ELONGATIONAL FLOW IN MULTIPLE SCREW EXTRUDERS

J. E. Loukus and A. C. Halonen
GS Engineering
Houghton, MI 49931

M. Gupta
Plastic Flow, LLC
Houghton, MI 49931

Abstract

Flows of a low-density polyethylene in a co-rotating twin-screw extruder and in a twelve-screw ring extruder are compared. Effect of the shear as well as elongational viscosity of the low-density polyethylene is included in the simulation. Even though the velocity and pressure distributions in the two extruders have many similarities, because the intermeshing regions constitute a larger fraction of the ring extruder than that of the twin-screw extruder, the degree of elongation, and hence, the quality of mixing, is found to be better in the ring extruder.

Introduction

The screw extruder [1] is certainly the most important piece of equipment in the polymer processing industry. The most common application of a screw extruder is melting and pumping of molten polymer through a die. Single-screw extruders are particularly suitable for melting of polymers because the flow in single screw extruders is highly shear dominated. The large amount of heat generated by viscous dissipations in this shear flow provides a major portion of the heat required to melt the solid polymer. However, the large amount of heat generated due to viscous dissipations can cause thermal degradation of thermally sensitive material or the materials such as polyvinyl chloride, which have poor flow characteristics. Multi-screw extruders, which have positive displacement flow in the intermeshing region between the screws, are more suitable for processing of such materials. Another limitation of single screw extruders is their poor mixing characteristics. In general, shear-dominated flows, such as in a single screw extruder, provide only a limited mixing of the constituents. In contrast, elongational flows are known to provide much better dispersive mixing [2]. Therefore, for the polymer processing operations such as compounding, devolatilization, and chemical reaction which require extensive mixing of the constituents, multi-screw extruders are preferred over single screw extruders. The elongational nature of the flow in the intermeshing region of multi-screw extruders provides a much better mixing for such applications.

Twin screw extruders [3], which are the simplest multi-screw machines, are known to have much better mixing and thermal degradation characteristics than single screw extruders. However, a typical screw extruder has deep helical channels. The polymer in these deep channels of a twin screw extruder has a small surface area. In extruders with more than two screws, such as the ring extruder from Century Extruders [4] which has twelve co-rotating screws with shallow helical channels, thin layers of polymer are exposed to a large surface area. The large surface area is particularly important for applications which need devolatilization of solvents, or efficient heat exchange for accurate temperature control. Furthermore, since the intermeshing zones in a ring extruder constitute a larger fraction of the extruder than the similar zones in a twin screw extruder, a ring extruder is expected to have better mixing characteristics than a twin-screw extruder.

In the present work, the flow in a ring extruder is compared with the flow in a twin screw extruder. The PELDOM software [5] is used for the three-dimensional simulation of the flow in the two extruders. Effect of the shear-thinning behavior of polymer viscosity as well as that of the strain-rate dependence of the elongational viscosity of the polymer is included in the simulation.

Geometry of the Extruders

The twin-screw as well as the ring extruder used in this work has a double-flighted screw design. Various dimensions of the screws used in the two extruders are given in Table 1. The axial length of 60 mm and 30 mm, which is the same as the lead of the screws in the two extruders, was used for the flow simulation in the twin screw and the ring extruders respectively. For all of the flow simulations reported in this paper, the screws in the two extruders were rotated at 600 RPM.

Shear and Elongational Viscosity Models

Material properties for the low-density polyethylene (Dow 132i at 215ºC) were used in the present work to simulate the flow in the twin-screw and ring extruders. The Carreau model and the Sarkar-Gupta model were used for strain rate dependence of shear (η_s) and elongational (η_e) viscosities, respectively.

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

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

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 viscosities, with $\dot{\varepsilon}$ being the elongation rate. In equations (1) and (2), T_r, the Trouton ratio at low strain rates, is 3 for an axisymmetric flow and 4 for a planar flow, whereas η_0, δ, λ, λ_1, λ_2, n and m are material parameters. Values of these parameters for Dow 132i at 215°C are given in Table 2.

