EFFECT OF WALL SLIP ON THE FLOW IN A FLAT DIE FOR SHEET EXTRUSION

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Abstract

Flow in a flat die with coat hanger type of manifold is simulated allowing slip on die walls. Flow in the same die was also simulated by enforcing the no-slip condition on the walls. With slip on the die walls, the pressure drop, shear rate, stress, as well as temperature increase in the die, all were smaller than the corresponding values with no-slip condition on the walls. For the case with slip on die walls, since the shear rate is smaller, the elongation rate in the die is found to be the dominant fraction of the total strain rate. Due to its high computational efficiency, the software employed in this work can be effectively used to design extrusion dies for fluids exhibiting slip on die walls.

Introduction

Extrusion, or molding, of highly filled suspensions is often encountered in manufacturing of various specialty products. These powder processing techniques involve processing of a suspension, which is filled close to its maximum packing fraction, to form a "green" impact. The suspension fluid (binder) acts as a lubricant between the powder particles, and between the particles and die/mold walls to allow the flow of the paste-like suspension. The "green" compact is then sintered to coalesce the particles. During sintering, density of the green compact increases, and it shrinks significantly in size. An example of powder processing is cold processing of polytetrafluoroethylene (PTFE), which is difficult to process as a melt because of its high melting point and high melt viscosity [1]. Other examples of powder processing include processing of a metal/polymer paste [2], or that of a suspension of a ceramic in a wax [3].

Processing of a powder/binder paste involves unique phenomena such as apparent slip of the powder/binder paste at die walls, and presence of a yield stress before the paste starts to flow. Because of these additional complexities, if a software package for simulation of the flow of polymer melts is used for designing the dies for extrusion of highly filled suspensions, the predictions from the simulation software can be very different than the corresponding experimental data. Therefore, in the present work, the die design software polyXtrue [4] was modified to allow slip of the powder/binder paste on die walls. This paper compares the predictions from a simulation with slip on die walls with those from a simulation with no-slip condition enforced on the walls. The flow in a flat die with coat-hanger type of manifold, which is commonly used for sheet extrusion, is analyzed for this comparative study.

Slip on Die Walls

The apparent slip of powder/binder mixture on walls is generally explained by formation of an essentially particle-free, binder-rich, low viscosity layer on the walls. Since the typical thickness of this lubricating slip layer (~1 μm) is much smaller than the size of solid particles (1 to 200 μm) [5], the flow of highly concentrated suspensions is generally analyzed by ignoring the slip layer, and by considering the velocity at the interface between the slip layer and the concentrated suspension as the slip velocity at the walls.

Slip velocity at the die walls increases as the shear stress on the die walls is increased. The dependence of shear velocity on shear stress is generally determined by the classical technique developed by Mooney [6, 7] Mooney's analysis involves a set of capillary rheometer experiments with various dies having different capillary radius (R). The apparent shear rate in the capillary ($\dot{\gamma}_a = 4Q/\pi R^3$, where Q is the flow) is then plotted against $1/R$. Since the apparent shear rate and the true shear rate ($\dot{\gamma}_T$) are related by the following equation [8]:

$$\dot{\gamma}_a = \dot{\gamma}_T + \frac{4V_s}{R} \qquad (1)$$

The slope of the $\dot{\gamma}_a$ versus $1/R$ curve gives the value of slip velocity (V_s). By plotting the $\dot{\gamma}_a$ versus $1/R$ curves at various shear stress values, the dependency of slip velocity on shear stress can be easily determined by the Mooney analysis.

Variations of slip velocity with shear stress can be easily captured by a power-law model [2]:

$$V_s = \alpha(T)\tau_w^c \qquad (2)$$

where α and c are material dependent parameters. Furthermore, the temperature dependence of the slip velocity can be captured with the consistency coefficient, α, as an exponential function of temperature (T),

$$\alpha(T) = a\,\exp(bT) \qquad (3)$$

where a and b are material dependent parameters.

