GROOVED FEED SINGLE SCREW EXTRUDERS - IMPROVING PRODUCTIVITY AND REDUCING VISCOUS HEATING EFFECTS

Bruce A. Davis*, Paul J. Gramann*, Maria Del P. Noriega E.**, and
Tim A. Osswald**

***Polymer Processing Research Group and Rheology Research Center*
Department of Mechanical Engineering
University of Wisconsin-Madison
Madison, Wisconsin 53706

**The Madison Group: PPRC*
Madison, WI 53711

ABSTRACT

Due to their high productivity, pressure invariance, and controlled throughput and melt temperature, groove feed systems are becoming widely accepted for the extrusion of pipes, blown films and blow molded articles. Within the research presented in this paper, a fully instrumented 45 mm extruder equipped with a grooved fed bushing was used to measure pressure distributions, screw and die characteristics, and melt temperature profiles. The screw geometry included decompression and compression zones, and Saxton distributive and Maillefer dispersive mixing heads. The screw and die characteristic curves show the high system productivity where throughputs comparable to 60 and 90 mm conventional extruders were measured. The high throughput induced a dramatic reduction in melt temperature measured at the tip. To better understand and confirm our experimental findings analytical models were used.

INTRODUCTION

In single screw extrusion we know that for an effective transport of solids in the feed section, the friction on the inner barrel surface must be larger than the friction on the screw surface. This was first demonstrated by Decker (1) as early as 1941, and later, in 1956, by Darnell and Moll (2) with a complete model that has been used and somewhat modified by several researchers in the polymer processing community.

The simplest mechanism for ensuring a high friction between the polymer and the barrel surface is grooving its surface in the axial direction. Today, extruders with a grooved feed section are called grooved feed extruders. Typically, the length of the grooved portion in a single screw extruder is only between 3D and 3.5D to avoid excessive pressures that would lead to barrel or screw failure. A schematic diagram of the grooved section in a single screw extruder is presented in Fig. 1. This concept was first introduced by Menges and his co-workers at the Institute for Plastics Processing (IKV) in Aachen (3), Fuchs (4) and extensively studied at BASF (5) after the introduction of their high molecular weight HDPE (6). These materials, which exhibit high viscosity and very low coefficients of friction, posed great processing problems such as excessive melt temperature and reduced productivity. This was, perhaps, the key factor that propelled the development and refinement of the grooved feed extruder. Menges and his co-workers continued their research efforts to study the grooved feed extruder (7-10), and helped propel industrial acceptance of the new concept throughout Europe (6). The abscence of these driving factors in the United States, slowed the introduction of the grooved feed extruders in the Americas.

Essentially, in a grooved feed extruder, the conveying and pressure build-up tasks are assigned to the feed section. The main advantages over conventional systems is that with grooved feed extruders not only the transport capabilities, reflected in higher productivity, were improved, but also the grooved feed systems showed higher melt flow stability and pressure invariance.

During the years that followed several advances were made in grooved feed extruder technology. Helical grooves were introduced in the 1970's by Langecker and co-workers (10) and modeled by Grünschloß (11). Later, Menges and co-workers (12) found that the energy efficiency of the grooved feed system can be increased considerably by raising the cooling water temperature from 5^{o}C to 70^{o}C. Many papers address the capabilities and applicability of grooved feed systems (13-16). In addition, numerous papers have been published regarding models and calculations that can be used to predict process performance or that explain phenomena typically observed in grooved feed systems (13,17-20).

Today, the grooved feed single screw extruder is widely accepted in Europe for high molecular weight polyolefin applications such as the extrusion of films, pipes and blow molded articles. Because of its high productivity and pressure invariance one can introduce dispersive and distributive mixing sections without compromising productivity and causing excessive temperature.

This paper introduces the reader to a modern grooved feed extrusion system using experimental results performed on a well instrumented 45 mm extruder with and without the grooved feed section. Simple models are used to explain common phenomena in grooved feed single screw extruders.

