INVESTIGATION IN POWER CONSUMPTION OF TWIN SCREW EXTRUDERS IN RESPECT OF SCALE-UP THEORY

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Abstract

In the field of polymer recipe development the homogenization of components is one of the most important points. For reasons of economy on the one side, and to receive a convenient machine configuration on the other, practical investigations are carried out on lab scale extruders. Subsequently the optimized process has to be transferred to an industry scale extruder during a scale-up process.

On the basis of temperature and power consumption measurements at a tightly intermeshing, co-rotating twin screw extruder an approach for process transferability is discussed. By keeping the screw diameter constant the influence of throughput on the system energy balance is specified for several polymers. A theoretical approach for partly filled, geometrically similar systems is validated by means of experimental data extracted from a Coperion W&P ZSK-30. The results provide a basis to transfer operating points for co-rotating twin screw extruders.

Introduction

Increasing demand for the products made of thermoplastic polymers result in higher requirements on the properties of the resins. To achieve these requirements polymers usually have to be compounded. For reasons of economy the development of these compounds is generally carried out on lab scale extruders. After modifying a raw plastic into a compound with the required properties the process has to be transferred on a production extruder. By using scale–up rules, operating and design data of known machines, can be applied to larger and smaller extruders. These scale-up rules are commonly based on the principle of similarity. Equation (1) shows a typical example of a scale–up rule:

$$\frac{\dot{m}}{\dot{m}_0} = \left(\frac{D}{D_0}\right)^{2+\Psi-\chi} \tag{1}$$

An survey of scale-up rules for single screw extruders can be found in the reference [1]. These rules are generally accepted. In the case of twin screw extruders these rules have to be adjusted because of geometrical and thermodynamic restrictions [2-5]. The channel depth which is given by screw diameter and centerline distance represents a typical geometrical restriction for tightly intermeshing twin screw extruders:

$$h_{th} = D - a_{th} \tag{2}$$

Another important issue is the heat transfer between polymer and cylinder wall. Investigations show problems at scaled-up extruders not removing adequate heat from the polymer melt during the compounding process. To minimize this effect the heat dissipation has to be reduced without taking influence on the product quality. In this paper a general correlation of the power consumption and the temperature development during a scale-up process is identified.

This work is part of a research project focused on scale-up models for co-rotating twin screw extruders. The project´s target is to develop models which enable the user to transfer operating points under different boundary conditions. The findings will be integrated in the simulation software SIGMA.

Theoretical Approach

The energy balance of a stationary extrusion process, as shown in Figure 1, is described by the fundamental theorem:

$$P + \dot{Q} = \dot{m}\left(h_2 - h_1\right) = \dot{m}\,\Delta h \tag{3}$$

According to the principle of similarity, all physical and technical facts described by the same dimensionless characteristic values are similar. Therefore, equation (3) can be written in a dimensionless form.

$$\Pi_P = 1 - \Pi_{\dot{Q}} \tag{4}$$

By forming a quotient of model and main machine equation (4) can be transferred in (5), in which the index 0 describes the model machine.

$$\left(\frac{\Pi_P}{\Pi_{P0}} - 1\right) = \left(1 - \frac{\Pi_{\dot{Q}}}{\Pi_{\dot{Q}0}}\right)\left(\frac{1}{\Pi_{P0}} - 1\right) \tag{5}$$

The power introduced by the screw can be distinguished into one part which arises from to viscous dissipation and into another due to the pressure build-up. The influence of kinetic energy can be neglected [6]

$$P = P_{Diss} + P_{Vol} = P_{Diss} + \Delta p\,\dot{V} \qquad (6)$$

In partly filled systems no pressure build-up occurs, which means that power consumption is then dominated by viscous dissipation. In this case equation (5) can be written as:

$$\left(\frac{\Pi_{P,Diss}}{\Pi_{P0,Diss}} - 1\right) = \left(1 - \frac{1}{\Pi_{P0}}\right)\left(\frac{\Pi_{\dot{Q}}}{\Pi_{\dot{Q}0}} - 1\right) \qquad (7)$$

