EFFECT OF ELONGATIONAL VISCOSITY ON THE FLOW IN A SPIRAL DIE

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Abstract

Three-dimensional flow of a low-density polyethylene in a spiral die for blown-film extrusion is simulated. Effect of elongational viscosity on the flow in the spiral die is analyzed. Elongational viscosity is found to have significant effect on the velocity distribution at the die exit and on the pressure and temperature distributions in the die.

Introduction

In the blown film process [1] for making thin plastic sheets (thickness less than 0.25 mm), a thin circular tube of plastic is extruded from a die. As the tube comes out of the die, it is inflated into a much larger diameter tube by the air blowing inside the tube. The increase in the tube diameter reduces the film thickness. A thickness reduction of as much as 25:1 or even larger can be obtained in a well-designed blown film process. Because of the larger thickness of the extruded tube (in comparison to the film thickness), not only the pressure required to push the molten plastic through the die is reduced, but the probability of encountering any instability due to viscoelastic nature of the polymer, is also smaller.

The main challenge in design of a die for blown film extrusion is to obtain a uniform velocity distribution along the circumference of the polymer tube at the die exit [2]. A variation in the tube thickness will result in a larger inflation of the thinner portion, further increasing the nonuniformity of the thickness variation. Therefore, a variation of $\pm$ 10% is often obtained in blown film thickness. To eliminate the velocity variation due to spider legs, which support the cylindrical mandrel in the annular die, spiral grooves are typically machined in the mandrel. The spiral grooves distribute the melt circumferentially to increase the uniformity of the velocity at the die exit.

Typical geometry of a spiral mandrel die is shown in Fig 1. The die has a primary distributive system, which consists of the channels for conveying the molten polymer from the die inlet to the beginning of the spiral grooves in the mandrel. The depth of the spiral grooves is large near the inlet and decreases gradually towards the outlet as the spirals wind around the cylindrical mandrel. In contrast, thickness of the annular gap between the outer cylindrical die body and the mandrel is small near the entrance and increases gradually towards the die exit.

Since the geometry of the flow channel in a spiral mandrel die is quite complex, an analysis of the flow in the die channel is important for a good die design. Earlier analyses of the flow in spiral mandrel dies involved separate one-dimensional or two-dimensional analyses of flows in spiral and slit regions of the die [3 – 7]. A full three-dimensional simulation of the flow in spiral mandrel dies is important for an accurate analysis of the flow in the die [2, 8]. Coyle and Perdikoulias [2], used a commercial flow simulation software for an isothermal simulation of the flow in a spiral mandrel die. Based upon the flow simulation for different thicknesses of the annular gap between outer cylindrical die body and the spiral mandrel, Coyle and Perdikoulias [2] concluded that an appropriate selection of the thickness of the annular gap is important. For a large annular gap they obtained only a limited circumferential distribution of the melt, whereas a much smaller annular gap resulted in excessive deformation rate and increase in pressure drop across the die. Skabrahova, Svabik and Perdikoulias [8] analyzed the effect of variation of flow rate at the inlet of the different spirals on the velocity and temperature distributions at the exit of the die. Only the flow starting from the entrance of the spirals was analyzed in reference [2, 8]. That is, the flow in the channels in the distribution system before the spirals was not included in the simulation.

In the present work, a three-dimensional simulation of the flow in a spiral mandrel die was performed using the PELDOM software [9]. Effect of the elongational viscosity of a low-density polyethylene on the flow in the spiral die is also analyzed.

Die Geometry

The finite element mesh used for the flow simulation is shown in Fig. 2. The die has six equally spaced spirals. The outer diameter of the annular die is 10.9 cm, whereas the mandrel diameter decreases from 10.7 cm near the inlet to 10.16 cm at the die exit. The radius of the six spiral channels is 0.635 cm. The depth of the spiral channels decreases linearly, starting at 2.1 cm at the beginning to 0 cm at the end. Each spiral winds around the mandrel for 360^o. The finite element mesh shown in Fig. 1 has 337,744 linear tetrahedral finite elements.