EXPERIMENTAL SET-UP

Several experiments were performed on a highly instrumented 45 mm diameter , single screw extruder with an L/D of 25. A smooth barrel extruder and an extruder with a grooved feed section were analyzed, Table 1 and 2. Each system has a screw appropriate for the barrel design. The systems had the same heating band temperatures at 180^{o}C from 5D to 10D, 190^{o}C from 10D to 14D, 200^{o}C from 14D to 18D and 220^{o}C from 18D to 25D. Four different die openings were used to simulate four different die restrictions, along with four different screw rotational speeds. The material used in all the trials was the low density polyethylene with properties shown in Table 3.

The conventional system was formed by a three zone plasticating screw with a compression ratio of 2.667 (8mm to 3mm), a pineapple distributive pre-mixer, a Maddock distributive mixer and a pineapple distributive mixer intended for temperature homogenization.

The grooved feed system was formed by a 3.5D grooved feed section, a decompression zone, a 1.75 compression ratio section (7mm to 4 mm), a Saxton distributive pre-mixer and a Maillefer dispersive mixing head with 4 pairs of channels.

The decompression zone is important to reduce torque requirement in grooved systems and avoid screw failure. The screw used in the conventional barrel is therefore inappropriate for grooved system.

EXTRUDER PRODUCTIVITY

Depending on the type of screw or barrel utilized in a single screw extruder, different pressure profiles build-up along the screw. A conventional (smooth barrel) single screw extruder generally has a steady rise in pressure along the screw until it reaches a pressure consuming section such as a mixing head. Figure 2 shows the pressure build-up along the screw for the extruder. The maximum pressure occurs near the end of the metering section. In a conventional single screw extruder with a smooth barrel the main task of the metering section is to build up the pressure for the subsequent mixing and pumping operations. The pressure rise in the solids conveying section is low; just enough for initial compaction of the material and to displace the solid bed in the down-channel direction. The dependence on the metering section to build-up the pressure for the pumping operation leads to screw characteristic curves (throughput vs. pressure curves) that are highly pressure dependent. Figure 3 presents the throughput as a function of die pressure for the smooth barrel extruder. The curves, which are typical of modern conventional single screw extruders, were generated for four different die openings or restrictions and four different screw rotational speeds.

Due to the high frictional forces in the grooved feed section, the maximal pressures are encountered at the end of the grooved section. Figure 4 presents the measured pressure profile along the screw for the grooved feed extruder with decompression used in our experiments. Also shown in this figure, is a typical pressure profile along a 45 mm diameter grooved feed single screw extruder without decompression (5). The high back-pressure generated in the solids conveying section leads to a pressure invariance in the screw characteristic curves. Here, due to the type of pressure transducers, we could only measure the pressure after the melt film formation in the decompression zone. However, we can assume the pressure to be as high as 1000 bar (15,000 psi) at the higher screw rotational speeds. This pressure is intentionally reduced in the decompression zone in order to avoid mechanical failure of the screw. However, the high back-pressure in the grooved feed section maintains the pressure invariance of the extruder's throughput; until the die restrictions lead to pressure requirements in the same order of the grooved feed section pressure. At that point the throughput versus pressure curves exhibit a dramatic drop. Figure 5 presents the throughput as a function of pressure for the grooved feed extruder from our experimental set-up.

The behavior of the two extruders is best compared with the throughput and the pressure build-up non-dimensionalized as

$$\hat{m} = \frac{m_k}{rND^3} \qquad (1)$$

and

$$\Delta\hat{p} = \frac{DpD}{hNL} = \frac{DpD}{mN^n L} \qquad (2)$$

where a characteristic viscosity of $h = mN^{n-1}$ was used. In eq (2), L represents the total length of the channel and for a 25 L/D extruder is 25D/sinϕ, where ϕ is 17.65^{o} (square pitch). Figure 6 presents the dimensionless results shown in Figs. 3 and 5, using eqs (1-2). The figure clearly shows the higher productivity of the grooved feed extruder where the throughput is more than 50% higher than observed with the conventional system for comparable applications. The same tendencies were observed when comparing 90mm diameter 30 L/D smooth and grooved extruders (21). With care, Fig.6 can also be used for scale-up and scale-down of the systems.