Material

To analyze the effect of wall slip on the flow in a flat die, a mixture of stainless steel powder (SUS316L with mean particles of 8 μm) and an EVA-based binder was employed for the flow simulation. The viscosity of the stainless-steel/EVA mixture (shown in Figure 1) was modeled by the Cross-Arrhenius equation,

$$\eta = \frac{\eta_0}{1+\left(\eta_0\dot{\gamma}/\tau^*\right)^{1-n}}\text{, with } \eta_0 = B\exp\left(\frac{T_b}{T}\right) \qquad (4)$$

where B, T_b, τ^* and n are material parameters, and $\dot{\gamma}$ is the shear rate. For 50% volume fraction of the steel powder, the values of the material parameters for the stainless-steel/EVA mixture, which were taken from reference [2], are given in Table 1.

It is noted that the Cross-Arrhenius viscosity model does not account for the yield stress which is often observed during flow of highly filled suspensions. Effect of yield stress on the flow, which is not included in the analysis presented in this paper, and may be included in the analysis in future.

In order to analyze the effect of die wall slip, the flow in the flat die was also simulated with the same viscosity parameters as those in Table 1, but with no-slip condition enforced on die walls.

Table 1: Properties of the stainless-steel/EVA mixture [2].

Viscosity parameters	
B (kg/m s)	5.19×10^{-3}
T_b (K)	5.37×10^{3}
τ^* (Pa)	6.37×10^{4}
n	0.18
Slip velocity parameters	
a (m/Pa^c.s)	5.846×10^{-13}
b (1/K)	2.7454×10^{-2}
c	1.4984
Other material properties	
Density (kg/m^3)	4.59×10^{3}
Heat Capacity (J/kg K)	7.01×10^{2}
Thermal conductivity (W/m K)	5.09×10^{-1}

Die Geometry and Processing Conditions

Geometry of the flat die with coat-hanger type of manifold used in this work is shown in Figure 2. At the entrance, the die cross-section is 10.16×5.08 cm, and the sheet dimensions at the die exit are 101.6×0.102 cm. Other details of the geometry of the flat die are available in reference [9].

For the simulation results presented in the next section, a uniform velocity of 5 cm/s was specified at the entrance. The die wall temperature as well as the fluid temperature at the die entrance was specified to be 393 K.

Results and Discussion

As mentioned earlier, in the present work, the die design software, polyXtrue [4], was modified to allow slip on the die walls. In particular, using the numerical scheme employed by Hwang and Kwon [2], on all the nodes on die walls, in the two directions parallel to die walls the shear stress given by Eqn. (2) was enforced as the boundary condition, whereas the velocity component in the direction perpendicular to the die wall was specified to be zero to enforce the no-penetration condition on the die wall nodes.

The velocity distribution in the mid-plane of the flat die with slip allowed on the die walls is shown in Figure 3 (a). The corresponding velocity distribution with no-slip condition on the walls is given in Figure 3 (b). For the simulation with no-slip condition as well as for the simulation with slip at die wall, the variation of velocity along the centerline at the die exit is shown in Figure 4. As expected, since the flow rate in the two flow simulations is the same, the centerline velocity in Figure 4 is lower with slip allowed on the die walls. It is evident from Figures 3 and 4 that for the stainless-steel/EVA mixture the velocity at the center of the flat die is much larger than the velocity away from the center. That is, the die geometry shown in Figure 2, which was originally developed for a low-density polyethylene [9], is not properly balanced for the stainless-steel/EVA mixture. Even though the die geometry employed in this paper is not properly balanced, the simulation results presented here do exhibit the effect to wall slip on the flow in an extrusion die.

Figure 5 shows the velocity distributions on the die walls. As expected, with the no-slip condition enforced on the die walls, in Figure 5 (b), the velocity is zero everywhere on the walls. With slip allowed on die walls, in Figure 5 (a), the velocity is non-zero on the walls. In particular, it is noted that the velocity on die walls is quite large in the region where the fluid leaves the rectangular channel near the entrance and enters the coat-hanger manifold. Also, in Figure 5 (a) the slip velocity is large in the center of die land and in the center of the converging region before the die land. As discussed before, the slip velocity increases as a power of the shear stress on die walls (Eqn. 2). The shear stress at the die walls predicted by the software is shown in Figure 6. The strain rate corresponding to the stress shown in Figure 6 is shown in Figure 7. In Figures 6 (a) and 7 (a), with slip on die walls the shear rate and shear stress on die walls are also larger in the region where the slip velocity is large in Figure 5 (a), that is, near the entrance of the coat-hanger manifold, in the center of the die land, and in the center of the converging region before the die land.

