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Experimental analysis of the influence of pellet shape on single screw extrusion

Manuel Längauer,[1] Keyan Liu,[1] Christian Kneidinger,[1] Gernot Schaffler,[2] Bianca Purgleitner,[2] Gernot Zitzenbacher[1]

[1]University of Applied Sciences Upper Austria, School of Engineering and Environmental Sciences, Stelzhamerstraße 23, 4600 Wels, Austria

[2]Transfercenter fuer Kunststofftechnik GmbH, Franz-Fritsch-Straße 11, 4600 Wels, Austria

Correspondence to: M. Längauer (E-mail: manuel.laengauer@fh-wels.at)

ABSTRACT: Extrusion technology is one of the most prominent methods for processing polymers. The shape of polymer pellets plays an important role in conveying solid material through the extruder and thus directly influences the mass flow rate. In the course of this article, the influence of the pellet shape of a polypropylene homopolymer on the processing conditions using a smooth barrel single-screw extruder is evaluated. Especially the mass flow rate, the melt temperature, and the pressure build up in the barrel are investigated. It can be shown that processing long cylindrical pellets leads to a higher mass flow rate than comparable experiments with virgin pellets or short cylinders. Additionally, screw cool and pull-out tests, measurements of the external coefficient of friction as well as the bulk density of the different pellet geometries are performed. The interaction of the screw geometry and the pellet shape is found to have the biggest influence. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2015**, *132*, 41716.

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INTRODUCTION

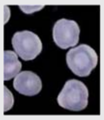
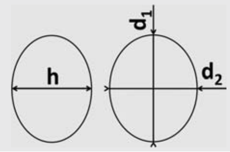
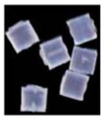
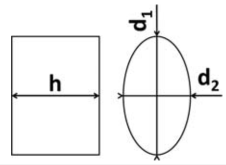
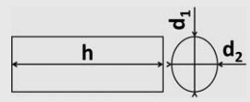
Extrusion technology is one of the most important methods for processing polymers with prominent products as films, sheets, pipes, and profiles manufactured by its means. The screw is used to convey, compress, melt, pump, and homogenize bulk polymer materials that are fed to the extruder mainly in pellet or powder shape. Polypropylene is mostly used in pellet form, including processes on small-scale machines. Powder shaped bulk materials are most common in polyvinylchloride processing. A typical single screw extruder is composed of different functional zones: the hopper zone, the solids conveying zone, the delay zone, the melting zone, and the metering zone. The barrel in the feeding section can be either smooth or grooved, depending on the application and requirements of the finished product.

Many authors published or reworked models to describe solids conveying.[1–5] Common simplifications and assumptions include that the channel of the screw is fully filled and the bulk polymer materials form a plug in the solids conveying zone, responding as one large unit rather than multiple small ones.[6] Pressure anisotropy coefficients are often used to demonstrate anisotropic pressure propagation. External coefficients of friction are introduced to describe the friction between the polymeric material and the screw and the barrel's surface.

In grooved feeding zones the internal coefficient of friction also plays a role, as it describes the friction that occurs between the pellets in the grooves and those in the screw channel.[7,8] The models conclude that there is a higher possible output with a higher ratio between the external coefficients of friction of the pellets on the barrel and the screw surface. More recent works deal with discrete polymer pellets using the discrete element method.[9–12]

It is well known from extrusion experience that the shape and the dimensions of the pellets influence the conveying behavior and the mass flow rate of single screw extruders. In literature, only few studies investigate friction of polymer pellets.[13–21] Gamache investigated the frictional behavior of bulk materials in a shearing cell with an annular gap.[16] He considered the shape of the pellets but found only a minor influence on the external coefficient of friction. Campbell and Spalding concluded that the pellet shape does not play a role in pressure build-up and output when doing experiments with spherical and cylindrical high-impact polystyrene on a 63.5 mm diameter extruder. They argue that the particles lose their characteristic shape when compacted into a solid bed.[21] Sikora reported, that the length of polyvinylchloride pellets plays a vital role in small-scale single screw extrusion and that the effects are screw speed dependent.[22]

Table I. Different Shapes and Dimensions of the Used Polypropylene Pellets

	Pellet shape	d_1 [mm]	d_2 [mm]	h [mm]	Measured dimensions
	Virgin	4.3 ± 0.4	3.5 ± 0.5	3.2 ± 0.9	
	Short cylinders	4.6 ± 0.1	2.6 ± 0.2	3.4 ± 0.1	
	Long cylinders	2.3 ± 0.3	1.9 ± 0.3	6.3 ± 0.2	

d_1, d_2: maximum and minimum diameter of the cross-section; h: length of the expansion or cutting.

This article depicts an experimental study to investigate the influence of the shape and the dimensions of polypropylene pellets on the output and the processing conditions of a single screw extruder. The experimental work is done using spheroidal shaped virgin pellets and two different cylindrical pellet geometries (long and short cylinders) and a laboratory-single screw extruder with a screw diameter of 20 mm and an L/D ratio of 25. The mass flow of the extruder is determined when processing different pellets under the same set of conditions (die gap height, screw speed, and barrel temperature profile). Furthermore, the pressure and the temperature behavior are recorded on three different positions along the barrel wall.

Additional tests include differential scanning calorimetry (DSC) for estimating a possible degradation of the polypropylene as a result of the compounding step that was used to produce the cylindrical pellets and measurements of the apparent density of the bulk material according to EN ISO 60. The apparent bulk density is considered an important indicator of the flowability of solids. As previously mentioned, the mass flow rate in the solids conveying zone is assumed to be directly influenced by the external coefficient of friction. For this reason, it is measured for all three different pellet shapes on a previously developed screw tribometer using a polished metal shaft as the frictional partner.[23]

The results of the investigations show that, due to a larger possible contact area, long cylindrical pellets exhibit a higher external coefficient of friction, when pressed onto a rotating steel shaft. This and the interaction between the pellets dimensions and the screws geometry directly influence the mass flow rate of the extruder, which is in fact higher for this pellet shape than it is for virgin or short cylindrical pellets.

