

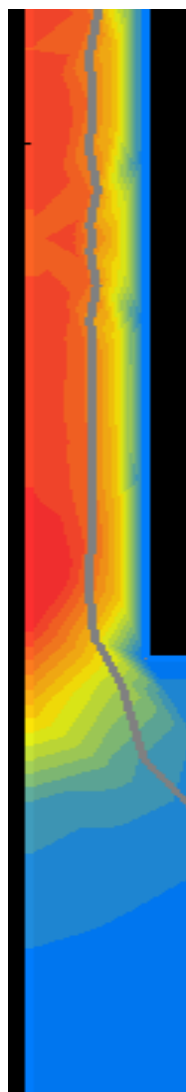
Measurement Note

Polymer flow incorporating slip and implications for polymer processing simulation

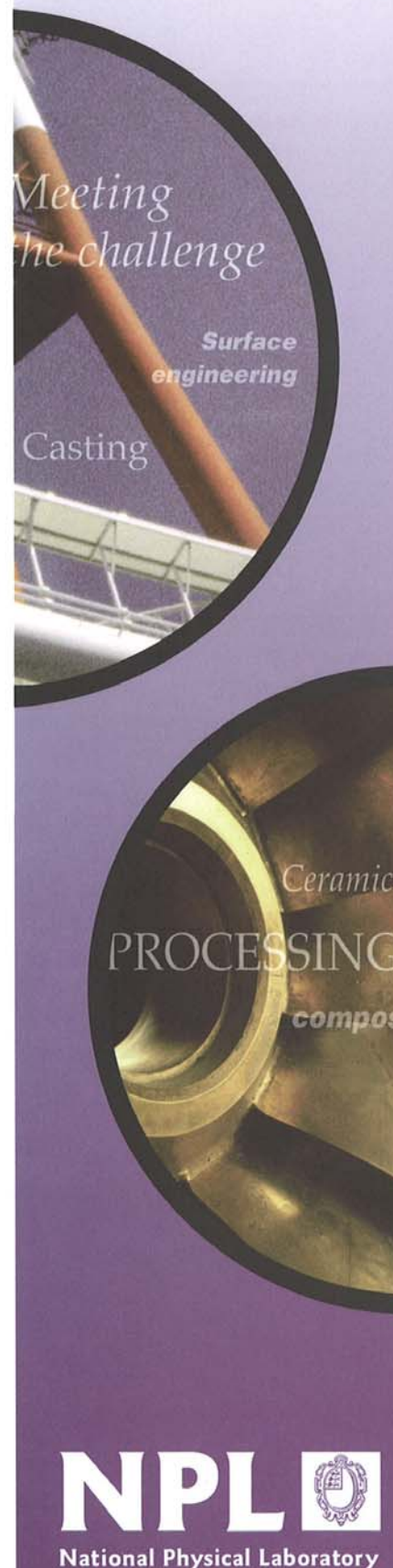
SUMMARY

Slip occurs in the flow of heavily filled polymers and can also be positively encouraged through the use of lubricant additives to improve processability and reduce energy consumption. However, the issue of slip in flow of polymers is normally ignored, both in terms of characterising the material's flow behaviour and in the numerical simulation of flow. Slip can have a very significant effect on flow behaviour, for example it can increase the flow rate by a factor of eight for the same pressure [1]. Slip affects not only the processing pressures but also, for example, the melt temperature profile as the heat generated due to viscous dissipation will be significantly reduced. Slip may also affect the surface finish of products and, through reduced dissipation, may also result in improved mechanical properties due to reduced thermal degradation. Although a method for slip velocity determination using various extrusion die diameters exists, its reliability had not been quantified until recently.

The measurement of slip flow has been the subject of recent work: good measurement practice along with the results of an intercomparison and an evaluation of the uncertainties in slip velocity measurement are presented elsewhere [1]. This Measurement Note presents results illustrating the effect of incorporating slip flow on simulation predictions.