Comparison of stress and strain rate distributions for the case with slip on die walls in Figures 6 (a) and 7 (a), respectively, with the corresponding distributions with no-slip boundary conditions in Figure 6 (b) and 7 (b) reveals that wall slip has a major effect on the strain rate and stress distribution in extrusion dies. With slip allowed on the die walls, as expected, the maximum stress and strain rate in Figures 6 (a) and 7 (a) are much smaller than the corresponding values with no-slip condition in Figures 6 (b) and 7 (b). Furthermore, the regions where the strain rate and stress are the maximum are also different when the slip is allowed on die walls. With no-slip condition on the walls, in Figure 6 (b) and 7 (b), the stress and strain rate are the maximum in the die land near the exit where the velocity is large and the die gap is the smallest. In contrast, with slip on die walls, the strain rate and stress is the largest near the entrance of the coat-hanger manifold, in the center of the die land, and also in center of the converging region near the entrance of the die land. With slip allowed on the die walls, the shear rate in the die decreases by a large extent. However, the elongation rate in the converging (or diverging) regions remains relatively unchanged. Because of the reduction in the shear rate, with slip on the die walls, a large portion of the strain rate is contributed by the elongation rate in the flow. Accordingly, with wall slip in Figures 6 (a) and 7 (a), the strain rate and stress is the highest in the regions with high elongation rate near the entrance of the die manifold, and in the converging region before the die land. It is also noted that the strain rate, stress, as well as slip velocity are quite large near the entrance of the die. The large values of these variables near the die entrance are due to the uniform velocity of 5 cm/s specified at the die entrance. As the uniform velocity near the entrance changes rapidly to a fully developed velocity profile, it gives a large strain rate, resulting in the large stress and large slip velocity near the die entrance. That is, the large value of the predicted slip velocity near the die entrance is an erroneous numerical artifact, and should be ignored.

Figure 8 shows the predicted pressure distributions in the flat die. As expected, with slip allowed on the walls (Figure 8 a), the predicted pressure drop (0.3 MPa) is much smaller than the pressure drop with no-slip condition on the die walls (0.6 MPa, Figure 8 b).

The temperature distributions predicted by the two flow simulations are shown in Figure 9. For both simulations the predicted temperature increase due to shear heating is very small (< 0.1 K). Since the strain rate and stress in Figures 6 and 7 were larger with the no-slip condition on the die walls, as expected, the predicted temperature increase is also larger when the no-slip condition is enforced on die walls (Figure 9 b).

Conclusions

Flow in a flat die with coat hanger type of manifold was simulated by allowing slip on the die walls. The flow in the same die was also simulated with no-slip condition on the die walls. It was found that the velocity, pressure, temperature, strain rate, and stress in the die are very different for these two simulations in the same die. In particular, because the shear rate in the flows with slip on die walls is smaller, with slip on die walls the elongation rate is found to be the dominant component of the total strain rate in the flat die. Therefore, for design of the dies for extrusion of highly filled suspensions, it is important to account for the slip on die walls. The flow simulation software employed in this work is highly computationally efficient, requiring less than half hour of computation time (on a Personal Computer) for the flow simulations in extrusion dies. The software can be effectively used to design extrusion dies for fluid suspensions which commonly exhibit slip on die walls.