EXPERIMENTAL

Polymeric Material

The used polymeric material was a polypropylene homopolymer type HD120MO from Borealis, Linz, Austria. Its main properties are a density of 908 kg/m^3, an MFR value of 8 g/10 min at 230°C and a load of 2.16 kg and a tensile modulus of 1500 Pa (1 mm/min).

Preparation of the Used Polypropylene Pellets

In addition to the virgin polypropylene, cylindrical pellet shapes were produced using a co-rotating twin screw extruder type Thermo prism TSE 24 HC ($D = 24$ mm; $L/D = 28$) with a strand pelletizer. The barrel temperature profile was set to 40, 180, 190, 190, 200, 200, 200°C and a nozzle temperature of 210°C was chosen. The screw speed was 400 min^{-1} with a torque of 37 Nm.

To minimize the possibility of thermal damage, the mass temperature is deliberately kept low at 210°C. The different pellet geometries diverge in their dimensions as Table I shows. Next to the dimension of the cross section (d_1, d_2) the length of the pellets (h) is measured.

Differential Scanning Calorimetry

To estimate a possible degradation of the polypropylene caused by the compounding step that was needed to create the different pellet shapes, a DSC test is carried out using a Mettler DSC 30. The samples are heated, cooled and reheated during the experiments. Isothermic phases of 5 min are chosen between the heating and cooling steps. The tests are carried out between 60 and 200°C, with a heating rate of 10°C/min, a cooling rate of 20°C/min and sample masses of approximately 6 mg.

Extrusion Experiments

The influence of the shape of the polypropylene pellets on the mass flow rate is studied using a Dr. Collin E20M single screw extruder with a smooth feeding zone. The geometry data of the 20 mm diameter three-section-screw are shown in Table II.

A slit die with a width of 50 mm and a variable height of 0.2 to 2 mm is used to adjust the screw counter pressure. The chosen die gap heights are 0.25, 0.50, and 0.75 mm. Two different temperature profiles (shown in Table III) and three different screw

Table II. Geometry Data of the Used Three Section Screw Including the Zone Lengths, the Resulting Compression, and the Compression Ratio

Screw dimensions [mm]		Dimensions	
D	20	L1 (Solids conveying zone)	8 D
h_1	4.0	L2 (Compression zone)	6 D
h_2	1.1	L3 (Metering zone)	11 D
Axial flight width	2.5	Pitch	1 D
Channel radius pushing flight	1.0	Compression	3.08
Channel radius trailing flight	2.5	Compression ratio	3.64

D is the screw diameter, h_1 the channel depth in the solids conveying zone, and h_2 the channel depth in the metering zone.

speed settings (60, 120, and 180 min^{-1}) were used for the extrusion experiments. The feed opening is water-cooled.

The output was studied using thin sheets produced on a Dr. Collin CR 136/350 chill-roll unit. In addition, the conditions within the barrel during the extrusion process were recorded using three thermocouples and three pressure transducers that are allocated along the barrel at 8 D, 16 D, and 24 D effective axial screw length measured from the front edge of the hopper.

Moreover, screw cooling and pull out experiments were carried out to show the melting differences and the processing behaviour using different pellet geometries. The chosen parameters for those observations were temperature profile T2, screw speeds of 30 and 120 min^{-1} and a nozzle height of 0.25 mm. The different pellet shapes are processed for 20 min at those conditions. Then the drive is switched off and the barrel is cooled to 140°C with the aid of integrated cooling fans. When the temperature is reached, the die is disconnected and the screw is pulled out.

Tribological Tests

A previously developed Tribometer (Figure 1) is used for the tribological experiments.[23] The bulk polymer solids are filled into the sample chamber and pneumatically pressed onto a rotating shaft using a piston. The normal force is predefined and the frictional force is measured from which the external coefficient of friction can be calculated. The chosen shaft is hardened and polished screw steel (1.4523) with a measured surface roughness of 0.06 µm (in longitudinal and circumferential direction). The shaft has an inner diameter of 80 mm, an outer diameter of 100 mm, a length of 143 mm, and a hardness of 58 HRC.

To simulate extruding conditions, a large (9 cm^2 cross-sectional area) and a small sample chamber (1 cm^2 cross-sectional area) are used. As a result, an apparent pressure from 8 to 20 bar with the large sample chamber and an apparent pressure from 50 to 200 bar with the small sample chamber can be achieved. The circumferential velocity is varied between 0.1 and 1.2 m/s. The measurements are performed at room temperature. The external coefficient of friction is then averaged over a measuring duration of four revolutions excluding the acceleration phase of the rotating shaft. This test relates well to extrusion conditions as a curved metal surface is used, comparable speeds and pressures are applied and the frictional distance is rather short.

Table III. Used Temperature Profiles for the Processing of Polypropylene

Temperature profile	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
T1 [°C]	20	195	215	230	230	230
T2 [°C]	20	210	230	250	250	250

Zone 5 symbolizes the die adapter, zone 6 the die.

A contact mechanics model is used to estimate the contact area between the polymer pellets and the shaft under the applied load. The simplest contact model is the Hertzian surface pressure. It is based on non-adhesive contact. Even though it only delivers approximations, it is widely used due to its simplicity. Two elastic bodies with a curved surface are pressed onto each other, which ideally causes a dot-like or linear contact. In reality a flattening of the elastic bodies happens to create a contact area. This area exhibits a characteristic tension distribution with its peak in the center. In case of a sphere and a plane pressed together, the projection of the contact area is a circle with its pressure dependent contact radius a as shown in (1):

$$a=\sqrt[3]{\frac{3}{4}(1-\nu_1^2)F\frac{\left(\frac{1}{E_1}+\frac{1}{E_2}\right)}{\left(\frac{1}{r_1}\right)}} \quad (1)$$

where ν is the Poisson ratio, F the contact force, $E_{1,2}$ are the moduli of elasticity of the sphere and the plane, and r_1 is the radius of the sphere.

