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Modeling of the Dissipation in the Solid Conveying Section in Single Screw Extruders

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Abstract. In addition to the task of supplying the melt dominated sections with sufficient material, the solids conveying section also is important for the drive dimensioning, since a considerable part of the drive power is converted in the form of dissipated friction power. The dissipation energy is caused between the granules and screw or barrel and by the internal friction of the material caused by relative movements in the solid block. The latter is not taken into account in current power models due to the complex kinematic movements of the granules. For simplification, it is assumed that there is a block flow of the granule bed in which the energy is passed purely by heat conduction to the granules in the interior of the block. However, this assumption is inadequate for many applications and the studies presented in this paper show that internal dissipation accounts for a significant proportion of temperature generation in the solids conveying section. Due to the current achievable resolution in the area of DEM simulations, the description of the granules in the solid block is now made tangible. In this way, investigations can be done regarding the granular shape influence on the development of heat by dissipation. In the case of cylindrical particles, for example, there is the possibility that the particles regularly align themselves in the screw channel and unroll beneath each other. This is of great importance for practical applications, as it is well known that a poor melting behavior of cylindrical polyamide on universal screws is observed. The influence of the granulate form and the material parameters as well as other process parameters has been investigated and mathematically recorded. Numerous simulations based on the Discrete Element Method (DEM) have been performed and validated by experimental data. The results are summarized in this paper.

Keywords: solid conveying, discrete element method, dissipation, temperature, drive power.
PACS: 89.20.Bb, 89.20.Kk, 89.90.+n

INTRODUCTION

An essential part in designing single-screw extruders is the dimensioning of the drive. Analogous to the calculation of the throughput, the melt conveying sections must be considered as decoupled from the feed section for the drive power. Nevertheless, a not inconsiderable part of the drive power is converted into dissipated friction power in the solids conveying section. Current power models in the solids conveying section are based on the assumption that a block flow occurs [1-3]. Therefore, neither the effects of the granule shape and size nor the internal dissipation, which can be caused by the movement between the granules are taken into account. Heat is hereby generated only on the friction-surfaces screw/granulate and/or barrel/granulate. Accordingly, Schneider [1] differentiates in his modeling between a power consumption at the barrel and at the screw. Therefore, he considers surface elements in which frictional forces can be calculated via the prevailing pressure and the known sliding speeds. The friction force on the barrel is only generated by the pressure exerted on the barrel surface. For the friction forces at the screw, different sliding speeds and pressures are taken into account, since a differentiation must be made between the screw base and screw flights. Consequently, the total power depends on the pressure and it is proportional to the screw speed. The approach was taken up again in the course of introducing grooved bushings. In particular the focus was set on determining the transition screw speed, which describes the speed at which melting occurs in the grooved bushing. To calculate the transition screw speed, an energy balance in the feed section is used. Hereby, the limiting case is reached when the crystallization or glass transition temperature is exceeded on the barrel wall. In this state, the dissipated power of the solids conveying section overcomes the heat flow dissipated via the cooling channels in which it is assumed, that the dissipation heat generated is completely dissipated by the cooling medium. The averaged dissipated power is calculated by means of an average grooved bushing pressure and the averaged relative velocity on the barrel wall. The relative velocity is determined by the conveying angle averaged over the grooved bushing length. [2] Kleineheismann [3] extends the modeling by dividing the solids conveying section into volume elements that differentiate the groove, the shear gap and the screw channel. In each element, the acting forces and the relative speeds of the elements are determined compared to their respective adjacent partners. The total power is calculated as the

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sum of the products of all relative speeds and forces between the friction partners. However, the granule properties within the block flow model are still not considered. Complex movements such as the sliding of individual layers or the rolling of individual granules can be observed in the solid block. Once again, correlations with the granule form are conceivable. Cylindrical granules tend to aligned in the conveying direction and roll beneath each other, whereas slip effects are more likely to be expected from spherical granules.

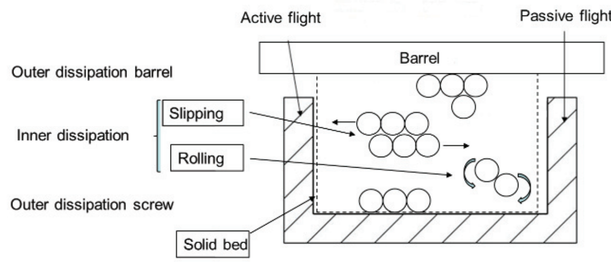


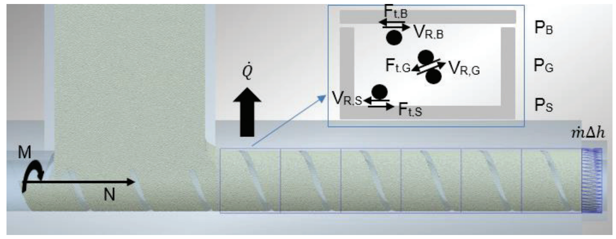
FIGURE 1. Effects Occurring in the Solids Conveying Section [4].

