Received: 14 July 2020 | Accepted: 3 November 2020

DOI: 10.1002/pamm.202000221

Numerical simulation of flow processes of wood-polymer in extrusion dies

Fabian Liese[1,*] and **Olaf Wünsch**[1]

[1] Institute of Mechanics, Chair of Fluid Mechanics, University of Kassel, D-34125 Kassel

The addition of wood to polymers results in wood-polymer composites (WPC), whereby the wood content can be up to 80 %. This composite is mainly processed in extruded deckings. The extrusion die is an essential part of the process, which determines both process parameters and the final product. A characteristic of WPC extrusion dies is a partial solidification of the melt before leaving the die. This solidification is necessary to ensure a dimensionally stable extrusion. For the design of WPC extrusion dies numerical flow field calculations are increasingly used. Based on rheological measurements, both the shear thinning flow behaviour and the temperature dependence of the viscosity are modelled. In the parallel zone a pure shear flow is present, while in the transition elements such as the flange to the extruder or the mandrel due to the cross-sectional changes strain rates are dominant. High-density polyethylene (HDPE) with wood fibers has shear thinning and strain thickening behavior, so different models are needed to describe it. The results of the numerical simulations are compared with experimental values of an extrusion die for a square hollow profile.

1 Introduction

The market for wood-polymer composites has been growing for years, so that the design of the extrusion dies plays an increasingly important role. Simulation methods are already often used for standard polymers, but rarely for WPC, so that cost- and time-intensive design based on experience is still common. For the numerical design, the shear-thinning behavior in material modeling is considered in the literature [1]. However, in an extrusion die there are not only shear-dominant flow areas such as the parallel zone but also strain-dominant areas, especially at the transition areas to the extruder and in front of the mandrel. Due to the strain-thickening behaviour, viscosity is increased in these areas, which will be investigated in more detail in this work.

2 Material model

To investigate the thermorheological behaviour of HDPE with 30 % wood content, measurements from the rotation and capillary rheometer are used. Figure 1 shows the shear-thinning behavior with the formation of a first Newtonian plateau as well as a strain-thickening behavior, whereas measured data could not be recorded at higher strain rates. A Carreau-Yasuda model with various parameters in combination with an Arrhenius approach is used to model both shear viscosity η_s and strain viscosity η_D as a function of deformation and temperature, as shown in equation (1).

$$\eta_{s/D}(\dot{\gamma}/\dot{\epsilon}, T) = \eta_0 \left[1 + (\lambda|\dot{\gamma}|/|\dot{\epsilon}|)^{\alpha}\right]^{\frac{n-1}{\alpha}} \cdot e^{\frac{E_0}{R_0}\left(\frac{1}{T} - \frac{1}{T_0}\right)} \quad (1)$$

One possibility to consider both shear and strain viscosity in the stress calculation $\mathbf{T} = \varphi_1 \mathbf{D}$ is to use a hybrid interpolation model according to [2], which smoothly interpolates the respective viscosities depending on the deformation present:

$$\varphi_1 = 2\eta_s(\dot{\gamma}, T) + \sqrt{3\frac{\dot{\epsilon}^2}{\dot{\gamma}^2}} \left[\frac{2}{3}\eta_D(\dot{\epsilon}, T) - 2\eta_s(\dot{\gamma}, T)\right] \quad (2)$$

For the classification of the flow in shear and strain flows the parameter κ is introduced depending on the invariants:

$$\kappa = \frac{III_D}{(-II_D)^{\frac{3}{2}}} = \frac{\det(\mathbf{D})}{\left(\frac{1}{2}\operatorname{tr}(\mathbf{D}^2)\right)^{\frac{3}{2}}} \quad (3)$$

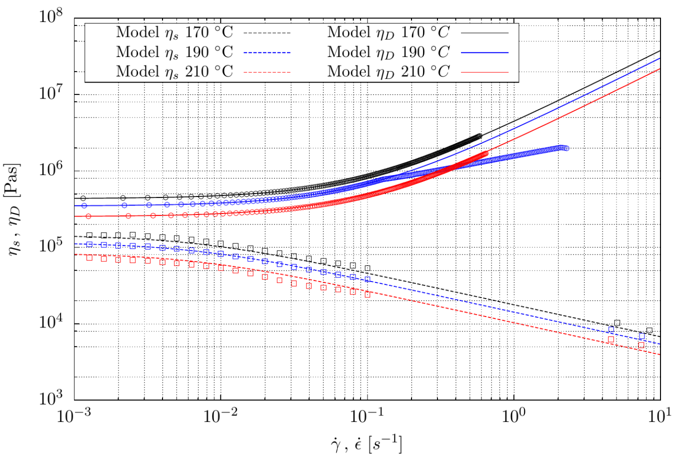

Fig. 1: Shear and strain viscosity measurements (symbols) and model (lines)

* Corresponding author: e-mail fluiddynamics@uni-kassel.de, phone +49 561 804 3252, fax +49 561 804 2720

3 Numerical simulations

In order to determine the influence of strain viscosity in the extrusion die, numerical simulations are carried out and compared with experimental data of the pressure at the points s_{p0}–s_{p3}, which were collected by SKZ - Das Kunststoffzentrum. The boundary conditions are defined as a mass flow between 20 kg/h to 40 kg/h and a temperature of 190 °C. The flow is incompressible and stationary. Figure 2 shows the pressure at the surface of the die and in the diagram the numerically determined pressure is compared across the 370 mm long die with the experimental data at the four measuring points. In the simulation, the temperature-dependent shear viscosity from equation (1) is taken into account. For a closer analysis of the flow condition, the parameter κ from equation (3) is used, which is shown in figure 3 on the symmetry plane of the die. Secondly, the viscosity increase using the hybrid material model from equation (2) compared to the pure shear viscosity from equation (1) is shown. This difference in figure 4 can be used to assess the influence of the strain viscosity.