References

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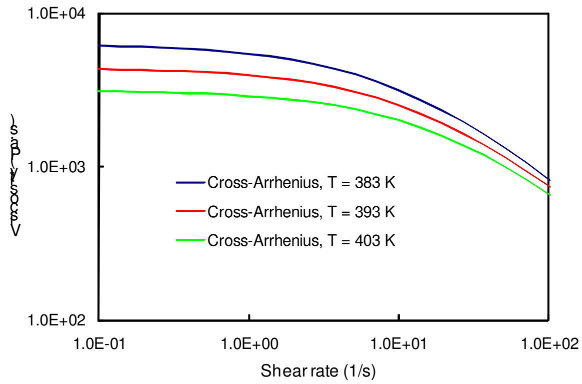


Figure 1 Viscosity of the stainless-steel/EVA mixture.

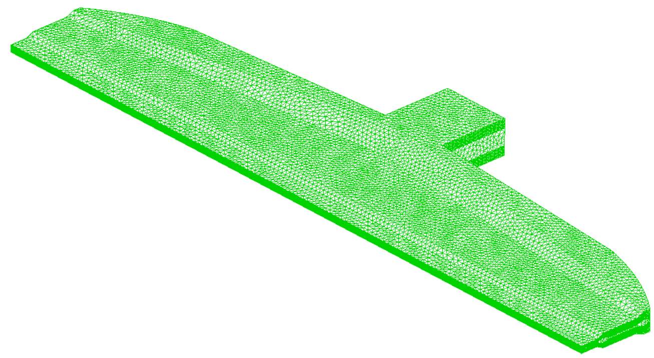
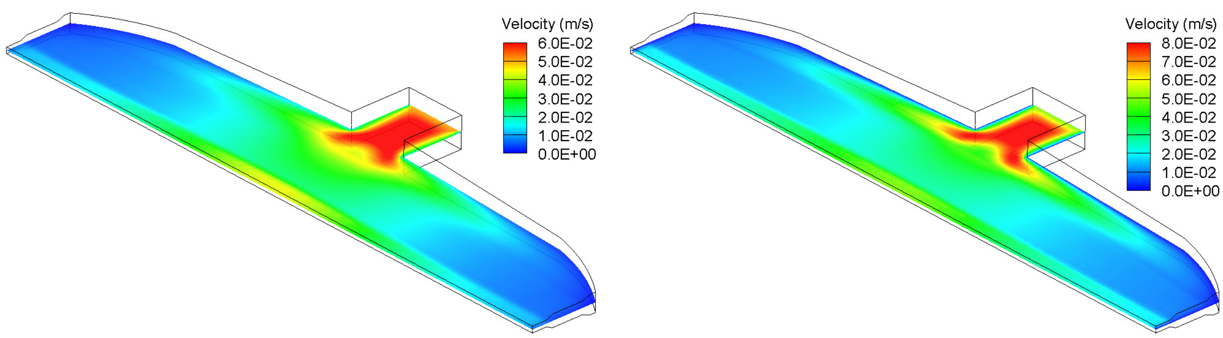


Figure 2 Finite element mesh of tetrahedral elements in the flat die.



(a) (b)

Figure 3 Velocity distribution in the mid-plane of the die (a) with slip on die-walls, (b) with no-slip condition on the walls.

