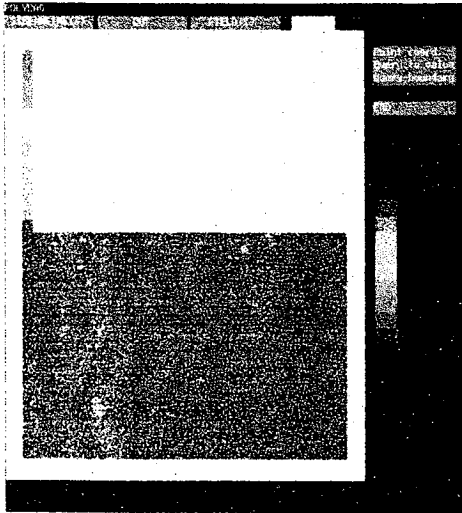


Figure 7. Predicted pressure field.

CONCLUSION

The work presented here clearly shows that the software predictions are very close to those of the Mooney model for an HPDPE. However the overriding aim is not to profess the definitive answer to wall slip, but to raise awareness of a phenomena that is often employed with no prior knowledge at all. The paper set out to revisit an historical approach to the treatment of wall slip and to provide a feel for the degree of confidence, via a computational method, that can be expected. The results show that the degree of confidence in wall slip values calculated via Mooney is good, although some assumptions have been made. As stated earlier, this model may be too simplistic for more complex systems, but as far as homogeneous HDPE is concerned the work appears to show that Mooney calculated wall slip velocities can be used with some confidence.

REFERENCES

1. Mooney, M., Explicit Formulas for Slip and Fluidity, *J.Rheol.* 2, 210 (1931).

2. Lupton, J.M and Register, J.W., Melt Flow of Polyethylene at High rates, *Polym. Eng. Sci.* 5, 235 (1965).
3. Blyler, L.L. and Hart, A.C., Capillary Flow Instability of Ethylene Polymer Melts, *Polym. Eng. Sci.* 10, 193 (1970).
4. Worth, R.A. and Parnaby, J., Wall Slip and its Implications in the design of Single Screw Melt-Fed Extruders, *Polym. Eng. Sci.*, 17, 257 (1977).
5. Geiger, K RheologiCAL Characterisation of EPDM compounds, *Kautsch Gummie Kunststoffe*, 43, 273-283 (1989).
6. Weigrefe, S., Untersuchungen Zum Wandgleitverhalten von EPDM und SBR, *Kautsch Gummie Kunststoffe*, 44, 216-221 (1991).
7. Mourniac, P.H., Agassant, J.F. and Vergnes, B., Determination of the wall slip velocity in the flow of a SBR compound, *Rheological Acta.* 31, 565-574 (1992).
8. Hatzikiriakos, S.G., The Onset of wall Slip and Sharkskin Melt Fracture in Capillary Flow, *Polym. Eng. Sci.*, 34, 19 (1994).
9. Lau, H.C, and Scowalter, W.R, A Model for Adhesive Failure of Viscoelastic Fluids During Flow, *J.Rheol.*, 30, 193 (1986).
10. Hill, D.A., Hasegawa, T. and Denn, M.M., On The Apparant Relation Between Adhesive Failure and Melt Fracture, *J.Rheol.*, 34, 891 (1990).

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