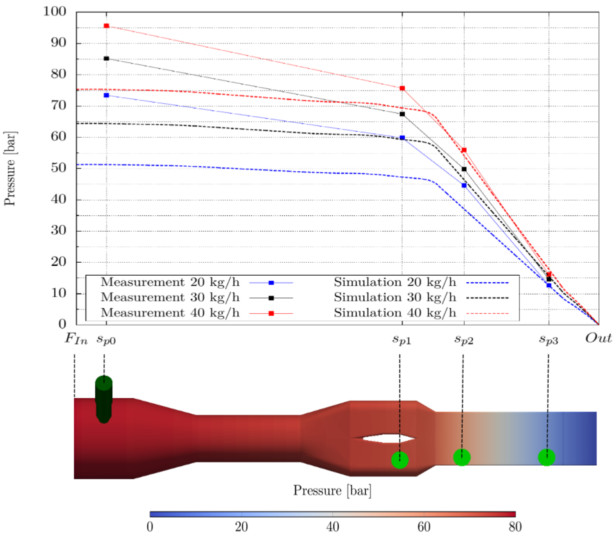

Fig. 2: Pressure measurements and simulation

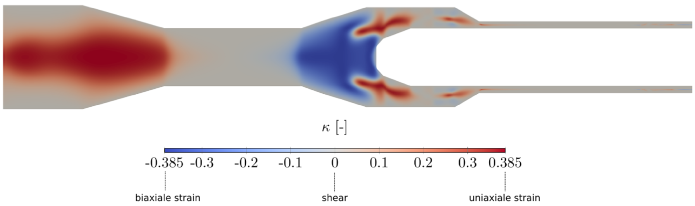

Fig. 3: κ-value on symmetry plane

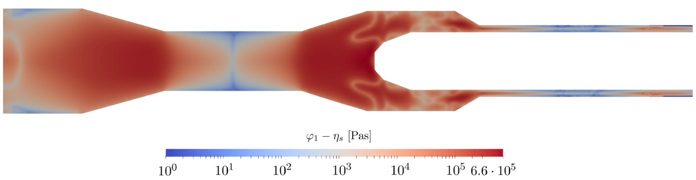

Fig. 4: $(\varphi_1 - \eta_s)$-value on symmetry plane

Figure 2 reveals a moderate pressure loss at the inlet where as the pressure loss is dominated by the parallel zone at the outlet. This is plausible for the creeping flow since the cross section reduces significantly from the inlet to the outlet. If the measured values are compared with the numerical values, a good agreement is shown at the points s_{p2} and s_{p3}. However, the deviations increase in the direction of the extruder and experimentally a significantly higher pressure loss between s_{p0} and s_{p2} is shown, which is not captured by a numerical model base on pure shear viscosity. Therefore, the κ value is shown in figure 3 on the symmetry plane of the die for closer analysis. This makes it clear that pure shear flow is only present in areas of constant cross-section such as the parallel zone. However, a biaxial strain is shown in front of the mandrel tip in blue and a uniaxial strain in front of the parallel zone and behind the extruder in red. Figure 4 shows the increase in viscosity when considering the hybrid model compared to pure shear viscosity. In areas of high strain such as in front of the parallel zone and in the cross-sectional reduction behind the extruder, the viscosity increases by more than 10^5 Pas due to the shear thinning and strain thickening behavior, which explains the increased pressure drop between s_{p0}–s_{p2}.

4 Results and discussion

For the design of WPC extrusion dies, simulative methods have rarely been used so far, and when they are applied, only the shear thinning behaviour is considered in the material model. However, by using several pressure measuring points along the die, a significant pressure loss between die inlet and parallel zone could be measured experimentally, for which the strain thickening provides an explanation. But the hybrid interpolation model leads to more numerically instability than the model of pure shear thinning and the determination of the strain viscosity by means of a capillary rheometer proves to be complex, so that further numerical and experimental investigations are necessary also on other extrusion dies.

Acknowledgements Open access funding enabled and organized by Projekt DEAL.

References

[1] N. Gonçalves, P. Teixeira, L. Ferrás, Design and optimization of an extrusion die for the production of wood–plastic composite profiles, Polymer Engineering and Science **55**, 1849-1855 (2014).
[2] G. Böhme, Strömungsmechanik nichtnewtonscher Fluide Vieweg+Teubner Verlag, Stuttgart, (2000), p. 156.