The maximum pressure on the contact area p_{max} is show in (2):

$$p_{max}=\sqrt[3]{\frac{6F\left(\frac{1}{r_1}\right)^2}{\pi^3(1-\nu_1^2)^2\left(\frac{1}{E_1}+\frac{1}{E_2}\right)^2}} \quad (2)$$

In case one deals with cylinders instead of spheres the maximum pressure can be determined by (3):

$$p_{max}=\sqrt{\frac{F\left(\frac{1}{r_1}\right)}{\pi(1-\nu_1^2)\left(\frac{1}{E_1}+\frac{1}{E_2}\right)l}} \quad (3)$$

with l being the length of the cylinder.[24]

Table IV contains the values used for the calculation of the contact mechanics of a pellet monolayer. Several assumptions are made to simplify the calculation. Those include that the force is distributed

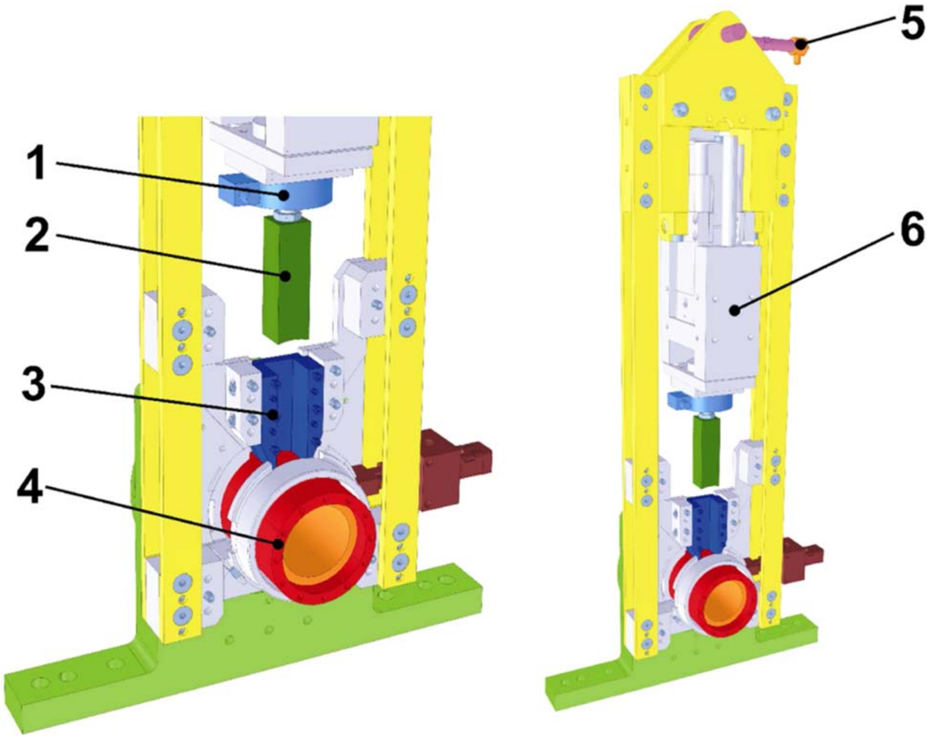


Figure 1. Detailed view of the used tribometer. Load cell: normal force (1), piston (2), sample chamber (3), shaft (4), load cell: frictional force (5), pneumatic cylinder (6). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

evenly over the single pellets and that the dimensions of every pellet match the mean length and radius.

Because of the fact that the work is done with different sample chambers and pellet geometries, the pellet count for each shape during the measurement is different as depicted in Table V.

Measurement of the Apparent Bulk Density

The apparent density of the polymeric material is considered an important factor for the feeding behaviour of the extruder.[6] It is measured according to EN ISO 60 using a standardized apparatus.

RESULTS

Influence of the Shape and the Dimensions of the Polypropylene Pellets on the DSC-Plot

Although the cylindrical pellets had an additional compounding step compared to the virgin material, the DSC-plot shows almost no deviations (Figure 2). The small divergences can be explained by different sample masses and slight differences in the contact area of the samples. The cooling and the reheating phase also delivered similar results for all the pellet shapes (data not shown).

Influence of the Shape and the Dimensions of the Polypropylene Pellets on the Extruder Output and the Extrusion Conditions

Figure 3 shows the extruder output characteristics using the virgin and the long cylindrical polypropylene pellets for different screw speeds and the temperature profile T1. When processing the long cylindrical polypropylene pellets, the measured screw characteristic exhibits a significant higher mass flow rate compared to the virgin material in all cases. This accounts to up to 29.6% at a die gap of 0.5 mm and a screw speed of 60 min^{-1}. Due to a very high pressure build-up when processing the long cylindrical pellets, the values for a nozzle height of 0.25 mm

Table IV. Values Needed for the Calculation of the Hertzian Surface Pressure for the Different Pellet Shapes

Property	Symbol	Value
Tensile modulus polymer	E_1	1,500 MPa
Tensile modulus steel shaft	E_2	223,000 MPa
Poisson's ratio polymer	v_1	0.425
Poisson's ratio steel shaft	v_2	0.280
Mean radius (sphere)	r_1	2.15 mm
Mean radius (cylinder)	r_2	2.30 mm (Short cylinders) 1.15 mm (Long cylinders)
Mean length (cylinder)	l	3.40 mm (Short cylinders) 6.30 mm (Long cylinders)

Table V. Number of Pellets in the Monolayer for the Tribological Tests

Sample chamber	Used for	Pellet count: Virgin	Pellet count: Short cylinders	Pellet count: Long cylinders
Large	8, 20 bar test	60	44	46
Small	50, 100 bar test	5	4	5

could not be obtained. One can observe the high pressure that is occurring with the long cylindrical pellets in Figure 4. It is notable, that at the axial positions 8 and 16 D the pressure is lower for higher screw speeds when working with the long cylinders. The corresponding melt temperature distributions are depicted in Figure 5. It can be observed that the melt temperature at the axial position 8 D is always lower for the long cylindrical pellets than for the virgin ones (Figure 5). Depending on the screw speed, the pressure at the same position for the long cylinders is between 130 and 200 bar higher than for the virgin pellets.

