Calculating Power of Extruder Melt Sections

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Background

The classic approach to calculating the power has been through a torque balance for the screw multiplied by screw speed[1-5]. The torque is calculated through an assumed stress model. Some models assume constant viscosity[1-3], and many are two-dimensional[2-6]. The influence of the flight clearance is demonstrated[2,3], and the effects of flight clearance and temperature are shown with finite difference methods for two-dimensional flow of power-law viscosity[5]. A macro-energy equation is used to discuss power and heat, but details of quantifying calculations are not presented[6]. This final approach is basic to the starting point of this work.

Math Model

Energy Balance The conservation of energy for a single barrel zone (Figure 1) of the melt section is assumed to be similar to that of a heat exchanger but with internal heat generation. The melt flows axially through the screw channel and exchanges heat with the barrel. The temperature of the melt changes to account for its heat loss or gain. The screw may also perform pumping work against external pressure. The power to the screw is then given by the conservation of energy as follows:

$$W = \int_{z1}^{z2} [hC(T - T_B) + mC_p dT / dz)]dz + \frac{m}{\rho}\Delta p \quad (1)$$

Melt Temperature The crux of the solution to equation 1 is the melt temperature, T (z).This has been previously modeled[7] with viscosity given by

$$\eta = \eta_B e^{-(T-T_B)/B}(1 + (\lambda\gamma)^a)^{(n-1)/a} \quad . (2)$$

The resulting governing equation for the melt temperature in dimensionless form is given[7] as

$$\frac{d\theta}{d\chi} = -\frac{N_k}{N_{cy}}\theta + e^{-\theta} \quad (3)$$

Dimensionless Numbers

The dimensionless system[7] used for equation 2 maintains the identity of important process parameters, i.e., each dimensionless parameter uniquely contains a process parameter. In this way the relative sensitivity of the several parameters is easily determined from the dimensionless functions and their solutions.

Dimensionless Melt Temperature This is defined as

$$\theta = (T - T_B) / B. \quad (4)$$

Heat Transfer Number A key parameter to temperature and power is the heat transfer number, so called because only it contains the heat transfer coefficient[7]. It is given as

$$N_h = \frac{hHB}{V^2 \eta_B}, \quad (5)$$

which is the ratio of heat transfer to viscous heat generation or an inverse version of the Brinkman number based on heat transfer coefficient instead of melt thermal conductivity. The heat transfer coefficient has been shown to greatly depend on flight clearance[7].

Carreau-Yasuda Number The influence of shear thinning of the polymer is included by a dimensionless Carreau-Yasuda parameter given by

$$N_{CY} = Vo_c(1 + (\lambda\gamma)^a)^{(n-1)/a}(1 + 12(v / V)^2) + Vo_f H_R^2(1 + (\lambda H_R)^a)^{(n-1)/a}. \quad (6)$$

It is the only dimensionless number in this analysis that contains the shear constants from the Carreau-Yasuda equation, λ, a, and n. Therefore, its value uniquely indicates the influence of these constants which describe shear dependence of viscosity.

The Carreau-Yasuda number includes three aspects of shear heating in the model: (1) shear in the channel, (2) shear in the flight clearance, and (3) shear resulting from the axial pressure gradient in the channel.

Dimensionless Length The axial length coordinate z, is made dimensionless as

$$\chi = N_{CY} \frac{z \eta_B V^2}{B \rho C_p H^2 v}. \quad (7)$$

Dimensionless Power Function If flow rate is approximated as

$$m = \rho C H v, \quad (8)$$

then equation 1 for the power can be written with dimensionless parameters of equations 4-7 and equation 8 to give

$$N_W = \frac{N_h}{N_{CY}}\int_1^2 \theta d\chi + \theta_2 - \theta_1 + N_{WP}$$, (9)

where dimensionless screw power number is

$$N_W = W / (BmC_p)$$, (10)

and dimensionless pumping power number is $$N_{WP} = \frac{\Delta p}{B \rho C_p}$$. (11)

Equation 2 is solved[7] by numerically by the Runge-Kutta finite- difference method to obtain $\theta(\chi, N_h/N_{CY})$, and the result is used to evaluate equation 9. The integration of θin equation 9 is done numerically by the trapezoidal method, and the functions of θ for power are shown in Figure 2. Pumping power N_{wp}, must be added to the result plotted in Figure 2 for the total power N_w, of the melt section.