Results and Discussion

The finite element meshes used to simulate the flow in twin-screw and ring extruders are shown in Fig. 1. The finite element meshes in Fig. 1 (a) and (b) have 678,135 and 1,154,448 tetrahedral finite elements, respectively. These finite element meshes have only one element between the screw flight and barrel, and in some of the volume between the two screw flights. Therefore, some of the details such as the leakage flow between the barrel surface and the screw flight could not be captured in the results reported here. To capture these details, even larger number of finite elements will be required in the two meshes. All of the nodes on the screw surfaces in the twin-screw as well as the ring extruder were assigned a velocity of 600 RPM. The no-slip condition was enforced on the barrel surfaces, whereas the no-traction (stress free) condition was used at the entrance and exit of the extruder.

Fig. 2 shows the velocity distributions in the mid-sections of the two extruders. As expected, for both extruders, the velocity is the maximum at the screw tips. For the configuration of the two screws at the mid-section of the twin-screw extruder, the velocity is also quite high in the intermeshing region. For the configuration at other sections of the twin-screw extruder, the velocity in the intermeshing region may not be as high as in Fig. 2 (a). In the ring extruder, Fig. 2 (b), depending upon the configuration of the adjacent screws, velocity is quite high in some of the intermeshing regions and relatively low in the other regions. It is noted that the velocity distribution in Fig. 2 (b) is not only symmetric across the diagonal, but is also repeated after every third screw.

The axial velocity distributions in the mid-planes of the two extruders are shown in Figs. 3 (a) and (b). In both extruders, the axial component of the velocity is the maximum in the intermeshing regions. Again, the symmetry of the velocity distribution after every third screw of the ring extruder is evident in Fig. 3 (b).

Pressure distributions in the mid-plane of the two extruders and on the barrel surfaces are shown in Figs. 4 and 5, respectively. It should be noted that a logarithmic scale has been used for the coloring schemes in Figs. 4 and 5. For the twin-screw as well as the ring extruder, in Figs. 4 and 5, there is a sharp pressure drop across the screw flights. The pressure changes from a very high value near the leading edge to a very low value near the trailing edge of the flight. The pressure in Fig. 4 (b) is also symmetric after every third screw.

The degree of elongation in the mid-planes of the extruders is shown in Fig. 6. The degree of elongation is zero for a pure shear flow and one for a purely elongational flow. As expected, in Fig. 6, the highest degree of elongation is in the intermeshing regions of the two extruders. In the translational regions the flow is predominantly shearing in nature. The average degree of elongation for the twin-extruder used in this work is 0.127, whereas that for the ring extruder is 0.18. The predicted degree of elongation is 41% larger for the ring extruder because the intermeshing zones in the ring extruder constitute a larger fraction of its cross-section than the intermeshing zones in a twin-screw extruder. Since elongational flows are known to have much better mixing characteristics than shear flows [2, 7, 8], a ring extruder is expected to have better mixing capability than a twin-screw extruder. This hypothesis of better mixing in a ring extruder is also supported by the polymer samples obtained from the experiments with the two types of extruders.

Since the symmetry after every third screw is observed in the velocity as well as the pressure in the ring extruder, a logical extension of the current work is to exploit this symmetry in modeling and simulate the flow only in one periodic module of the extruder. Development of periodic boundary conditions that are realistic for such a modeling of the flow has proved to be very complicated. An attempt to simplify the ring extruder geometry using the periodicity mentioned above is in progress using the Fluent software [6].

Conclusions

Three-dimensional flow of a LDPE in a twin-screw extruder and a twelve-screw ring extruder was simulated including the effect of shear as well as elongational viscosity of the polymer. For all screw configurations, the velocity was the maximum at the screw tips. A large pressure drop was observed across screw flights of the two extruders, with the pressure being very high on the leading edge and very low on the trailing edge of the flights. The average degree of elongation in the ring extruder is found to be 41% larger than that in the twin-screw extruder, indicating a better quality of mixing in the ring extruder.