Figure 6 shows the extruder output characteristics using the virgin, the short and the long cylindrical polypropylene pellets for different screw speeds and the temperature profile T2. All experiments are feasible due to a lower pressure distribution at higher temperature. The higher mass flow rate when processing the long cylindrical pellets can also be seen for temperature profile T2. The highest increase of 33% is noted at a screw speed of 60 min^{-1} and a die gap of 0.25 mm. Furthermore, the measured mass flow rate when processing the short cylindrical pellets lies between the virgin and the long cylindrical pellets. Moreover, a very high melt pressure at the screw tip is encountered when working with the short cylinders.

The melt pressure along the screw is significantly higher at the beginning of the compression zone (8 D) and at the beginning of the metering zone (16 D) using the long cylindrical polypropylene pellets. This is shown in Figure 7 by a typical example. The high pressure also has a crucial influence on the extruder output, especially at lower screw speeds. Nonetheless, the lowest melt temperature at the beginning of the compression zone is recorded when processing the long cylindrical pellets. The virgin pellets and the short cylinders exhibit a higher melt temperature at that stage in all the experiments. One typical example is shown in Figure 8. It appears that a low melt temperature in early stages is an indication for a higher output.

One can also compare the specific output for the processing of the three pellet types (Figure 9). There is an obvious correlation between screw speed and the specific output as the latter is reduced with rising screw speed in every experiment. The most significant decrease can be seen for the long cylindrical pellets and a nozzle height of 0.25 mm. In this case, the decline accounts to as much as 20% as the screw accelerates from 60 to 180 rotations per minute. Nonetheless, the specific output after this drop is still higher than for the experiments with the other pellet geometries.

Moreover, it can be observed, that the long cylindrical materials specific output is not that dependent on the nozzle height as for the other pellet geometries. The virgin pellets exhibit a higher specific output with increasing die gap. This is also true for every experiment at a screw speed of 180 min^{-1}.

Screw Cool-Down and Pull-Out Tests

Figure 10 shows the results of the screw cool-down and pull-out tests. An addition of 1% blue coloured masterbatch shall point out differences in the melting and the conveying behaviour of the different pellet shapes. Note that the axial position values for these experiments are measured from the beginning of the screw channel, not from the front edge of the hopper as in the melt temperature and pressure development graphs.

Figure 10(a) shows the result of the screw pull-out test when processing the virgin material. At an axial position of 5 D (10 cm), the material is highly compressed, thus it is not falling out of the screw channel as the filled screw is pulled out of the barrel. After this point, melting commences at a fast pace and at an axial position of 7 D, the channel is filled with melt only.

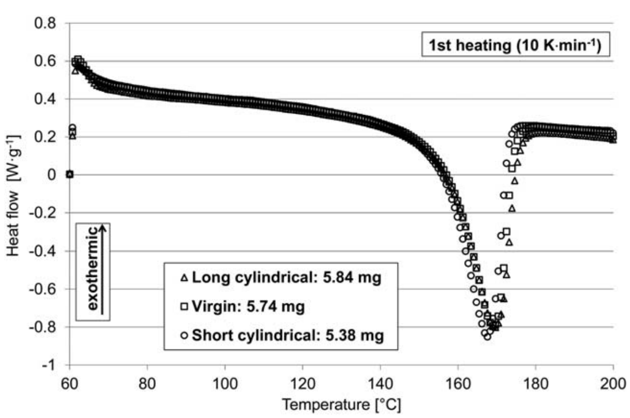


Figure 2. DSC-thermogram for different polypropylene pellet geometries dependent on the sample temperature.

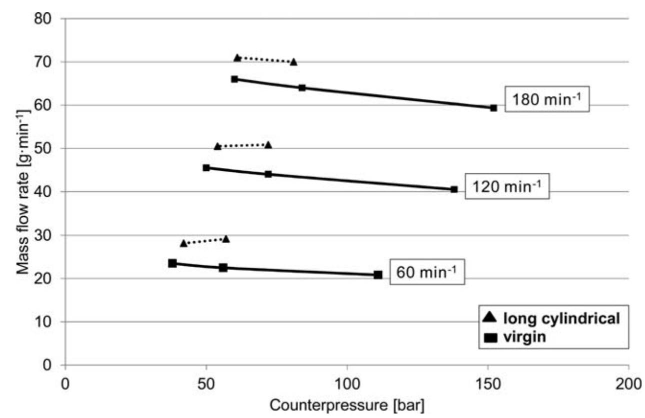


Figure 3. Screw characteristics for virgin pellets and long cylindrical polypropylene pellets processed at temperature profile T1 and a screw speed of 60, 120, and 180 min^{-1}.