EXTRUDATE TEMPERATURE

As a result of the increased throughput, the effect of viscous dissipation is reduced significantly with a grooved feed system. Figure 7 presents temperature profiles measured with a thermocomb at the screw tip. On the left, temperatures profiles measured on our conventional extruder are shown for several rotational speeds. On the right, the temperature profiles for a comparable die restriction on a grooved feed extruder are shown for several rotational speeds. While in a conventional system the temperature rises 35^{o}C above the heater temperature, in the grooved system the temperature drops 15^{o}C for the same rotational speed. This phenomena can be explained with a simplified heat transfer model. We first define a characteristic time for thermal equilibrium of the polymer in the screw channel as

$$t_{cond} = \frac{h^2}{a} \qquad (3)$$

and an average residence time as

$$t_r = \frac{Vr}{m_k} \qquad (4)$$

where h is the channel depth in the metering section and V is the volume of the material contained within the screw. We can also define a dimensionless average temperature in the screw channel as

$$\bar{T} = \frac{T - T_{room}}{T_{heater} - T_{room}} \qquad (5)$$

which can be solved analytically as a function of the Fourier number (Fig.8) defined by

$$Fo = \frac{t_r}{t_{cond}} \qquad (6)$$

Since Fig.8 only includes conduction, one must add the effect of viscous dissipation. A simple way to estimate the average temperature rise inside the extruder is by using

$$\Delta\bar{T} = \frac{mv^{n+1}}{12kh^{n-1}} \qquad (7)$$

where v=pDN, and h is the channel depth in the metering section. Using eqs (3-7) we calculated the average extrudate temperature which is plotted against the average measured temperatures in Fig.9. Both calculation and measurement agree: a rise in temperature with increasing rotational speed when using a conventional extruder and a drop in temperature with a grooved feed extruder.

DISCUSSION

Most results shown here and found in the literature (mostly German) point to the advantages of the grooved feed extruder over the conventional machines: higher productivity and reduced viscous dissipation. Not all papers that have been written speak positively of the grooved feed systems (22). For example, the wear problem, which has been overcome throught the use of decompression zones, has been a key point in slowing the advancement of these systems in certain circles. However, as they have evolved, the grooved systems have proven to work well for all polyolefins and other materials such as polystyrene, ABS and SAN. The later ones require less intensive helical grooves with semi-circular cross-sections. In Europe, most polyolefins, and a large number of other thermoplastics are processed using grooved feed extruders. Grooved feed systems are not applicable for hard (undeformable) polycondensates such as polyesters and polyamides.

One disadvantage of the grooved barrel extruders is the high power requirements to drive the screw. Thus, larger driving systems are necessary for their operation which together with the grooved section increase the machine cost somewhat In the US, the argument is often used that for the same cost of the grooved system one can purchase a larger smooth barrel extruder to achieve the higher productivity.

CONCLUSIONS

For high molecular weight, high viscosity polymers with typically low coefficients of friction, a grooved feed extruder will not only result in a stable and predictable process, but it will significantly increase the productivity of the extruder. Depending on the restriction of the die, one may even double the mass throughput. Second, a grooved system significantly diminishes the effect of viscous dissipation in these high viscosity materials. Finally, the higher availability of pressure for pumping purposes allows one to use pressure consuming mixing heads for enhanced dispersive mixing.