References

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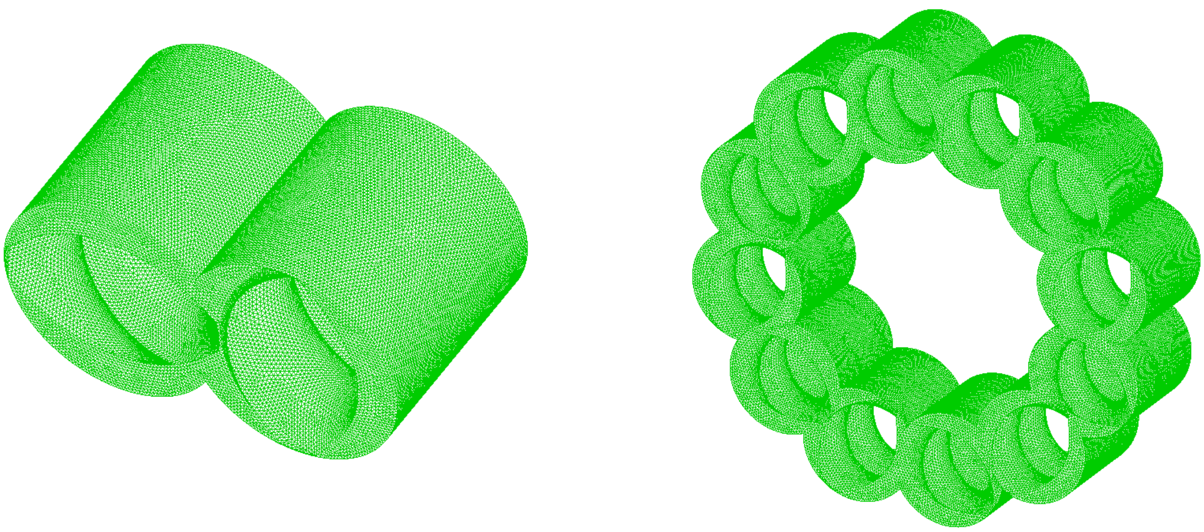
Key Words: Screw extrusion, Mixing, Elongational flow.

Table 1: Dimensions of the two screw extruders.

Twin-screw extruder	(mm)	Ring Extruder	(mm)
Barrel diameter	58.3	Barrel diameter	30.3
Screw tip diameter	57.8	Screw tip diameter	30.0
Screw root diameter	37.1	Screw root diameter	19.3
Centerline distance	48.0	Centerline distance between adjacent screws	25.0
Screw lead	60.0	Screw lead	30.0
		Centerline ring diameter	96.6

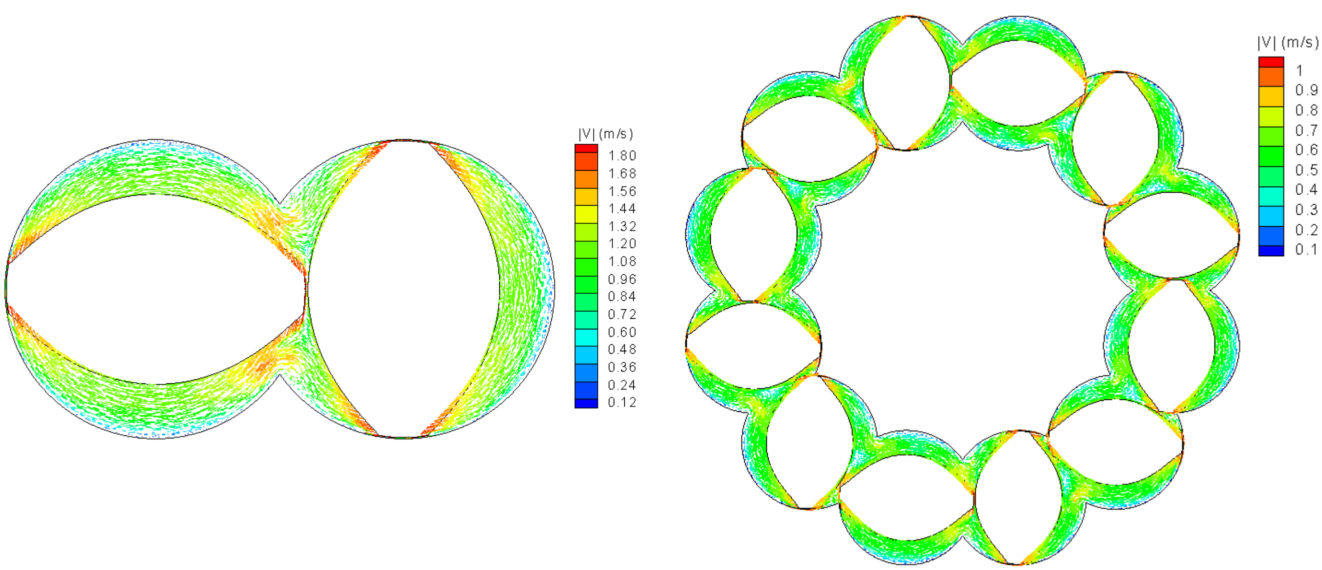
Table 2: Shear and elongational viscosity parameters.