Material Properties

A low-density polyethylene (Dow 132i) was used in the present work to investigate the effect of elongational viscosity on the flow in a spiral die. To capture the strain-rate dependence of shear (η_s) and elongational (η_e) viscosities of the low-density polyethylene, Carreau model [10] and Sarkar-Gupta model [11], respectively, were used in this work:

$$\eta_s = \eta_0 (1 + (\lambda e_{II})^2)^{\frac{n-1}{2}} \quad (1)$$

$$\eta_e = \eta_0 \left[T_r + \delta \left\{ 1 - \frac{1}{\sqrt{1 + (\lambda_1 e_{II})^2}} \right\} \right] (1 + (\lambda_2 e_{II})^2)^{\frac{m-1}{2}} \quad (2)$$

where, e_{II}, the second invariant of the strain-rate tensor is the same as the shear rate, $\dot{\gamma}$, for a shear flow, and $\sqrt{3}\dot{\varepsilon}$ and $2\dot{\varepsilon}$, respectively, for axisymmetric and planar elongational flows, with $\dot{\varepsilon}$ being the elongation rate. In equations (1) and (2), η_0, δ, λ, λ_1, λ_2, n and m are material parameters, and T_r, the Trouton ratio at low strain rates, is 3 for an axisymmetric flow and 4 for a planar flow. An Arrhenius-type model [10] is used here for temperature dependence of the zero-shear viscosity (η_0), in Eqns (1) and (2):

$$\eta_0 = A \exp(T_a / T) \quad (3)$$

where T is the temperature of the polymer, and A and T_a are material parameters.

The thermal conductivity (K), density (ρ) and heat capacity (C_p) of the polymer were assumed to be constant for the range of temperature in the flat dies. Since the actual values of K, ρ and C_p for Dow 132i were not known, typical values of K, ρ and C_p for low-density polyethylene were used for the flow simulation. These values of K, ρ and C_p along with those of the various material parameters in the viscosity models are given in Table 1 [12, 13].

Results and Discussion

The material properties given in the last section were used in the present work to simulate the flow of Dow 132i in the spiral die shown in Fig. 2. At the die entrance a temperature of 503 K was specified whereas 473 K was enforced at die walls. A flow rate of 3.63×10^{-4} m^3/s was used for the flow simulation.

Fig. 3 shows the magnitude of velocity in the three planes passing through the centers of the six distributive channels, which convey the polymer from die inlet to the entry ports of the spiral channels. Fig 3 (a) shows the velocity distributions predicted by using the Carreau model with the generalized Newtonian formulation, whereas the velocity distribution predicted by the PELDOM software including the effect of elongational viscosity is shown in Fig. 3 (b). The predicted velocity distributions in Figs. 3 (a) and (b) are almost the same, indicating that elongational viscosity has little effect on the velocity distribution in the spiral die. As expected, in Figs. 3 (a) and (b) the velocity is the maximum near the entrance of the distributive channels because of the smallest cross-sectional area in this region. Since the area of cross-section is constant in the distributive channels, the magnitude of velocity remains the same throughout the distributive channels. Beyond the distributive channels, the flow slows down significantly as the flow area increases in the spiral portion of the die. The velocity distributions at the die exit predicted by the generalized Newtonian formulation and after including the effect of elongational viscosity are shown in Figs. 4 (a) and (b), respectively. The velocity at the exit is slightly higher at the positions along the circumference where the six spirals ends and lower in between. The predicted non-uniformity in the exit velocity is higher when the effect of elongational viscosity is included in the simulation.