As a result, for the consideration of the dissipated power an inner component must also be extended. The influence of the granulate properties were already investigated in numerous publications [5-10], although a general mathematical description considering the effects does not yet exist. The investigations presented in this paper are intended to contribute to a complete understanding of the processes in the solids conveying section and therefore to further deepen the process know how. An important part of this understanding is currently being gained from numerical simulations based on the Discrete Element Method [11] which also will be the base for the modeling presented in the following.

SIMULATION

The dissipation simulations were implemented with the DEM software EDEM (software company: DEM Solutions Ltd.). Solids conveying sections with screw diameters of 30 and 60 mm were used for this purpose. As a further geometrical parameter, the channel depth was varied. In order to reduce the simulation scope, the variation of the channel pitch is neglected. The dimensionless speed Π_N in turn depends on the screw diameter as well as the solid density and shear modulus. Both material parameters are provided with averaged values for common polymers. If a value for the screw diameter is chosen, again dimensional values for the screw speed result. Thereby, for small screw diameters, higher speeds are generated as for larger diameters. In order to simulate different particle shapes, the L/D ratio is varied in addition to the particle diameter. All other simulation parameters used can be found in Table a. The contact model used is based on the hysteresis model. This model considers plastic deformations during a collision. A force field [12] at the system outlet is used to apply the back pressure. The Rayleigh time step is continuously 3.13x10-6 s. It represents the time during a collision and is automatically calculated from the shear modulus of the defined material [13]. However, it has been indicated that a smaller time step is required to calculate the numerous contacts and high overlaps in a stable manner. For the simulations used for this paper a reduced value of 20% of the Rayleigh time step is suitable. Furthermore, a normal distribution of the particles is set, whereby the distribution limits are 5 % of the particle diameter. The normal distribution in the simulation is varied by a random algorithm in which the distribution curve is varied automatically. The analysis of the dissipation in the solids conveying process is feasible in two ways. Firstly, it is assumed that the heat generation results from the frictional power and therefore from frictional forces and relative speeds. This enables a differentiated power analysis of the barrel, screw and in the solid bed (Equation 2-4). Therefore, the respective mean value of the relative velocities $\bar{v}_{r,i}$ and tangential forces $\bar{F}_{t,i}$ of all particles in contact in each segment is formed. The friction energy resulting on average per particle is calculated with the number of contacts X_i. On the other hand, the torque M acting on the barrel can be evaluated and calculated with the respective screw speed N. The resulting total drive power should then correspond to the cumulative friction power as indicated in Equation 1. Both approaches are based on the enthalpy change of the polymer. The energy input into the polymer takes place via the dissipated energy W_{diss} and a heat flow $\dot{Q}$, which can also be negative when heat is passing out of the system via the barrel. As indicated in Equation 5, $\dot{m}$ represents the mass flow and Δh is the enthalpy change of the polymer. The volume work described by a pressure change Δp over a mean density $\bar{\rho}$ is not considered further, since the granules are incompressible.

Parameter	Range	Unit
Diameter D	30…60	mm
Dimensionless Screw Speed Π_N	1.04x10^{-4}…4.43 x10^{-4}	-
Screw Speed (30 mm Screw)	150…640	min^{-1}
Screw Speed (60 mm Screw)	75…320	min^{-1}
Channel Depth h/D	0.15…0.2	-
Granule Diameter D_p	2…4	mm
Granule Form L_p/D_p	1…2	-
Backpressure p	36…164	bar
External COF μ_{St}	0.1…0.4	-
Internal COF μ_P	0.4…0.7	-
External COR$_{St}$	0.75	-
Internal COR$_i$	0.65	-
Density ρ	1150	kg/m³
Rolling COR μ_r	0.01	-
Poisson´s Ratio υ	0.43	-
Shear Modulus G	6x10^8	Pa
Gravitation g	9.81	m/s²



$$W_{diss} = \sum P_F = P_D = M \cdot N \; with \; \sum P_F = P_B + P_G + P_S \quad (1)$$

$$P_B = \bar{v}_{r,B} \cdot \bar{F}_{t,B} \cdot X_B \quad (2)$$

$$P_S = \bar{v}_{r,S} \cdot \bar{F}_{t,S} \cdot X_S \quad (3)$$

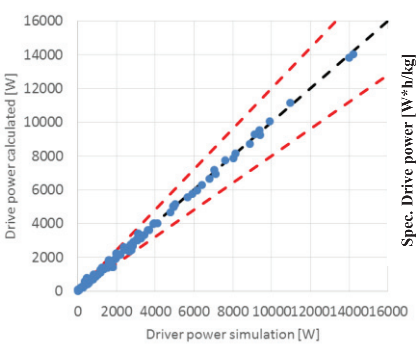
$$P_G = \bar{v}_{r,G} \cdot \bar{F}_{t,G} \cdot X_G \quad (4)$$