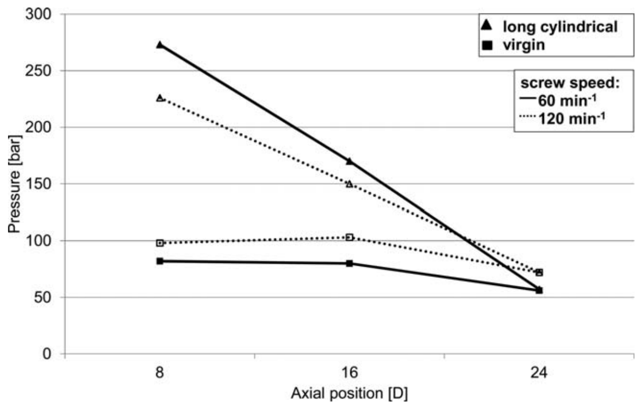


Figure 4. Recorded pressure along the barrel at three positions while processing virgin and long cylindrical polypropylene pellets at temperature profile T1, a screw speed of 60 and 120 min^{-1}, and a nozzle height of 0.5 mm.

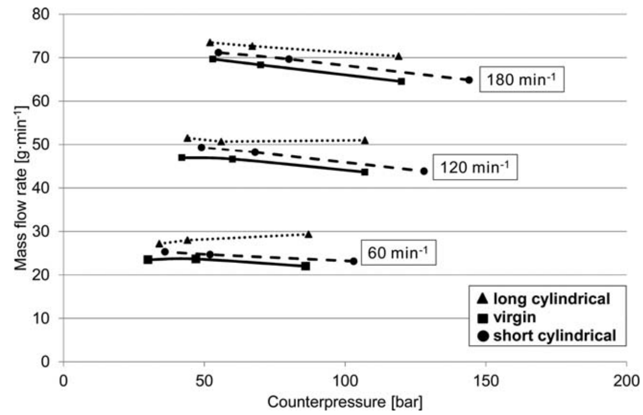


Figure 6. Screw characteristics for virgin, short, and long cylindrical polypropylene pellets processed at temperature profile T2 and a screw speed of 60, 120, and 180 min^{-1}.

When processing the short cylindrical pellets, melting occurs earlier (at an axial position of approximately 4 D), as Figure 10(b) shows. Because of this, the channel filling reaches a higher density, leading to a higher melt flow compared to the virgin pellets.

In the case of the long cylindrical pellets, melting takes place very fast. There is a very high degree of compression from the moment the pellets enter the screw channel. This is depicted in Figure 10(c). One can also see that a better arrangement is achieved in the channel. This can in fact be the reason for the high pressure that had been detected and for the significantly higher output.

The screw pull-out test were also conducted at a screw speed of 30 min^{-1} and a nozzle height of 0.25 mm and revealed very similar results as the discussed experiments (data not shown).

Effect of the Shape and the Dimensions of the Pellets on the External Coefficient of Friction of Polypropylene

The measured external coefficient of friction of the polypropylene pellets was in the range of 0.25 and 0.6. The temperature rise during the measurements is between 0.3 and 8.7°C, depending on the testing conditions. Figure 11 shows that an increasing velocity leads to an increase in the external coefficient of friction of polypropylene with different pellet shapes and dimensions in nearly all measured cases. A higher pressure leads to a decrease of the external coefficient of friction.

The external coefficient of friction of the long cylindrical polypropylene pellets is always higher in comparison to the short cylindrical and the virgin ones. Moreover, the short cylindrical pellets exhibit a higher coefficient of friction than the virgin material.

Influence of the Shape and the Dimensions of the Polypropylene Pellets on the Apparent Bulk Density

Table VI shows the average measured apparent bulk density and the standard deviation of the different pellet shapes that were used in the extrusion experiments and the tribological tests. The virgin pellets exhibit the highest apparent bulk density followed by the short cylindrical pellets. The lowest apparent bulk density is shown by the long cylindrical pellets.

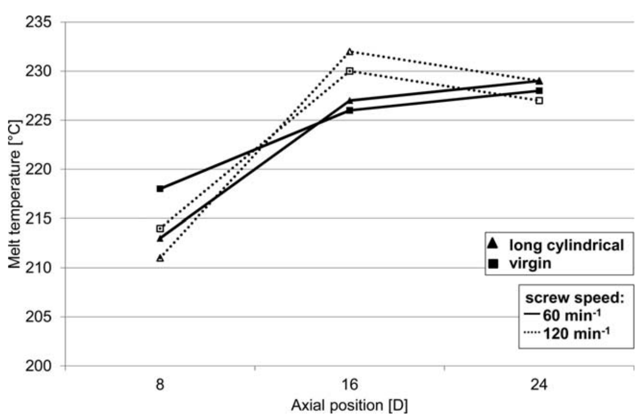


Figure 5. Recorded temperature along the barrel at three positions while processing virgin and long cylindrical polypropylene pellets at temperature profile T1, a screw speed of 60 and 120 min^{-1} and a nozzle height of 0.5 mm.

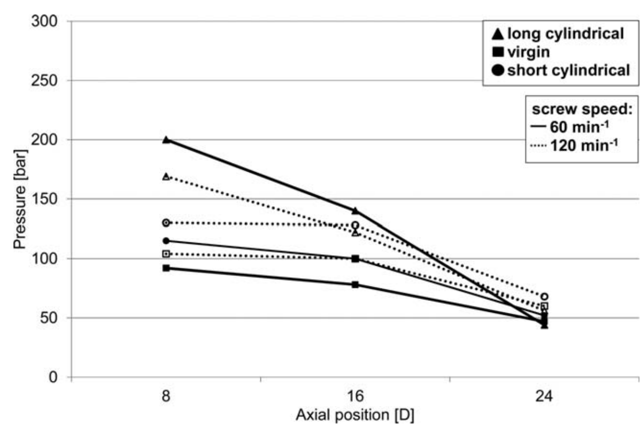


Figure 7. Recorded pressure along the barrel at three positions while processing virgin, short, and long cylindrical polypropylene pellets at temperature profile T2, a screw speed of 60 and 120 min^{-1} and a nozzle height of 0.5 mm.