Fig. 5 shows the effect of elongational viscosity on the pressure distribution in the spiral die. The pressure drop across the die predicted by the generalized Newtonian formulation (Fig. 5 a) is about 34% lower than the pressure drop predicted when the effect of elongational viscosity is included in the simulation (Fig 5 b). It is noted that the red color in Fig 5 (b) is limited to the region before the distributive channel, whereas in Fig. 5 (a) the color is red until the middle of the distributive channels. When the effect of elongational viscosity is included in the simulation, a large pressure drop is obtained near the entrance of the distributive channels. Because of the sharp change in the area of cross-section near the entrance of the distributive channels, flow in this region is highly elongation dominated. Therefore, a much higher pressure gradient is required to maintain the flow rate in this region if the effect of the high elongational viscosity of the polymer is included in the simulation.

Fig. 6 shows the temperature distributions in the three planes passing through the centers of the six distributive channels. The maximum temperature in Fig. 6 (b), which is obtained by including the effect of elongational viscosity on the simulation, is slightly higher than the temperature predicted by the generalized Newtonian formulation in Fig. 6 (a). It was noted in our earlier publication [13] that in elongation-dominated flows heat generation due to viscous dissipations depends on the elongational viscosity of the polymers. Accordingly, when the effect of the higher elongational viscosity of the polymer is included in the simulation, a larger amount of heat is generated due to viscous dissipation, resulting in the higher temperature in Fig. 6 (b). It is noted that the maximum temperature in the distribution channels in Figs.

6 (a) and (b) is not near the center of the channels, but near the walls. Formation of this hot layer due to higher viscous dissipations near the walls in channel flow has been reported earlier in the literature [10]. Besides the higher temperature in the distributive channels, in comparison to the temperature in Fig. 6 (a), the temperature in the spiral section and at the exit is also higher in Fig 6 (b). The higher exit temperature can significantly affect the bubble inflation and the final thickness of the film obtained by the blown film process.

Conclusions

Effect of elongational viscosity on the flow in a spiral die was analyzed. The predicted velocity distribution at the die exit and the pressure and temperature distributions in the die changed significantly when the effect of elongational viscosity was included in the simulation.

Acknowledgement

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Key Words: Spiral mandrel die, Elongational viscosity, Blown film extrusion, LDPE.

Table 1. Material properties of Dow132i [12, 13].

Thermal and mechanical properties		K	0.25 W/m K
		ρ	740 kg/m^3
		C_p	2300 J/kg K
Shear viscosity		A	469.08 Pa·s
		T_a	2721.7 K
		λ	0.6509
		n	0.401
Elongational viscosity	Planar	δ	37.3
		λ_1	11.795 s
		λ_2	0.4571 s
		m	0.45
	Axisymmetric	δ	0.0
		λ_2	0.02242 s
		m	0.349

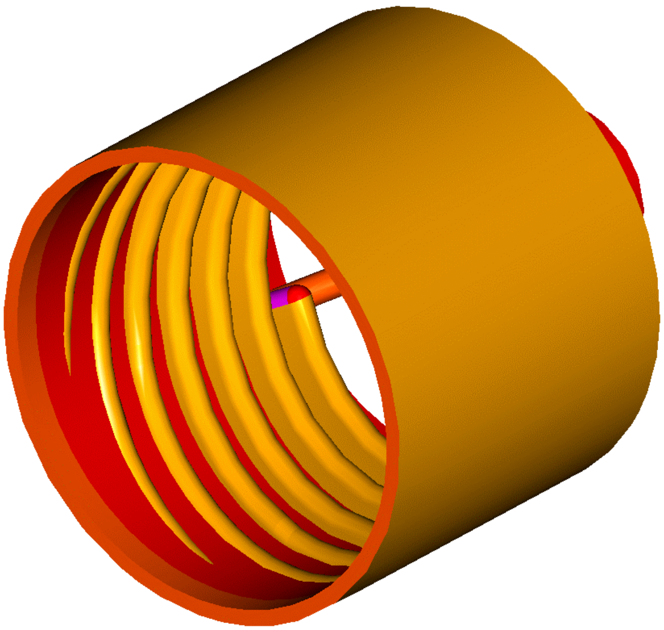


Fig. 1 Geometry of the spiral die.