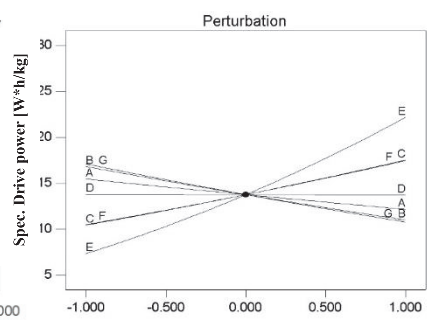
$$\dot{m}\Delta h + \dot{m}\frac{\Delta p}{\bar{\rho}} = W_{diss} + \dot{Q} \quad (5)$$

FIGURE 2. Left: Design of Experiments; Right: Differentiated Power Analysis in the Solids Conveying Section.

RESULTS AND DISCUSSION

Due to the simpler and more robust evaluability, the drive power for the regression model has been determined on the basis of the simulated drive power calculated by the torque. In order to assess the regression quality, the following Figure 3 (left) shows the comparison of the calculated values using the regression function with the drive powers of the simulations.





Level		-1	0	1
Factor				
Π_N	A	1x10^{-4}	3x10^{-4}	4x10^{-4}
h/D	B	0.15	0.175	0.2
D_p	C	2 mm	3 mm	4 mm
L_p/D_p	D	1	1.5	2
p	E	36 bar	100 bar	164 bar
COF	F	0.1	0.25	0.4
D	G	30 mm	45 mm	60 mm

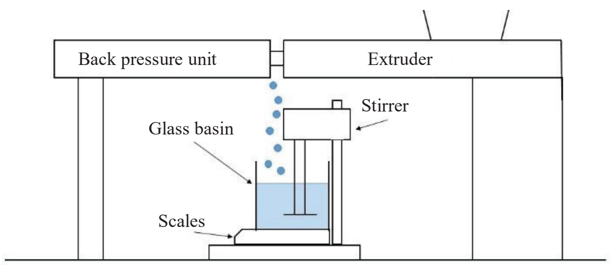
FIGURE 3. Left: Representation of the Quality of the Model Found; Right: Dependence of the Specific Drive Power on the Influencing Variables

In addition, the influencing variables have been examined in more detail. The former can be analyzed using a pertubation diagram (Figure 3, right). It graphically represents the effect of the parameter variation of each influencing variable on the target value. In this case, the specific drive power has to be considered, so conclusions can be derived on the efficiency of the solids conveying zone. In each case, only one factor is varied at a time between the marginal sizes of the experimental design (1 and -1). The other sizes are fixed at the value in the core of the experimental design (0). With an increasing screw diameter (G) or an increasing screw speed (A), a decreasing specific drive power and an increase of the economy in the area of the solids conveying section can be observed. The additional gain resulting from the increase in output is therefore more dominant than the growth in drive power which is to be applied for this purpose. An analogous behavior is indicated for the channel depth (B), which hardly affects the dissipation but has a positive effect on the throughput. The particle shape, represented by the L/D ratio (D), has almost no influence on the specific drive power. In an interim conclusion, it can be stated that the influence of the particle shape on pressure-dependent solids conveying processes plays only a minor role. The particle size (C), however, has significant influence on the specific drive power which can be explained by the bulk density that has a major influence on throughput.

Larger particles reduce the bulk density, thereby reducing the throughput and the specific drive power is decreased. Higher coefficients of friction (F) also have a negative effect on the efficiency of the solids conveying section. Therefore, the coefficient of friction has no significant effect on the solids throughput or at least not to the extent that it affects the drive power. For the processing of polymers with high friction values, it should therefore be taken into account that a throughput increase comes with a high increase in the required drive power. The counter-pressure (E) has the highest effect on the specific drive power. This was expected, as an increase in back pressure has a negative effect on both throughput and the drive power to be provided. In the next step the observed effects will be compared with practice.