Shear viscosity	η_0	1.24×10^5 Pa·s		
	λ	63.3 s	n	0.401
Elongational viscosity	Planar			
	δ	37.3	λ_1	2250.0 s
	λ_2	46.2 s	m	0.4
	Axisymmetric			
	δ	0.0	λ_2	2.18 s
	m	0.349		



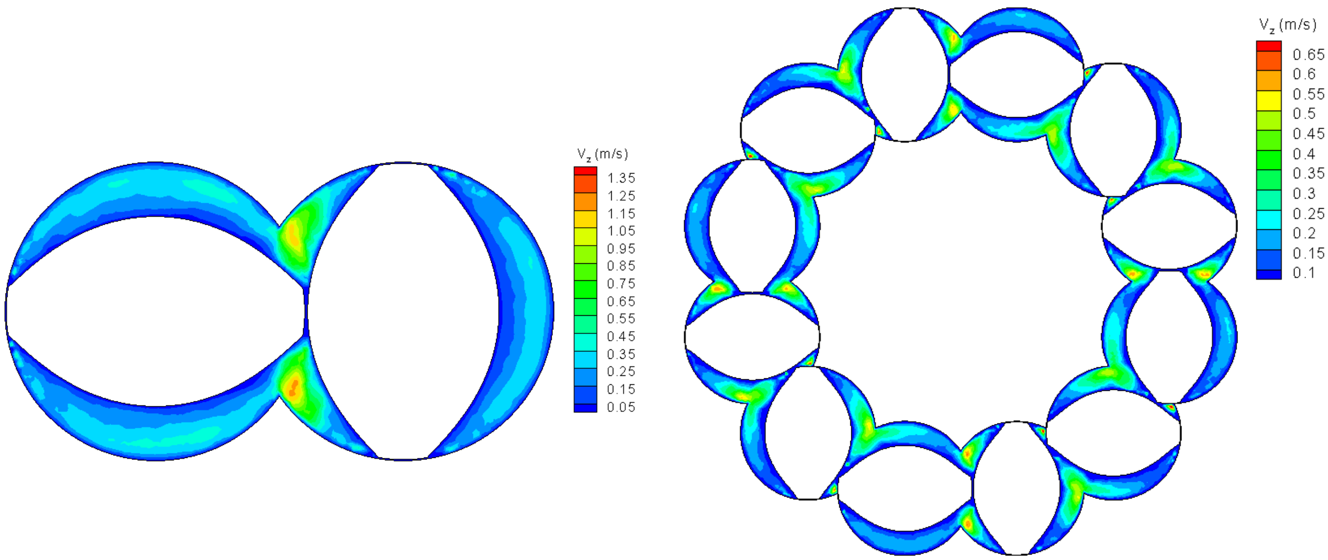
(a) (b)

Fig.1 Finite element meshes used for flow simulation is the twin-screw extruder (a), and ring extruder (b).