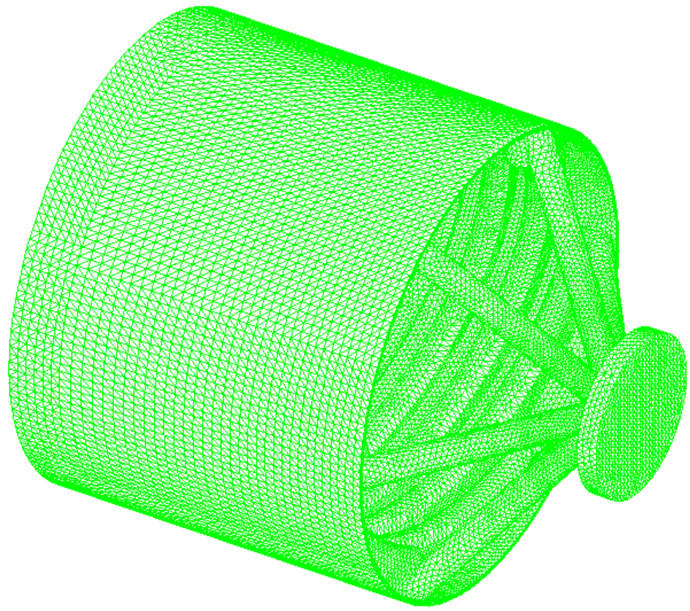


Fig. 2 Finite element mesh in the spiral die