Using an approach of [7] the dimensionless dissipated power ratio can be described as:

$$\frac{\Pi_{P,Diss}}{\Pi_{P0,Diss}} = \frac{K}{K_0}\frac{b}{b_0}\frac{z}{z_0}\left(\frac{h}{h_0}\right)^{n}\left(\frac{v_0}{v_{0,0}}\right)^{1+n}\left(\frac{\dot{V}_0}{\dot{V}}\right)\left(\frac{T_{10}-T_{00}}{T_1-T_0}\right) \qquad (8)$$

A substitution of the terms on the right side of equation (8) by scale-up rules and the arrhenius law leads to:

$$\frac{\Pi_{P,Diss}}{\Pi_{P0,Diss}} = \frac{1}{\Theta}\exp\left(-\beta\left(\frac{T_{10}-T_{00}}{1+b_T}\right)(\Theta-1)\right)\left(\frac{f_0}{f}\right)^{n}\left(\frac{D}{D_0}\right)^{n\Lambda+(1+\omega-n)-\Psi(1+2n)} \qquad (9)$$

Equation (9) is applied into (7), while the heat flow ratio is replaced by:

$$\frac{\Pi_{\dot{Q}}}{\Pi_{\dot{Q}0}} = \frac{1}{\Theta}\left(\frac{D}{D_0}\right)^{\Omega+2+\omega-\Lambda} \qquad (10)$$

This results in equation (11) which is a general combination of energy balance and scale-up rules.

$$\frac{1}{\Theta}\exp\left[-\beta\left(\frac{T_{10}-T_{00}}{1+b}\right)(\Theta-1)\right]\left(\frac{f_0}{f}\right)^{n}\left(\frac{D}{D_0}\right)^{n\Lambda+(1+\omega-n)-\Psi(1+2n)} = \left(1-\frac{1}{\Pi_{P0}}\right)\left[\frac{1}{\Theta}\left(\frac{D}{D_0}\right)^{2+\omega+\Omega-\Lambda} - 1\right] \qquad (11)$$

Equation (11) is simplified before validation. For better application the screw diameter remains unchanged ($D/D_0=1$). Keeping the screw speed constant ($N/N_0=1$) results in equation (12), in which the material coefficient b_1 has been added.

$$\frac{1}{\Theta}\exp\left[-\frac{b_1\beta}{1+b_T}\left(T_{10}-T_{00}\right)(\Theta-1)\right] - 1 = \left(1-\frac{1}{\Pi_{P0}}\right)\left[\frac{1}{\Theta}\frac{\dot{q}}{\dot{q}_0}\frac{\dot{m}_0}{\dot{m}_1} - 1\right] \qquad (12)$$

The dimensionless temperature Θ is defined by the initial temperature and the die temperature of each operating point:

$$\Theta = \frac{T_1 - T_0}{T_{10} - T_{00}} \qquad (13)$$

For the validation of equation (12) experimental investigations with a number of polymers (Table1) were carried out.

Experimental Setup and Evaluation

The investigations were run on a Coperion W&P ZSK-30 co-rotating twin screw extruder which was equipped with special torque probes (Fig.2). These probes have a working range of up to 160 Nm and provide separate data per screw. Pressure and temperature were measured at the die to gain additional data for a simulation process.

In the investigations six materials of different viscosity were tested. The screw geometry was kept unchanged for all materials (Fig.3). For PA and PC a vented barrel was used. As the filling degree is an important point in this approach, only small throughputs in the range of 2.5 kg/h to10 kg/h were considered. The screw speed was varied between 100 rpm and 400 rpm. Figure 4 shows measured torque data of ABS in the mentioned area. Equation (13) was used to calculate the power consumption after summing up the torque values of both screws.

$$P = 2\pi\, N\, M_d \qquad (14)$$

Power consumption data at different operation points are shown in Figure 5. As expected, power consumption increases with progressive screw speed and throughput. The twin screw simulation software SIGMA was used to verify the power consumption data. Further information about the calculation model can be found in [7]. As an example the results for ABS are displayed in Figure 6. Calculated and measured power data show good correspondence for PP, PE, and PA. Only in the case of low viscosity polycarbonate (Macrolon CD 2005) results show a major deviation between calculation and experiment. This deviation might be caused by degradation of the polycarbonate in the melting zone. As a result of this, further investigation with adjusted screw geometry will be carried out.