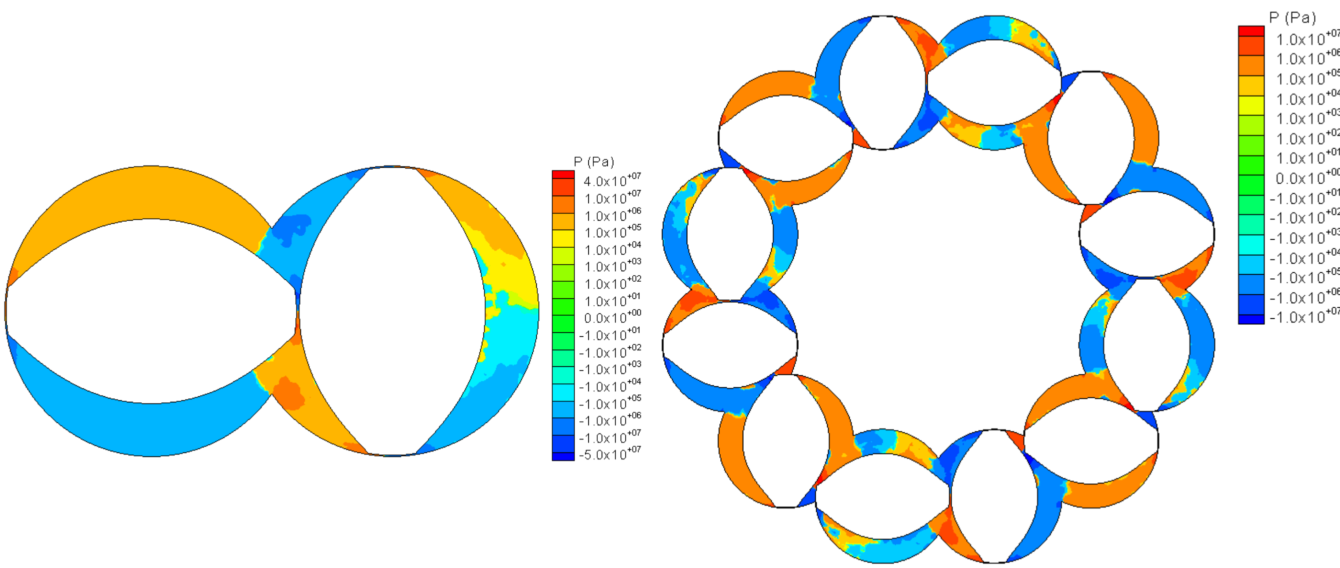
(a) (b)

Fig. 2 Velocity distributions in the mid-plane of the twin-screw extruder (a), and ring extruder (b).



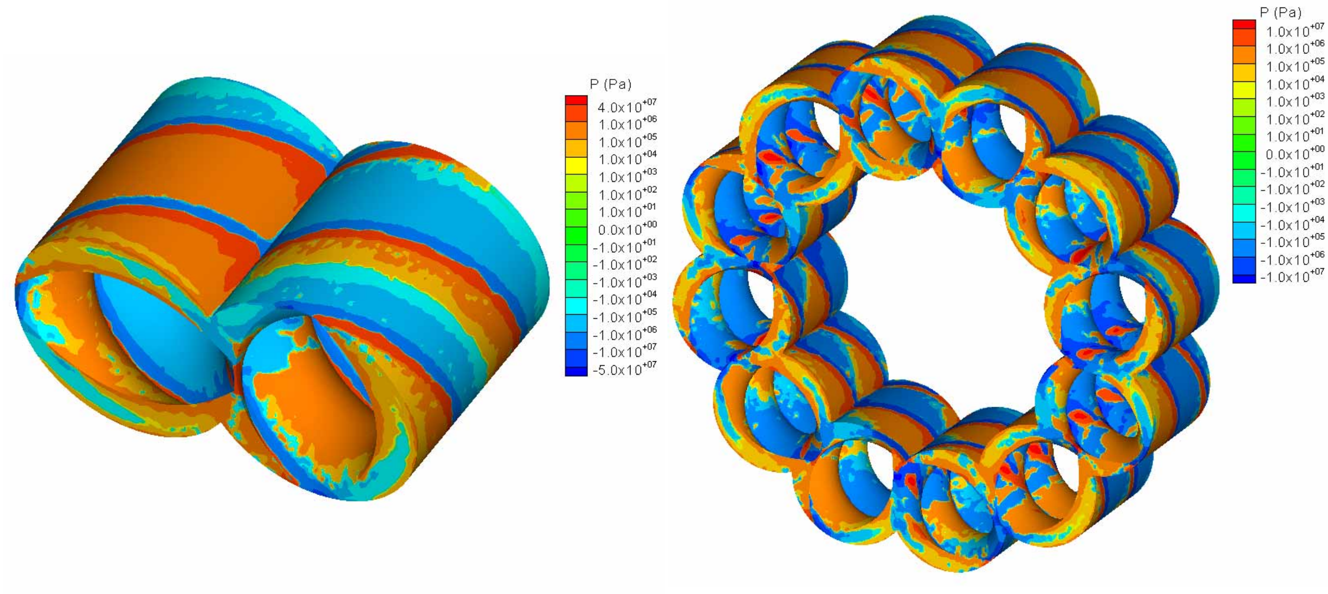
(a) (b)