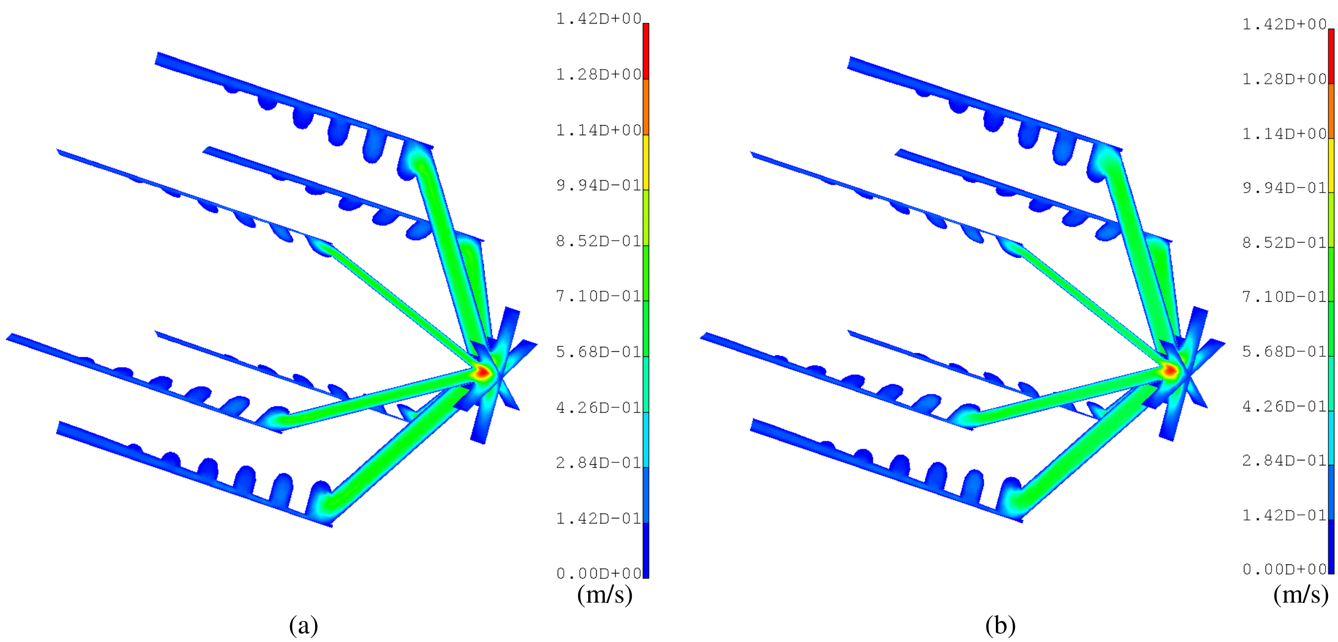
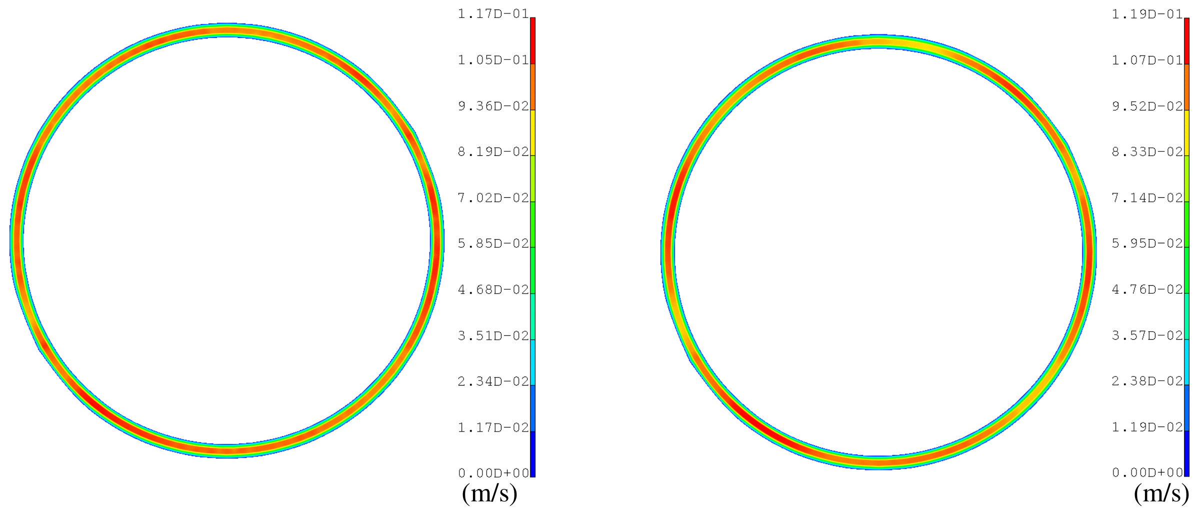
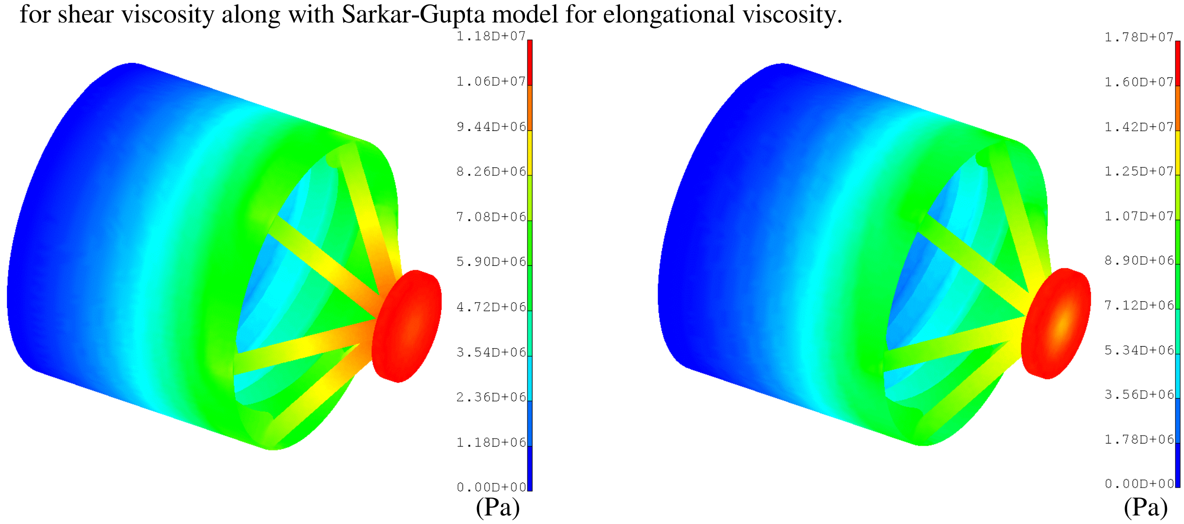