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INTRODUCTION

Slip in polymer flow has been studied by various workers, as reported by Rides [1]. It may be apparent as an obvious discontinuity in the flow curve but may also occur, without being obvious, over the entire range of the measured flow curve.

The most commonly used method for determining slip velocities is due to Mooney [2] in which different diameter dies are used in capillary extrusion rheometry. Shear viscosity is a material property and thus should be independent of the test geometry. However, if slip occurs then the measured shear viscosities are found to be dependent on the die diameter, e.g. Figure 1. This dependence is used to determine the slip velocities.

Slip velocity measurement

- Measure the shear stress – apparent shear rate behaviour of the material (ISO 11443) using at least two sets of dies of different diameter, yielding one flow curve for each diameter.
- Determine, by interpolation, the apparent shear rates corresponding to selected shear stresses for each die diameter.
- For each shear stress, plot the (interpolated) apparent shear rate values against the reciprocal of the die radius, and determine the gradient of the linear plot to the data.
- Calculate the slip velocity, given by the value of the gradient divided by 4.

Slip velocity V_s has been modelled as a function of shear stress, the most commonly used form being a power-law:

$$V_s = a \tau_w^b$$

where a and b are constants and τ_w is the wall shear stress. This form fits well the slip behaviour of the material in the slip region, Figure 2.

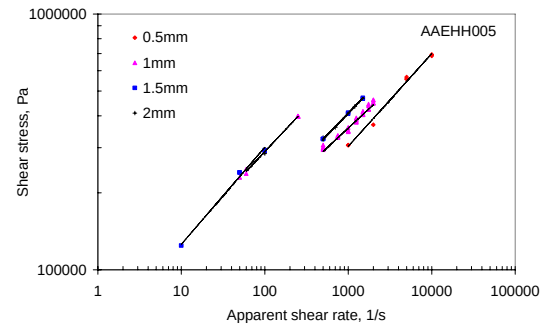


Figure 1: Shear stress data for different diameter dies indicating a die dependence above the slip transition. Filled EVA at 165 °C.

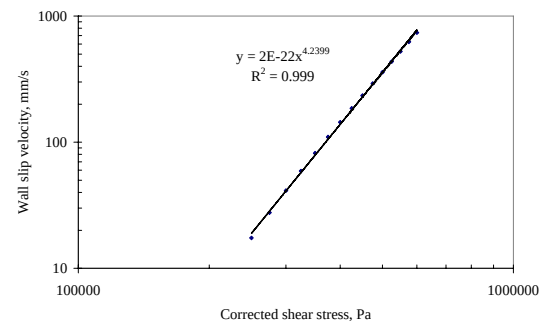


Figure 2: Fit of a power-law model to measured slip velocities for a filled polymer EVA at 165 °C.

For the filled EVA investigated in this work, the onset of slip at a shear rate of 300 s^{-1} was marked by oscillations in the extrusion pressure trace, typical of melt fracture, although fracture of the extrudate was not visually observed.

As described earlier, the incorporation of slip flow in modelling is not often done. This work considers the affect of incorporating slip flow on predictions.

MODELLING

Numerical modelling of the flow of polymers has been carried out using Compuplast Flow2000™ Virtual Extrusion Laboratory™ simulation software for extrusion processing. A Carreau (WLF) model was fitted to the rheological data. Furthermore, slip flow was modelled using a power-law, Figure 2.

Alternatively, slip flow can be mimicked, albeit approximately, by using a moving-wall boundary condition in which the wall velocity is set as an input parameter to the simulation. This latter approach is not considered as valuable for modelling the slip behaviour as the boundary condition is imposed and therefore constrains the calculated solution.