Initial Condition The initial condition for the solution is the temperature at the inlet to the melt section. The minimum value is the melting point of the polymer, which is assumed no lower than 150 ^oC below the barrel temperature. The polymer constant B, is assumed greater that 30 ^oC, so the minimum value of initial dimensionless temperature is, by equation 4, θ_1 =-150/30= -5. This value is low enough that all values of dimensionless length are close to zero ($\chi < 0.0068$) which adequately approximates the general condition that θ = - at $\chi = 0$ used to solve equation 2[7].

Special Cases

Fully Developed Melt Temperature The melt temperature is not changing in the axial direction (θ=constant.) This means that

$$\theta_2 - \theta_1 = 0.$$ (12)

so that equation 9 for power becomes

$$N_W = \frac{N_h}{N_{CY}}\theta(\chi_2 - \chi_1) + N_{WP}.$$ (13)

As would be expected, the power is a linear function of extruder length for fully developed melt temperature as is shown in Figure 1 for large χ and N_h/N_{CY}.

Adiabatic Barrel The power for the case where the barrel is fully insulated is obtained by making h = 0 (N_h/N_{CY} = 0,) so that equation 9 becomes

$$N_W = (\mathcal{E}_2 - \mathcal{E}_1) + N_{WP}. \quad (14)$$

Experimental Verification

Data of motor power, melt temperature, and barrel metal temperature for three different constant-depth screws pumping PET were recorded. Screw speeds varied from 40 rpm to 102 rpm, and melt temperatures varied from 260^{o}C to 294^{o}C. Barrel metal temperatures varied from 246^{o}C to 287^{o}C. The melt temperature was assumed fully developed with a melt-fed temperature within 2 ^{o}C of exit temperature. Therefore, equation 13 was applied for the calculation of screw power, which is plotted versus measured motor power in Figure 3. The dimensions of the screws are given in the following table.

Screw Dimensions for PET Data

63.5 mm diameter, 10 L/D

Flight Width = 6.35 mm

Screw	#1	#2	#3
Channel depth	1.88 mm	2.16 mm	3.3 mm
Lead	50.8 mm	63.5 mm	88.9 mm
Flight clearance	0.10 mm	0.25 mm	0.15 mm
Flights	Single	Double	Single

Figure 3 has a line which indicates the power of the screw if the drive is 85% efficient. This is a normally accepted efficiency for dc drives and gear boxes, and the calculated screw power is shown to follow the 85% correlation very well, which provides confidence that the model is accurate.

Conclusions

1. A method for calculating the contribution of the melt section to the power required by an extruder screw has been developed and demonstrated.

2. The method includes the shear in the channel, in the flight clearance, and from the axial pressure gradient on the power of the screw.

