ESTIMATING FULLY DEVELOPED MELT TEMPERATURE IN EXTRUSION

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Introduction

It is very useful to be able to predict melt temperature in extrusion, particularly in the extrusion of temperature sensitive polymers. Examples are extrusion of crosslinkable polymers, foamed polymers, and polymers that are susceptible to degradation. Unfortunately, the proper calculation of melt temperature is rather involved and requires the use of numerical techniques, the most popular one being finite element analysis.

This paper describes a method to predict the fully developed melt temperature in screw extruders based on simple analytical expressions. The method is easy to use and leads to quantitative results with a minimum of time expenditure.

Melt Temperature Calculation

The fully developed melt temperature is reached when the viscous heat generation is balanced by the heat flux away from the polymer melt. The viscous dissipation in the extruder will cause an increase in melt temperature resulting in reduced viscosity, which will result in a reduction in viscous dissipation. The melt temperature will reach a steady state value when the viscous dissipation has reduced to the point that it equals the heat flux from the polymer melt.

The viscous dissipation is determined by the product of shear stress and shear rate. The average shear rate in the screw channel can be approximated by the Couette shear rate:

$$\dot{g} = \frac{pDN}{H} \tag{1}$$

In equation 1, D is the barrel diameter, N the screw rotational speed, and H the depth of the screw channel

If the melt viscosity is described with a power law equation, the viscous dissipation can be written as:

$$q_v = m\dot{g}^{1+n} = m\left(\frac{pDN}{H}\right)^{1+n} \tag{2}$$

where m is the consistency index and n the power law index of the polymer melt

The consistency index is a function of melt temperature. The temperature dependence of the consistency index can be written as:

$$m(T) = m_0 \exp[a_T (T_0 - T)] \tag{3}$$

Where T is the temperature, T_0 the reference temperature, m_0 the consistency index at temperature T_0, and a_T the temperature coefficient of the viscosity. The viscous dissipation can thus be written as:

$$q_v = m_0 \exp[a_T (T_0 - T)]\left(\frac{pDN}{H}\right)^{1+n} \tag{4}$$

The viscous dissipation is a specific power consumption, i.e. power per unit volume. In S.I. units it is expressed in Watts per cubic meter [W/m³]. The heat flux away from the polymer melt is determined by the heat flux from the melt to the barrel and screw. If the screw is neutral the heat flux to the screw is usually small and can be assumed to be negligible. If screw cooling is used, this assumption will not be correct. The heat flux (heat flow per unit cross sectional area) for cooling the polymer melt is determined by Fourier's law of conductive heat transport:

$$q_c = -k_b \frac{\partial T}{\partial r} \tag{5}$$

Where k_b is the thermal conductivity of the barrel, $\partial T/\partial r|_b$ the temperature gradient in the barrel at the polymer/metal interface. If q_c occurs over unit length, then q_c represents the power per unit volume. Thus, if q_c is divided by the thickness, t, over which the heat conduction occurs, it attains the units of specific power, just as q_v.

In many cases, the temperature at the inside and outside barrel surfaces will not be known. In those situations we have to find another method to determine the heat flux through the barrel. This issue was studied Radovich (1) who compared the cooling capability of air and water-cooled extruder barrels.

The melt temperature will rise initially and then level off as the viscous dissipation reduces with increasing melt

temperature. When a steady state is achieved, the melt temperature no longer changes along the length of the extruder. This is called the fully developed melt temperature or equilibrium melt temperature. This temperature T_e can be determined from a simple energy balance equating the viscous dissipation to the conductive heat loss:

$$m_0 \exp[a_T(T_0 - T_e)]\dot{\boldsymbol{g}}^{1+n} = k_b \frac{T_{bo} - T_{bi}}{t_b^2} \qquad (6)$$

where T_{bi} is the inside barrel temperature, T_{bo} the outside barrel temperature, and t_b the thickness of the barrel.

This equation leads to the following expression for the fully developed melt temperature:

$$T_e = T_0 - \frac{1}{a_T}\ln\left(\frac{q_c}{q_{v0}}\right) \qquad (7)$$

Where q_c is given by equation 5 and q_{v0} is the viscous dissipation with the polymer melt at the reference temperature T_0; it can be written as:

$$q_{v0} = m_0\dot{\boldsymbol{g}}^{1+n} \qquad (8)$$

We now have a quantitative, analytical expression from which the fully developed temperature can be calculated. If we define the equilibrium melt temperature rise ΔT_e as the difference between the reference temperature and the fully developed temperature, $\Delta T_e = T_e - T_0$, we can write:

$$\Delta T_e = -\frac{1}{a_T}\ln\left(\frac{q_c}{q_{v0}}\right) \qquad (9)$$

When $q_c > q_{v0}$ the equilibrium melt temperature rise will be negative, when $q_c < q_{v0}$ the equilibrium melt temperature rise will be positive. Expression 9 provides a simple and convenient expression from which the effect of the various factors influencing the melt temperature becomes clear. These effects can be easily quantified as discussed next.