Fig. 3 Axial velocity distributions in the mid-planes of the twin-screw extruder (a), and ring extruder (b).



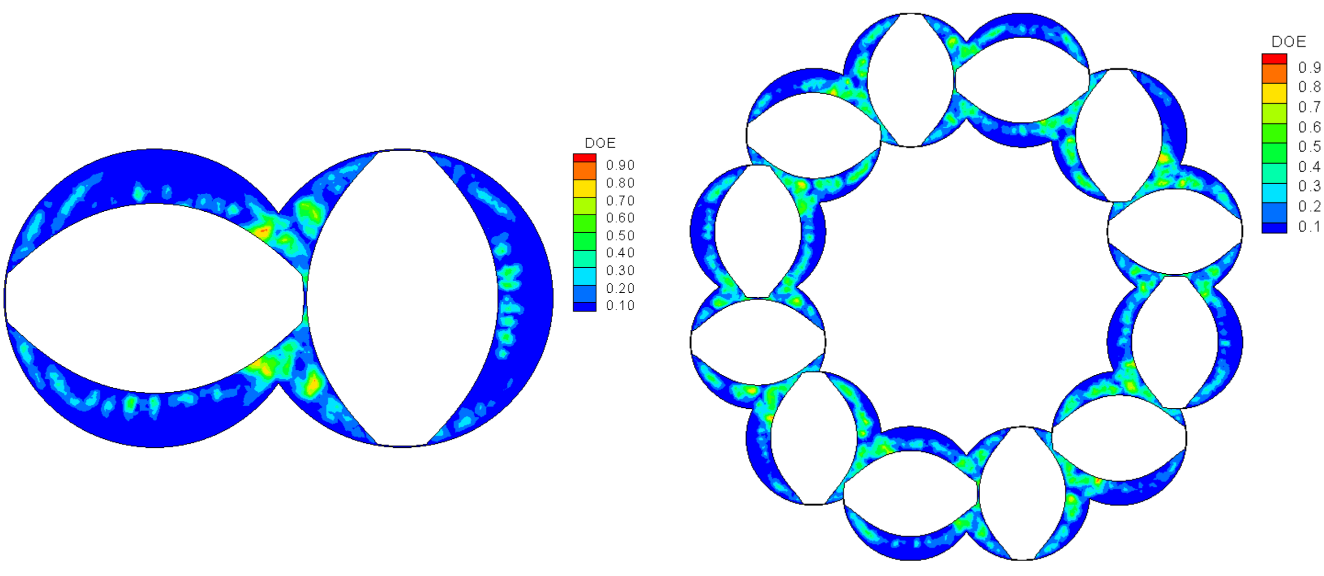
(a) (b)

Fig. 4 Pressure distributions in the mid-planes of the twin-screw extruder (a), and ring extruder (b).



(a) (b)

Fig. 5 Pressure distributions on the surface of the twin-screw extruder (a), and ring extruder (b).



(a) (b)

Fig. 6 Degree of elongation in the mid-planes of the twin-screw extruder (a), and ring extruder (b).