Comparison of Theoretical Approach and Experimental Results

Verified temperature and power data gained during our experimental investigations were applied to equation (12). As dimensionless power is needed it was calculated by:

$$\Pi_{P0} = \frac{P_0}{\dot{m}\, c\, \Delta T} \qquad (15)$$

In the next step data couples with constant screw speed ($N/N_0=1$) have been formed. At least ten of this couples for each material were used to calculate an average material coefficient b_1. Afterwards equation (12) was solved to calculate Θ and T_1. A comparison of the measured Θ and the calculated Θ for ABS is displayed in Figure 7. Figure 8 shows the measured and the calculated temperatures at the die of the main machine. The results give a satisfying description of the presented cohesions. Further investigations are planed.

Conclusion

An approach for describing the energy balance of a scale-up process has been developed. Starting with a fundamental theorem, the dissipated power of different operation points was applied. Using scale-up rules a general equation has been formed. A first validation was done by setting boundary conditions ($D/D_0=1$ and $N/N_0=1$). A material dependent constant describing the temperature behavior was calculated. Results of theoretical approach and experimental data show satisfying accordance.

Acknowledgement

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Nomenclature

a_{th}	theoretical centerline distance
b	channel width
b_1	material coefficient
b_T	temperature coefficient
c	specific heat capacity
D	screw diameter
f	filling degree
h	enthalpy, channel depth
h_{th}	theoretical channel depth
K	power law consistency
M_d	torque
$\dot{m}$	mass flow rate
N	screw speed
n	power law exponent
P	power, power consumption
P_{Diss}	dissipated power
P_{Vol}	pressure build-up power
$\dot{Q}$	heat flow
$\dot{q}$	heat flow rate
T_1	melt temperature at the die
T_0	initial temperature
v_0	circumferential velocity
$\dot{V}$	flow rate
z	channel section
Θ	dimensionless temperature
Δp	pressure difference
ΔT	temperature difference
β	parameter of the arrhenius law
Π_P	dimensionless power
$\Pi_{P,Diss}$	dimensionless dissipated power
$\Pi_{\dot{Q}}$	dimensionless heat flow
$\Psi, \chi, \Lambda, \Omega, \omega$	scale-up exponents

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Key words

Scale-up, power consumption, twin-screw extruder, compounding, optimization

Figures and Tables

Table 1: Materials

Typ	Brand		Producer
1 Polyethylen	Vestolen	P7000/0050	DSM
2 Polyethylen	LLDPE	LL1001 XV	Exxon Mobile
3 Polypropylen	Stamylan	P14 E10	DSM
4 ABS	Tairilac	AG15A0	Formosa Chemicals
5 Polyamid 6.6 GF	Zytel	EFE8071 NC-10	Du Pont
6 Polycarbonat	Macrolon	CD 2005	Bayer AG

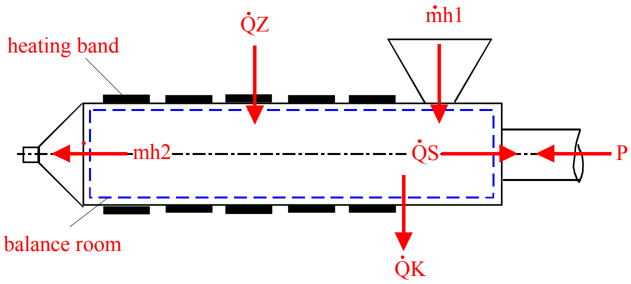

Figure 1: Energy Balance at a Twin Screw Extruder.

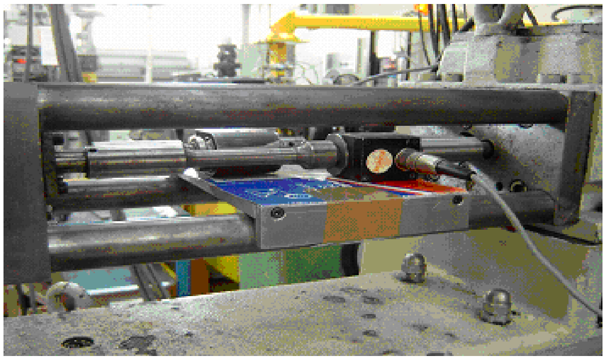

Figure 2: Power measurement probes mounted at a ZSK-30 Twin Screw Extruder.