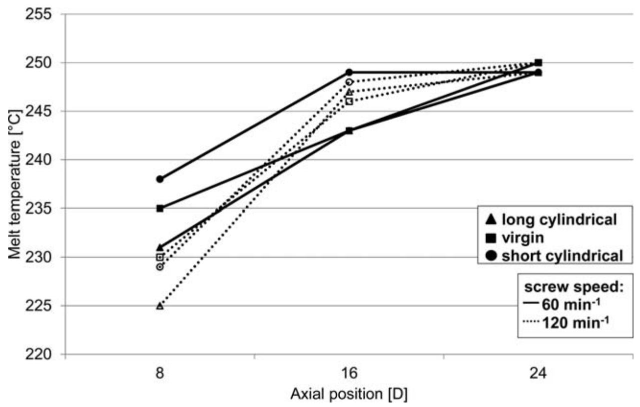


Figure 8. Recorded temperature along the barrel at three positions while processing virgin, short, and long cylindrical polypropylene pellets at temperature profile T2, a screw speed of 60 and 120 min^{-1} and a nozzle height of 0.5 mm.

DISCUSSION

The DSC tests confirm that the compounding process to produce the cylindrical pellets does not lead to degradation of the used polypropylene. This is an important factor, as a possible degradation would lead to inaccurate results in the extrusion experiments.

Although the apparent bulk density of the long cylinders is the lowest, the results of the extrusion experiments show that the long cylindrical pellets exhibit a higher mass flow rate than the other two pellet geometries in all the experiments. There is a decline of the specific output with rising screw speed that was also reported by Wortberg and Rahal and by Lessmann *et al.*[19,25,26] This can be seen for all pellet geometries in this experiment. It can be explained by the feeding behaviour that works less efficient as the screw accelerates to higher velocities. It remains noticeable, that the long cylindrical pellets show the steepest decline. This is also true for the pressure build-up. When processing the long cylindrical pellets, the pressure at an axial position of 8 D is always lower at higher screw speeds. That could suggest that the feeding behaviour of the long cylindrical pellets works best at low speeds and therefore has the highest potential to deteriorate.

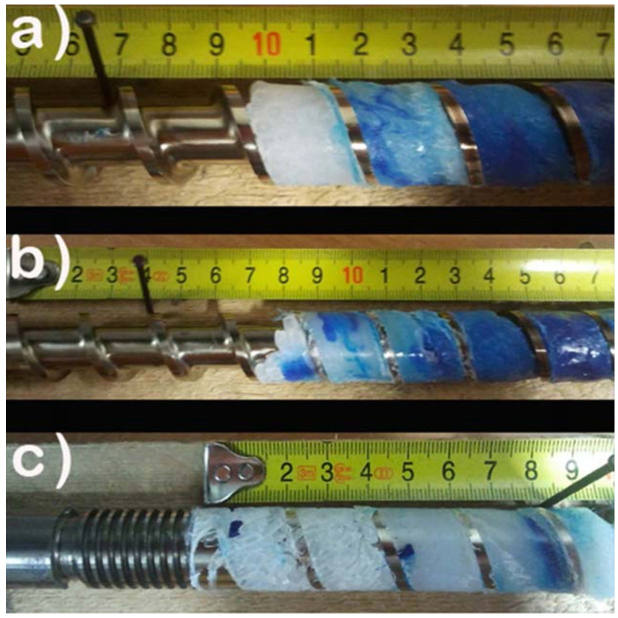


Figure 10. Screw pull-out tests after processing the virgin polypropylene pellets (a), the short cylindrical pellets (b), and the long cylindrical pellets (c) at temperature profile T2, a screw speed of 120 min^{-1} and a nozzle height of 0.25 mm. All the scales in the pictures are in centimetres and have their origin at the beginning of the screw channel. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Furthermore, the combination of the extruder size and the pellet geometry seems to be very important. For this small scale extruder, the long cylindrical pellets work best, yet it could be different for a larger extruder. The better filling of the screw channel can be explained by the dimensions of the long cylindrical pellets. The dimension of the cross section d_2 is lower than half the channel depth in the solids conveying zone. The length h is significantly higher than the channel depth. Therefore the pellets need a certain orientation to fit into the channel. Due to this, the pellets are rearranged forcefully when fed to the extruder. As shown by the screw pull-out experiments, a

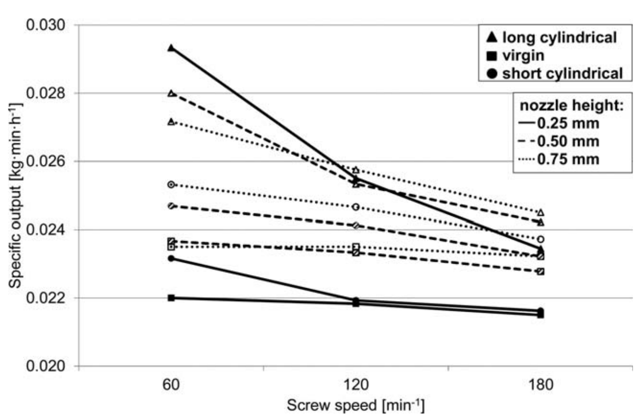


Figure 9. Comparison of the specific output of the extruder when processing three different polypropylene pellet geometries at different screw speeds and nozzle heights at temperature profile T2.