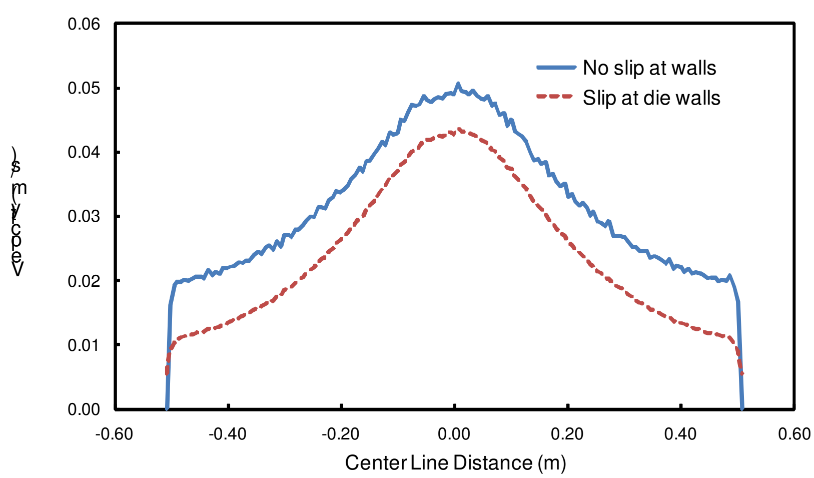
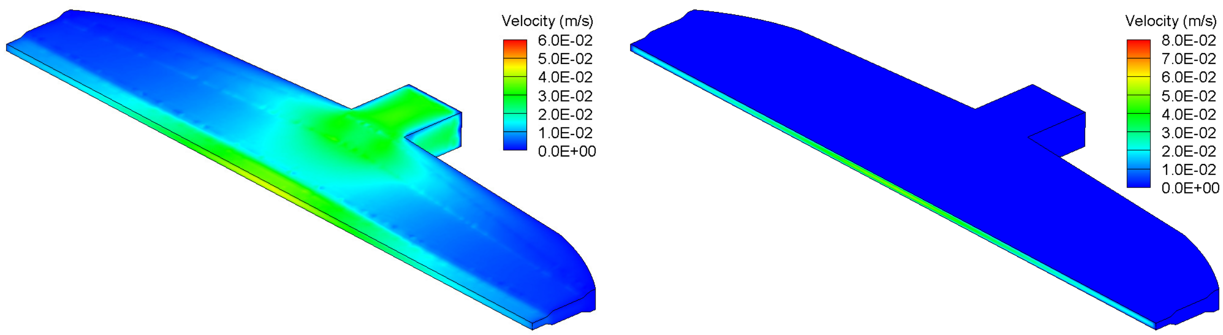
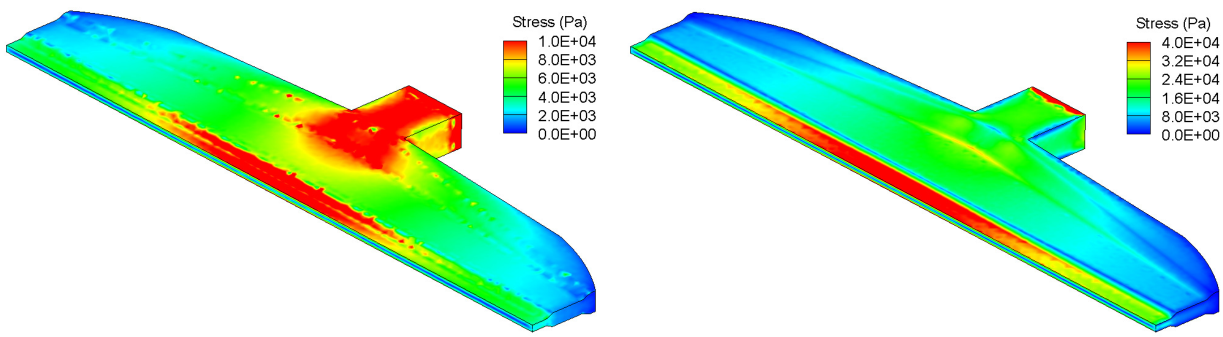


Figure 4 Velocity distribution along the centerline at the die exit.



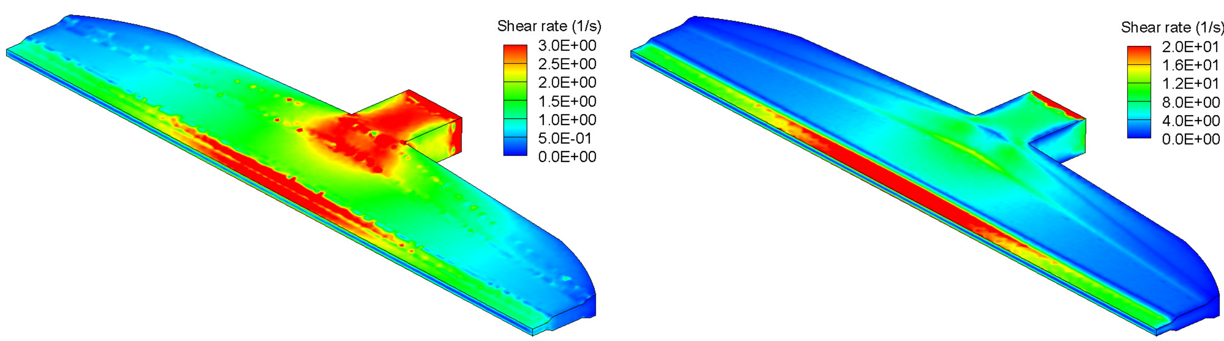
(a) (b)