Influence of Important Parameters

There are several factors that affect the melt temperature. They can be categorized in three main categories:

1. Material properties: barrel thermal conductivity, melt consistency index, power law index, and temperature coefficient of the melt viscosity

2. Operational parameters: screw speed and barrel temperature difference
3. Machine design parameters: barrel diameter, barrel thickness, and channel depth

The effect of the various parameters is shown qualitatively in the following table. Table 1 shows the effect of an increase in any top row variable on the equilibrium melt temperature rise.

	k_b	m	n	a_T	N	ΔT_b	D	t_b	H
ΔT_e	↓	↑	↑	↓	↑	↓	↑	↑	↓

Table 1, Effect of various parameters on equilibrium melt temperature rise.

As shown in table 1, an increase in the thermal conductivity of the barrel material reduces the melt temperature. Considering that the thermal conductivity of various metals varies substantially, it makes sense to consider using a highly conductive barrel material if low melt temperatures are required. The thermal conductivity of various metals is shown in table 2. Corrosion resistant metals tend to have low conductivity, while copper-containing alloys have a conductivity about three to five times higher than carbon steel.

Material	Thermal conductivity	
	[W/m°K]	[BTUft/ft^{2}hr°F]
Hastelloy C276	11.25	[6.5]
Inconel 718	11.42	[6.6]
Inconel 625	9.86	[5.7]
Monel 400	21.80	[12.6]
Monel 500	17.47	[10.1]
4140 steel	42.56	[24.6]
4340 steel	42.21	[24.4]
17-4 stainless	17.82	[10.3]
316 stainless	16.09	[9.3]
304 stainless	16.29	[9.4]
AlZnMgCu	160	[92.5]
CuBe-2	115	[66.5]
CuCoBe	210	[122.4]
Z 434	105	[60.7]

Table 2, Thermal conductivity of various metals.

An increase in the consistency index will increase melt temperatures because the viscous dissipation will increase, see equations 2 and 4. The numeric value of the consistency index is the same as the viscosity at shear rate one ($\dot{\boldsymbol{g}} = 1$) for a power law fluid. The consistency index, therefore, is closely related to the melt index (MI). A low melt index indicates a high value of the consistency index. Clearly, it will be much more difficult

to control melt temperature for a low MI material than for a high MI material. Figure 1 shows a graph of the equilibrium melt temperature rise vs. consistency index for two values of the cooling flux (q_c=10,000 W/m^3 and q_c=100,000 W/m^3) and the coefficient of viscosity a_T=0.02 [K^{-1}].

The straight-line relationship using a semi-log scale indicates that the melt temperature increases exponentially with the consistency index as expected from equation 9. An increase in the cooling flux by a factor of ten reduces the melt temperature rise by about 115°K for all values of the consistency index.

The power law index is a measure of the degree of shear thinning. Lower values of the power law index result in lower viscosity values at high shear rates. In other words, as the power law index becomes smaller, the polymer becomes more shear thinning. This will have a strong effect on the melt temperature rise, particularly at high shear rates, as shown in figure 2.

Figure 2 shows that an increase in power law index from 0.3 to 0.6 will increase the melt temperature about 35°K at a shear rate of 10 s^{-1} and about 70°K at a shear rate of 100 s^{-1}. This indicates that the power law index has a powerful effect on melt temperature (excuse the pun!). Figure 2 explains why LDPE tends to run at lower melt temperatures than LLDPE or metallocenes. LDPE has a power law index of about 0.3, while LLDPE and metallocenes have a power law index of about 0.6.

The effect of the temperature coefficient of the melt viscosity is quite clear from equation 9. When the temperature coefficient of the viscosity (a_T) increases, the melt temperature rise will reduce. Amorphous polymers generally have a much greater temperature coefficient than semi-crystalline polymers, the difference is about a factor of ten. This means that the melt temperature rise in semi-crystalline polymers will be about ten times greater than in amorphous polymers.

An increase in screw speed will raise the viscous dissipation and thus the melt temperature. Since shear rate is directly proportional to screw speed, see equation 1, the effect of screw speed can be seen from figure 2. However, it is more obvious by replotting the data with the shear rate along the horizontal axis, see figure 3.