RESULTS AND DISCUSSION

The effect of incorporating the slip behaviour into simulations, using the power-law slip velocity model, is illustrated by the results in Table 1. Extrusion pressures, predicted with and without the slip model, are presented for the EVA at 165 °C for a 1 mm diameter die. The differences between the predicted pressure drops and the experimentally measured values are also presented in brackets. These results illustrate that in the slip region when using the slip model the discrepancies were within 5%. A similar value was obtained when modelling the no-slip region without the slip model. However, inappropriate modelling, e.g. not incorporating the slip model in the slip region, resulted in an error in pressure values of up to 43%. The results also illustrate the problem associated with the use of the slip function in the no-slip region, which resulted in an error of some 30%, indicating the need to “switch off” the slip function, e.g. using a limiting shear rate value.

	No-slip region		Slip region	
Apparent shear rate, s^{-1}	100	250	1000	3000
Measured pressure drop, MPa	18.3	24.6	22.9	31.8
Predicted pressure drop – no-slip, MPa	19.2 (5%)	24.5 (-1%)	32.2 (43%)	38.8 (22%)
Predicted pressure drop - with slip, MPa	13.1 (-28%)	16.8 (-32%)	23.6 (3%)	30.3 (-5%)

Table 1: Comparison of pressure drop predictions with and without slip model

In modelling in the slip region, for smaller diameter dies the discrepancy between predicted values assuming no-slip and measured values would be greater as the measured shear stresses function decreases with decreasing die diameter in the presence of slip.

A 43% reduction in the pressure drop will result in a similar magnitude reduction in the heat generated by viscous dissipation. For these nominally isothermal tests the average temperature rise in the flow through the die was estimated to be ≈ 11 °C and 16 °C at $1000\ s^{-1}$ and $3000\ s^{-1}$ respectively.

An example of the through-thickness velocity profile, assuming a moving boundary simulating slip flow, is shown in Figure 3.

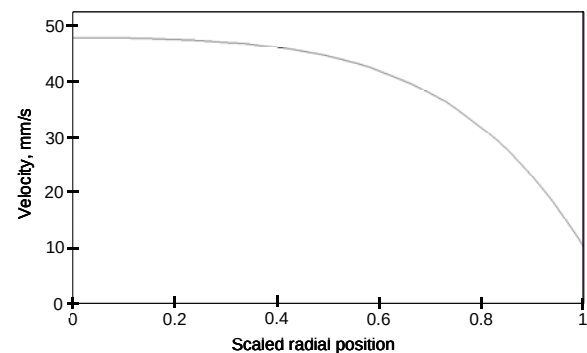


Figure 3: Velocity profile in a flow with “slip” – non zero wall velocity

These results indicate the magnitude of the errors due to the experimental data and the model is approximately 5%. These discrepancies may be due to scatter in the viscosity data and inaccurate curve fitting to that data. Data on the EVA were obtained at 165 °C, 175 °C and 185 °C and fitted using a Carreau model. The error in the fitted curve to the experimental data at 165 °C ranged from 2.6% to 4.2% with the fitted values all being high (due to fitting the model to data at all temperatures). Thus predicted pressures were estimated to be approximately 3% to 4% high from this factor alone.

CONCLUSIONS

Additives, including lubricants, are increasingly being used to modify the rheological behaviour of materials, and heavily filled materials are widely used. Both types of material can exhibit slip during flow. Although the measurement and modelling of slip is often overlooked, it can have a significant effect on the flow behaviour and thus on predictions of processing. To illustrate this, the onset of slip can result in a reduction in extrusion pressure by up to 50% [1]. Inappropriate characterisation of the material, for example through extrapolation of behaviour to higher shear rates, can result in significant errors in modelling predictions. Thus an understanding of slip flow and how to reliably measure and model it is important for accurate processing simulation. Through accurate simulation the benefits of right-first-time engineering and reduced times to market, for example, will be realised.

REFERENCES

- [1] Rides, M. and Allen, C.R.G., Measurement Good Practice Guide No. 90, Slip flow measurement by capillary extrusion rheometry, National Physical Laboratory, March 2006, ISSN 1368-6550.
- [2] Mooney, M., J. Rheology, April 1931, pp.210-222.

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