3. The method includes viscous shear thinning by the Carreau-Yasuda model.

4. The method includes the effect of temperature on the melt viscosity.

5. The melt temperature is assumed to be developing for the method.

6. The effect of pumping pressure is also included.

Acknowledgments

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Nomenclature

a Yasuda constant

B Exponential viscosity constant

C Barrel inside circumference

C_p Melt specific heat

h Heat transfer coefficient

H Screw channel depth

H_R Ratio of channel depth and flight clearance

m Mass flow rate

n Power-law exponent

N_{CY} Carreau-Yasuda shear number

N_h Dimensionless heat transfer number

N_W Dimensionless screw power number

N_{WP} Dimensionless pumping power

T Melt temperature

T_B Barrel temperature

v Axial melt velocity

V Surface speed of screw

Vo_c Volume fraction of melt channel

Vo_f Volume fraction of flight clearance

W Power supplied to the screw

W_P Pumping power done by screw

z Axial coordinate

γ Shear rate

Δp Pressure difference between inlet and exit of the melt section

η Viscosity

η_B Viscosity modulus at barrel temperature

θ Dimensionless temperature

λ Carreau constant

ρ Melt density

χ Dimensionless axial position or length

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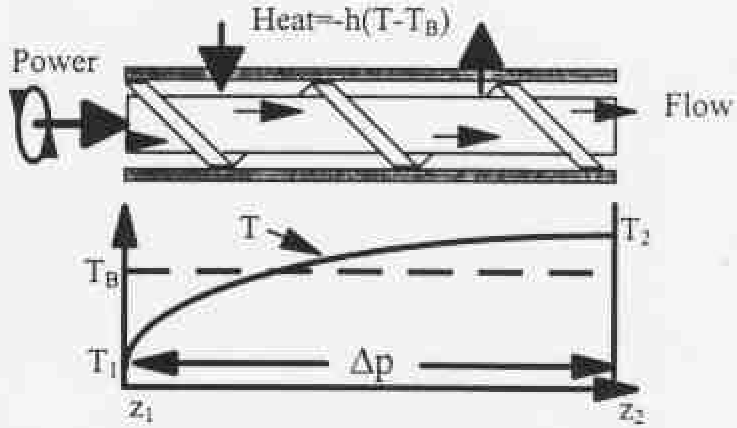

Figure 1. Section of extruder barrel and screw for energy balance.