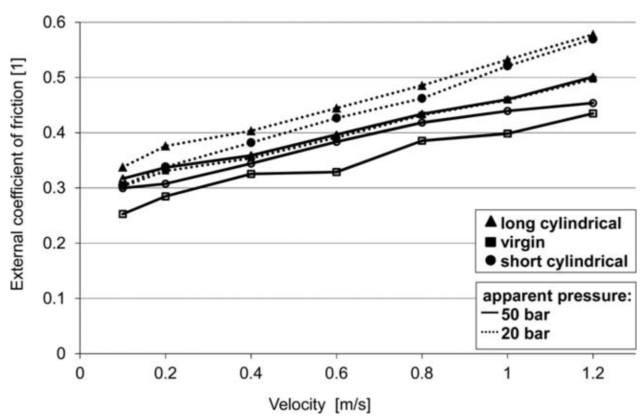


Figure 11. External coefficient of friction of virgin, short, and long cylindrical polypropylene pellets depending on velocity for a pressure of 20 and 50 bar at room temperature.

Table VI. Apparent Bulk Density for Three Polypropylene Pellet Shapes

Pellet shape	Apparent bulk density (kg/m^3)	Standard deviation (kg/m^3)
Virgin	514.80	1.81
Short cylindrical	478.50	2.07
Long cylindrical	422.80	3.43

predominant direction is formed and the initially loose packing of the pellets becomes very dense. In contrast to this, the dimension d_1 of the short cylindrical and the virgin pellets is greater than the depth of the channel and the other dimensions are higher than half of the channel depth. This means that the pellets cannot be stacked in the channel and the packing is rather loose. This can be observed in the screw pull out experiments where loose material falls out of the first few turns of the screw for the virgin and the short cylindrical pellets. In the experiments with the long cylindrical pellets the whole channel remains filled even when the screw is pulled out. Sikora's research proposed, while using polyvinylchloride instead of polypropylene in a comparable system, that the highest mass flow rate is achievable when the length of the pellets is close to their diameter at high screw speeds.[22] Yet, all used pellets geometries in his experiments had a diameter and a length greater than half the channel depth (4.2 mm) of the screw.

The experiments with the long cylindrical pellets exhibit very high pressures and low temperatures in the early stages. The high pressure at this point combined with the fact that the temperature is low is an indication of the high mass flow, leading to higher energy consumption as the material is molten. Evidence for this is delivered by the screw pull-out tests that showed the faster melting of the long cylindrical material in comparison with the other pellet shapes. These results contradict those found by Campbell and Spalding who could not prove a dependence of the temperature and pressure build-up on the pellet geometry. This could be due to the fact, that the extruder used in their experiments ($D = 63.5$ mm) was larger than the one used in this study.[21]

The pressure and the degree of filling in the solids conveying zone directly affect the frictional behaviour. With an almost ideal filling of the channel, the friction between the barrel wall and the polymer bulk materials gets higher. This leads to a higher thermal input which is needed for the fast melting of the material.

The frictional behaviour had to be investigated to support those conclusions. Experiments on the screw tribometer showed a high pressure and velocity dependence of the coefficient of friction. As reported by Chung *et al.*, the decrease of the coefficient of friction with higher pressure can be explained by a nonlinear relationship between the real contact area and the normal force in the case of polymeric materials.[13] This leads to the following relationship between the coefficient of friction μ and the applied apparent pressure p:

$$\mu \propto \left(\frac{S}{B}\right) \cdot \frac{1}{p^{1-n}} \tag{4}$$

where n is less than unity, S is the shear strength of the softer material (polymer), and B the yield pressure of the deforming material.

Myshkin *et al.* show that the velocity dependence of the coefficient of friction can be explained by the viscous resistance in the contact zone, which rises with increasing velocity.[27] The tests are conducted near the glass transition temperature, where the sliding velocity has a significant effect on friction.

To create comparable results of the different pellet shapes, the Hertzian surface pressure deformation model is used to calculate the contact area between the pellets and the metal surface. The cylindrical pellets have a rectangular contact area whereas a circular contact area can be approximated for the virgin pellets. At the same applied load the calculated contact area of the used cylindrical shaped pellets is higher due to a differing deformation. The higher calculated contact area explains the higher external coefficient of friction. The higher friction on the barrel surface can lead to higher output and pressure build up in the extrusion process.

Figure 12 shows that the calculated contact area between the long cylindrical polypropylene pellets and the shaft surface is higher than using the short cylindrical and virgin polypropylene pellets at a pressure of 20 and 50 bar. Especially at higher pressure, an increase in the external coefficient of friction of the polypropylene pellets with a higher calculated contact area for constant pressure and velocity can be seen (Figure 12).

Gamache *et al.* investigated the dynamic coefficient of friction of two polypropylene pellet shapes.[16] They also found a dependence of the coefficient of friction on the pellet shape. They used cylindrical pellets ($d = 3$ mm; $h = 3$ mm) and flattened cylinders ($d_1 = 2$ mm; $d_2 = 3$ mm, $h = 4$ mm). The results showed coefficients of friction between 0.2 and 0.6 and a clear pressure dependence which is also proven in this study. For low normal forces, the coefficient of friction of the flattened cylinders was far lower than for the cylindrical pellets but the difference got smaller with rising pressure.

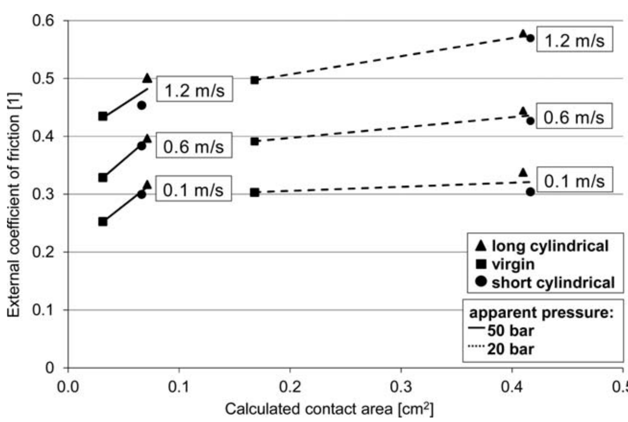


Figure 12. External coefficient of friction of virgin, short, and long cylindrical polypropylene pellets dependent on the calculated contact area at room temperature (pressure: 20 and 50 bar; velocity: 0.1, 0.6, and 1.2 m/s).