Figure 5 Velocity distribution on the die walls (a) with slip on die-walls, (b) with no-slip condition on the walls.



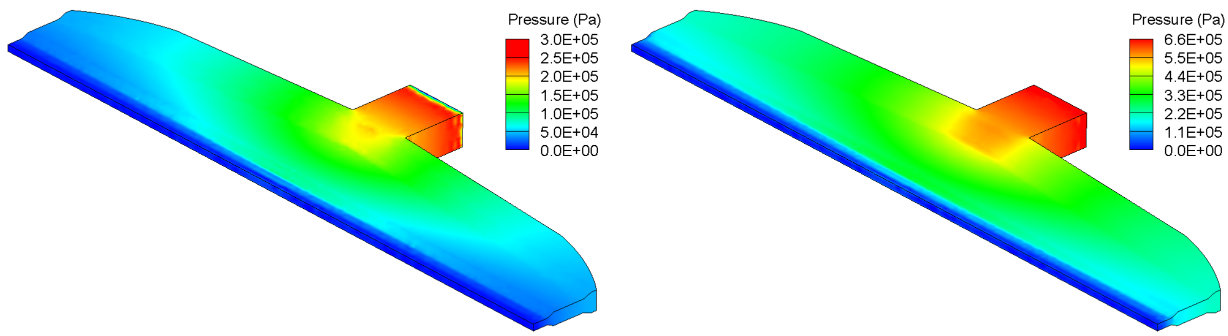
(a) (b)

Figure 6 Stress distribution on the die walls (a) with slip on die-walls, (b) with no-slip condition on the walls.



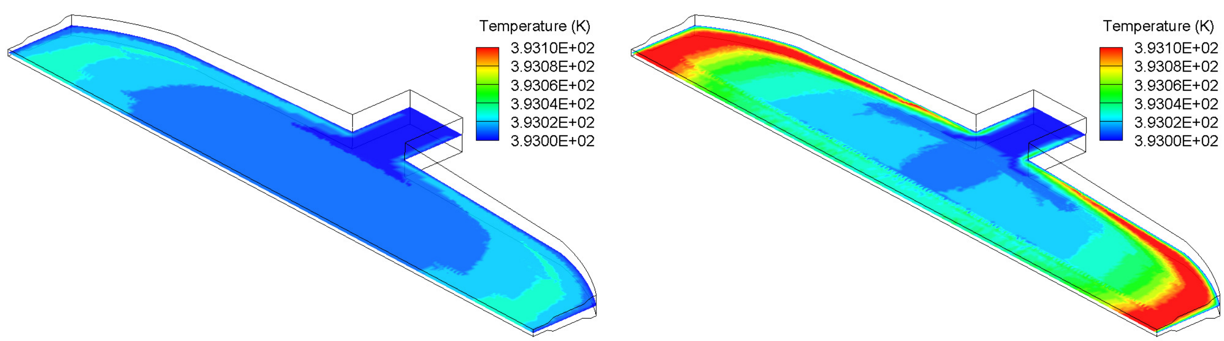
(a) (b)

Figure 7 Strain-rate distribution on the die walls (a) with slip on die-walls, (b) with no-slip condition on the walls.



(a) (b)

Figure 8 Pressure distribution in the flat die (a) with slip on die-walls, (b) with no-slip condition on the walls.



(a) (b)

Figure 9 Temperature distribution in the mid-plane of the die (a) with slip on die-walls, (b) with no-slip condition on the walls.