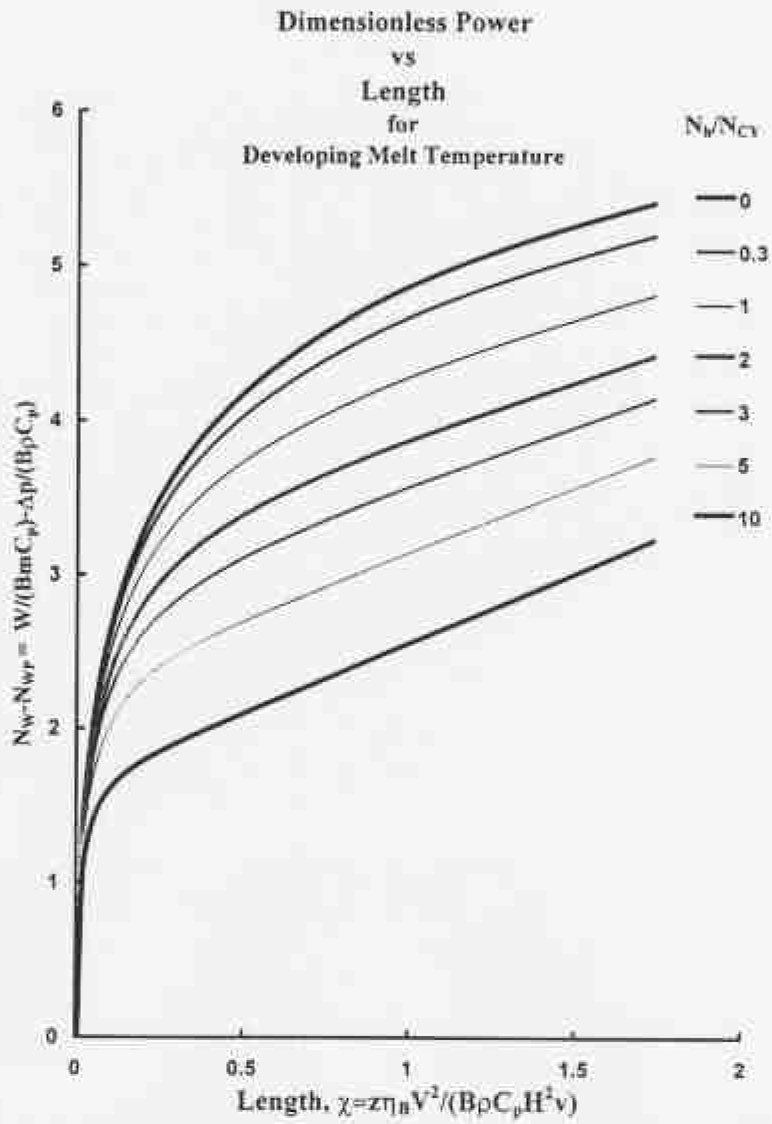

Figure 2. Dimensionless power versus dimensionless length for an extruder melt section. Barrel temperature is constant over length.

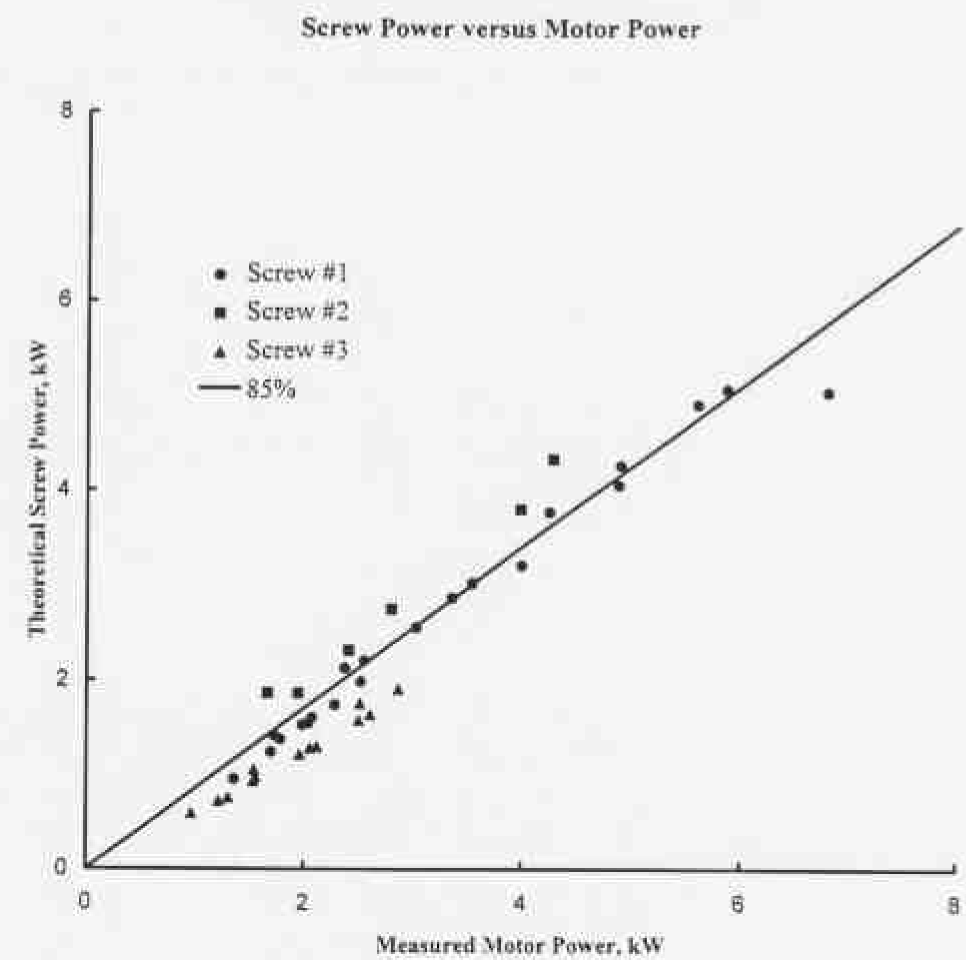

Figure 3. Theoretical power versus measured power for three screws. The extruder is a 63.5 mm x 10 L/D, and the hot melt enters the extruder. The screws are of constant depth and lead.

[Back to Abstract]

[Back to M2-Single Screw]