Fig. 3 Magnitude of velocity in the three planes passing through the centers of the six distributive channels of the spiral die. (a) Carreau model with generalized Newtonian formulation, (b) Carreau model for shear viscosity along with Sarkar-Gupta model for elongational viscosity.



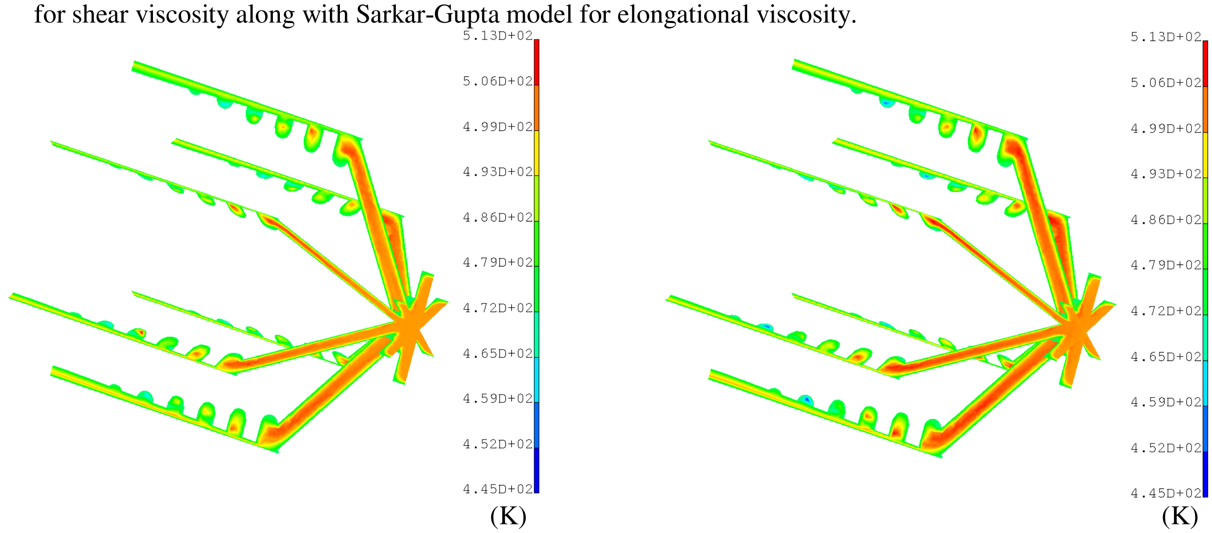
(a) (b)

Fig. 4 Velocity distribution at the die exit. (a) Carreau model with generalized Newtonian formulation, (b) Carreau model for shear viscosity along with Sarkar-Gupta model for elongational viscosity.



(a) (b)

Fig. 5 Pressure distribution in the spiral die. (a) Carreau model with generalized Newtonian formulation, (b) Carreau model for shear viscosity along with Sarkar-Gupta model for elongational viscosity.



(a) (b)

Fig. 6 Temperature distribution in the spiral die. (a) Carreau model with generalized Newtonian formulation, (b) Carreau model for shear viscosity along with Sarkar-Gupta model for elongational viscosity.