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REFERENCES

1. H. Decker, *Die Spritzmaschine*, Paul Troester Maschinenfabrik, Hannover (1941).
2. W.H. Darnell and E.A.J. Moll, *SPE Journal*, (12),20, (1956).
3. K. Schneider, Ph.D. Thesis, IKV-Aachen, (1968).
4. G. Fuchs, *Plastverarbeiter*, (19), 765, (1968).
5. D. Boes, *Kunststoffe*, (60), 294, (1970).
6. D.A. Boes, Krämer, V. Lohrbächer, and A. Schneiders, *Kunststoffe*, (80), 3, (1990).
7. G. Menges, W. Predöhl, R. Hegele, U. Kosel, and W. Elbe, Plastverarbeiter, (20), 79, (1969).
8. G. Menges, W. Predöhl, R. Hegele, U. Kosel, and W. Elbe, Plastverarbeiter, (20), 188, (1969).
9. G. Menges, U. Kosel, R. Hegele, and W. Elbe, SPE ANTEC, 784, (1972).
10. E. Lagecker, G.R. Langecker and W. Fillman, Plastverarbeiter, (28), 531, (1977).
11. E. Grünschloß, SPE ANTEC, 160, (1979).
12. G. Menges, W. Feistkorn, G. Fischbach, Kunststoffe, (74), 695, (1984).
13. H. Helmy, SPE ANTEC, 146, (1983).
14. A. Krämer,, Kunststoffe, (78), 21, (1988).
15. W. Löw, and H.-O. Schiedrum, Kunststoffe, (79), 34, (1989).
16. W.W. Bode, SPE ANTEC, 153, (1991).
17. R. Rautenbach, and H. Peiffer, Kunststoffe, (72), 136, (1982).
18. E. Grünschloß, Kunststoffe, (74), 405, (1984).
19. H. Potente, Kunststoffe, (78), 355, (1988).
20. E. Grünschloß, Kunststoffe, (83), 309, (1993).
21. F. Pöhler, Reifenhäuser GmbH, Germany, Personal communication, (1997).
22. E.L. Steward, SPE ANTEC, 75, (1989).

Table 1. Conventional Extruder Used

Diameter	45 mm
Length / Diameter (L/D)	25
Feed Throat	Smooth
Feed Zone	7 L/D
Plasticating Zone	12 L/D
Premixing	2 L/D
Dispersion Mixing	2 L/D
Distributive Mixing	2 L/D

Table 2. Grooved Feed Extruder Used

Diameter	45 mm
Length / Diameter (L/D)	25
Feed Throat	8 grooves
	3.5 L/D
rectangular	
Feed Zone	5 (L/D)
Plasticating Zone	12 (L/D)
Premixing	2 (L/D)
Dispersion Mixing	4 (L/D)

Table 3. Properties of LDPE used

Thermal Data	
Density, ρ	920 Kg/m^3
Heat capacity, C_p	3 kJ/kgK
Thermal conductivity, k	0.33 W/m/K
Thermal diffusivity, α	1.56×10^{-7} m^2/s
Viscosity Data at 200^{o}C(Power-law model)	
Consistency index, m	18,620 $Pa\text{-}s^n$
Power-law index, n	0.33

FIGURE CAPTIONS

Figure 1. Schematic of a grooved feed section.

Figure 2. Conventional extruder pressure distribution.

Figure 3. Conventional extruder screw characteristic.

Figure 4. Grooved feed extruder pressure distribution.

Figure 5. Grooved feed extruder screw characteristic.

Figure 6. Dimensionless screw characteristic curves.

Figure 7. Temperature fields at the tip of the screw.

Figure 8. Temperature as a function of Fourier number.

Figure 9. Melt temperature as a function of screw speed.

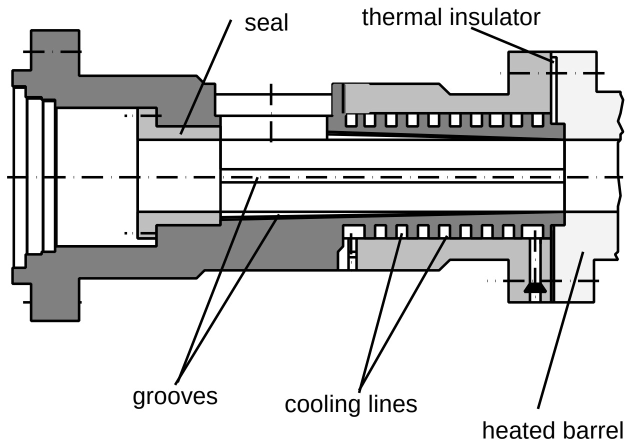

Figure 1 - Osswald