If the work would have also been done using polypropylene powder, the degree of filling of the screw channel could have been significantly better, possibly resulting in ever higher pressure and output.[28,29] Nonetheless, the area of application of powder shaped bulk materials in polypropylene processing is much smaller than for pellet shaped particles.

CONCLUSIONS

It is shown that the shape and the dimensions of the pellets have a significant influence on the output of a small scale single screw extruder when processing polypropylene. The output is higher when using cylindrical pellets compared to the virgin material, though the apparent densities diverge and would suggest the opposite.

The experiments exhibit a clear dependence of the melt pressure and the melt temperature on the pellet shape. Especially at low screw speeds, long cylindrical pellets develop a high pressure in the early stages of the process. The corresponding melt temperature at the beginning of the compression zone is always low when a high output is achieved. It appears that the feeding behavior in this application works ideally for the long cylindrical pellet shape, because its dimensions interact best with the screw geometry. It is obvious that due to the significant higher length of the long cylindrical pellets compared to the channel depth, the pellets are forcibly oriented resulting in higher bulk densities in the channel. Additionally, this results in higher external friction in consequence of a larger contact area.

Thus, both the dimensions and the higher external coefficient of friction of the long cylindrical polypropylene pellets explain the higher extruder output compared to the virgin pellets. Ultimately, these results need to be considered in relation to the product quality and the wear of the extruder.

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REFERENCES

1. Darnell, W. H.; Mol, E. A. *J. SPE J.* **1956**, *12*, 20.
2. Schneider, K. Der Fördervorgang in der Einzugszone eines Extruders; Ph.D. thesis, RWTH-Aachen, Germany, **1968**.
3. Broyer, E. Z.; Tadmor, Z. *Polym. Eng. Sci.* **1974**, *14*, 589.
4. Campbell, G. A.; Dontula, N. *Int. Polym. Proces.* **1995**, *10*, 30.
5. Grünschloß, E. *Kunststoffe* **1984**, *74*, 480.
6. Rauwendaal, C. Polymer Extrusion, 4th ed.; Hanser Publishers: Munich, **2001**, chapter 7.2.2, 223.
7. Miethlinger, J. Modellierung der Feststoffförderzone von Nutbuchsenextrudern, *Kunststoffe* **2003**, *4*, 49.
8. Jia, M.-Y.; Pan, L.; Xue, P.; Wang, K.-J.; Jin, X.-M. *Int. Polym. Proces.* **2013**, *28*, 267.
9. Yung, K. L.; Xu, Y.; Lau, K. H. *Int. Polym. Proces.* **2002**, *17*, 91.
10. Potente, H.; Pohl, T. *Int. Polym. Proces.* **2002**, *17*, 11.
11. Leßmann, J.-S.; Weddige, R.; Schöppner, V.; Porsch, A. *Int. Polym. Proces.* **2012**, *27*, 469.
12. Moysey, P. A.; Cloet, K. L. *Int. Polym. Proces. XXII* **2008**, *3*, 301.
13. Chung, C. I.; Hennessey, W. J.; Tusim, M. H. *Polym. Eng. Sci.* **1977**, *17*, 9.
14. Spalding, M. A.; Kirkpatrick, D. E.; Hyun, K. S. *Polym. Eng. Sci.* **1993**, *33*, 423.
15. Spalding, M. A.; Hyun, K. S. *Polym. Eng. Sci.* **1995**, *35*, 557.
16. Gamache, E.; Lafleur, P. G.; Peiti, C.; Vergnes, B. *Polym. Eng. Sci.* **1999**, *39*, 1604.
17. Hennes, J. P. Determination of Material Indices and Simulation of the Processes in the Feed Section of Conventional Single-Screw Extruders, Ph.D. thesis, RWTH-Aachen: Germany, **2000**.
18. Zitzenbacher, G.; Langecker, G. R.; Schatzer, R. *Kunststoffe Plast Europe* **2005**, Nr. *4*, 43.
19. Wortberg, J.; Rahal, H. *J. Plast. Technol.* **2007**, *3*, 1.
20. Kleineheismann, S.; Potente, H. *J. Plast. Technol.* **2009**, *5*, 201.
21. Campbell, A. G.; Spalding, M. A. Analyzing and Troubleshooting Single-Screw Extruder; Hanser Publishers: Munich, **2013**, Chapter 6, 238.
22. Sikora, J. W. *Int. Polym. Proces.* **2014**, *29*, 412.
23. Zitzenbacher, G.; Kneidinger, C.; Kögler, A. *Österreichische Kunststoffzeitschrift.* **2009**, *3/4*, 53.
24. Mennig, G.; Lake, M. Verschleißminimierung in der Kunststoffverarbeitung; Hanser Publishers: Munich, **2008**, Chapter 1.2.1, *30*.
25. Lessmann, J.-S.; Weddige, R.; Schöppner, V.; Porsch, A. *Kunststoffe Plast. Eur.* **2012**, *5*, 72.
26. Lessmann, J. S.; Weddige, R.; Schöppner, V.; Porsch, A. *Int. Polym. Proces.* **2012**, 27, 4, 469.
27. Myshkin, N. K.; Petrokovets, M. I.; Kovalev, A. V. *Tribiol. Int.* **2005**, *38*, 910.
28. Rautenbach, R.; Langecker, G. R. *Powder Technol.* **1975**, *12*, 179.
29. Butters, G.; Leng, S. A.; Thomas, A. F. *Powder Technol.* **1991**, *65*, 75.