VALIDATION

The validation of the model was implemented with a specially designed test bench. For this purpose, the extended feed section of a 30 mm extruder was used. It was equipped with an optimized hopper opening with a length of 90 mm [12]. The length of the screw from the end of the filling opening is 6 D. Furthermore, the occurring heat flows must be made measurable via the test stand. Therefore, the feed section has been provided with bores for thermocouples (type J). Those were inserted at three axial positions in two different depths which makes it possible to determine the heat flow. The enthalpy change of the granulate is a further target value. For this purpose, it is necessary to determine the granulate temperature which is measured indirectly. Therefore, the process is run stationary followed by a defined amount of granulate which is then conveyed into five liters of water at a known temperature. Under stirring, a mixing temperature sets from which the average granulate temperature can be calculated as presented in [4]. The heated granulate is fed directly from the extruder into the water filled glass basin for 36 seconds. The entire experimental setup is shown in Figure 4 (left). In addition an overview of the experimental investigations is given in Figure 4 (right).



Parameter	Unit	Value
Diameter D	mm	30
Channel Depth h	mm	5.5…7.5
Pitch t	mm	30
Flight Width e	mm	3
Backpressure p	bar	25…35
Screw Speed N	1/min	300…700
Material	-	PP, HDPE 1,
	-	HDPE 2, PA
COF μ_{ex}	-	0.25…0.306

FIGURE 4. Left: Sketch of the overall Test Stand [4]; Right: Overview of the Experimental Investigations

The backpressure is applied by a spring which can be adjusted via a screw. The counterforce is transmitted via a bar construction to an axially and rotatable mounted cone. Between the cone and the barrel flange the conveyed granules pass through the discharge gap. The backpressure results from the opposing force which is set in the process and the annular cross-sectional area of the cone at the outlet gap. In addition to the mass flow, the applied torque has also been measured. In the following the measured specific drive power is shown (Figure 5, left) as well as a comparison of the measured drive power with the calculated values (Figure 5, right).

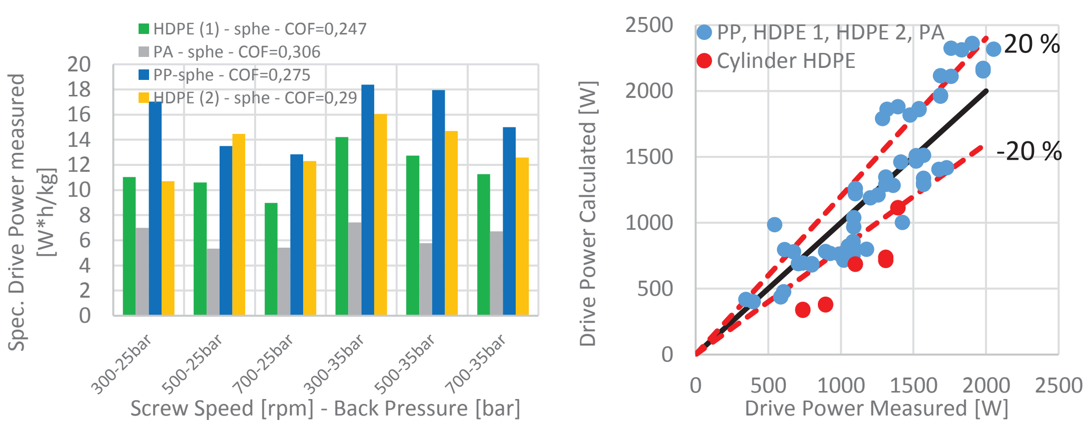


FIGURE 5. Left: Excerpt from the Experimental Investigations (channel depth 5.5 mm); Right: Comparison of the Measured and Calculated Drive Power

All in all, the experimental results are in a good agreement with the simulations (Figure 5, right). Operating points that are underestimated by the model are marked red in Figure 5. These data points have in common that they base on simulations with cylindrical HDPE. The influence of cylindricity on the drive power is therefore more pronounced in the simulations than observed in the experimental investigations. This effect is due to the idealized representation of the cylinder particles in the simulation. It consists of spheres shifted into each other which have a round cross-section area. As a result, the simulated cylinders can unroll easily against each other. However, the produced granules have a slightly elliptical cross-section area which inhibits the tendency to roll.

The experimental studies confirm that an increasing screw speed has a positive effect on the economic efficiency of the feed section (Figure 5, left). The increase in drive power is therefore disproportionate to the increase in output. The negative influence of an increasing coefficient of friction also coincides with the observations from the simulations. With similar material properties, in the form of two polyethylenes, the material with a higher coefficient of friction leads to a higher specific drive power. The back pressure has a negative effect on the efficiency of the solids conveying section. With an increase of 10 bar, an increase in specific drive power can be determined for all materials. Consequently, the experimental results underline the observations from the simulations. The mathematical model developed from this thus provides verifications for the design and optimization of solids conveying sections.

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