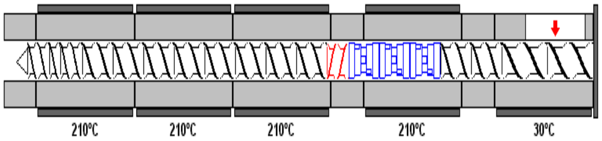

Figure 3: Screw configuration ZSK-30.

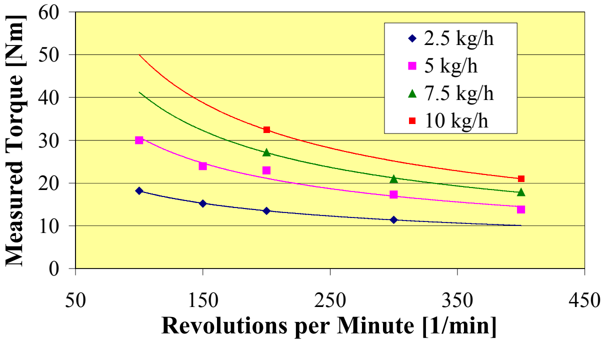

Figure 4: Torque measured at a ZSK-30. Material: ABS.

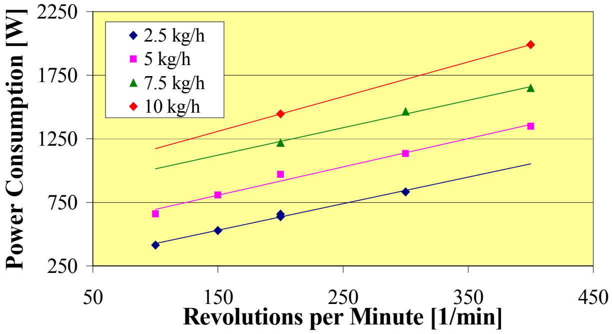

Figure 5: Power consumption at different operation points. Material: ABS.

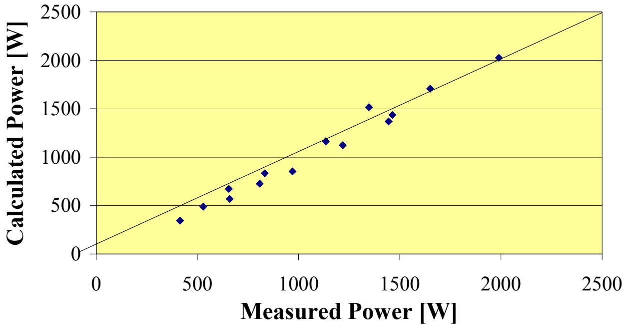

Figure 6: Verification of Power Consumption Measurement.

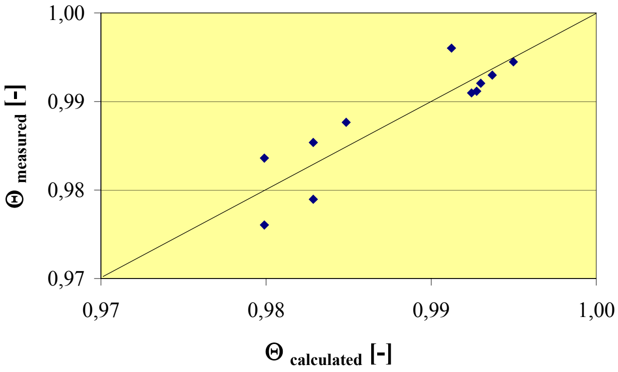

Figure 7: Validation of Equation 12 for ABS.

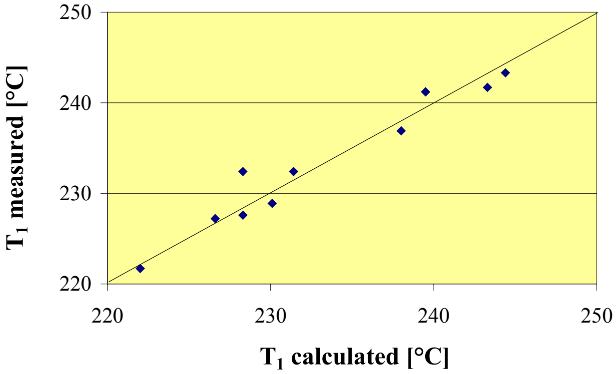

Figure 8: Temperature at the Die. Comparison for ABS.