Increasing screw speed will increase shear rate correspondingly. Figure 3 shows that the melt temperature increases rapidly at low screw speed and more slowly at higher screw speed. As discussed earlier, higher values of the power law index result in higher melt temperatures.

Increasing the barrel diameter will increase the shear rate - other factors being constant. This will increase viscous dissipation and melt temperatures as discussed earlier. Another problem with larger barrel diameters is that the heat transfer surface area increases with the diameter squared, while the channel volume increases with the diameter cubed. As a result, the heat transfer becomes less effective with larger diameter extruders. It is well known in the extrusion industry that the ability to influence melt temperature by barrel temperature changes is very limited for large extruders.

Increasing the barrel thickness will reduce the heat flux through the barrel assuming that the inner and outer barrel temperatures are the same. As a result, a thicker barrel will result in higher melt temperatures.

Finally, increasing the channel depth will reduce the shear rate and viscous heating as discussed earlier; this will result in lower melt temperatures. In fact, the channel depth is one of the most critical screw design parameters to control melt temperature. Deep flighted screws are used when the viscous dissipation and melt temperatures have to be minimized. That is why screws used to extrude rubber generally have deep channel. The same is true for cooling extruders in tandem extrusion lines for foamed polymers.

Conclusions

This analysis provides a simple and fast method to estimate the fully developed melt temperature in screw extruders. The effect of material properties, processing conditions, and machine design parameters can be determined quantitatively. As a result, the analysis can be used to predict how melt temperature will change when another plastic is extruded and how the screw design or processing conditions should be changed to change melt temperature.

It should be noted that several simplifying assumptions in the analysis. We have assumed that the melt temperatures are uniform across the depth of the channel. In reality this is not the case; in fact, large melt temperature changes can occur across the depth of the channel as discussed by Rauwendaal and Anderson (2). We can assume that the melt temperature calculated with this analysis corresponds to a bulk average melt temperature. We have also assumed that the fully developed melt temperature is reached before the end of the extruder. This is a reasonable assumption for small diameter extruders; however, this may not be a good assumption for large diameter extruders (2).

It was also assumed that the viscous dissipation in the flight clearance does not affect the melt temperature in the screw channel. This would appear to be a

questionable assumption. However, finite element analysis has shown that the actual melt temperature rise in the clearance region actually is relatively small (2). The reason is that the heat transfer in the flight clearance is very effective because the clearance is generally quite thin.

Lastly, it was assumed that the details of the screw geometry do not affect the heat transfer to the barrel; this is not completely true. The number of flights, the flight clearance, the flight helix angle, and the flight width all affect the heat transfer from the polymer melt to the barrel. If we want to study the effect of these parameters in detail we have to move to a more complicated, numerical analysis.

References

1. J.L. Radovich, "An Experimental Comparison of Heat Removal in Water or Air Cooled Aluminum Barrel Coolers," TAPPI Polymers, Laminations &Coatings Conference, 103-107 (1995)
2. C. Rauwendaal and J. Anderson, "Finite Element Analysis of Flow in Extruders," 52nd SPE ANTEC, 298-305, San Francisco, CA, (1994)
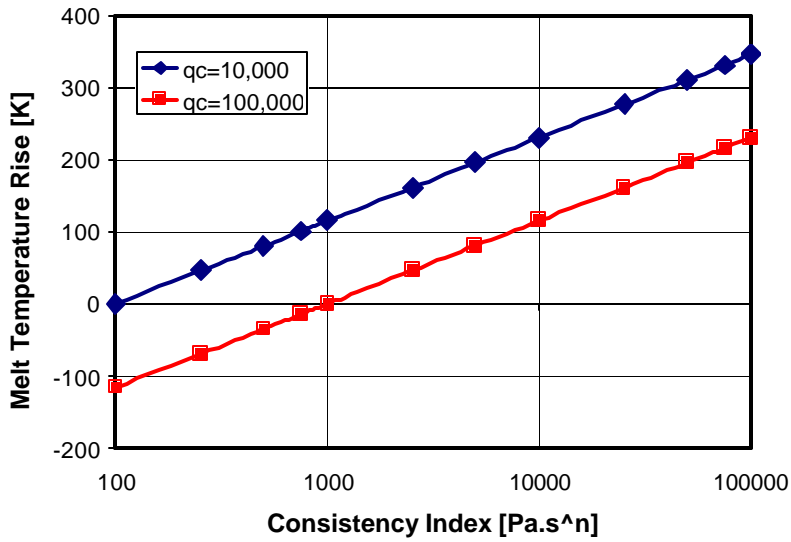
Figure 1, Equilibrium melt temperature rise versus consistency index.
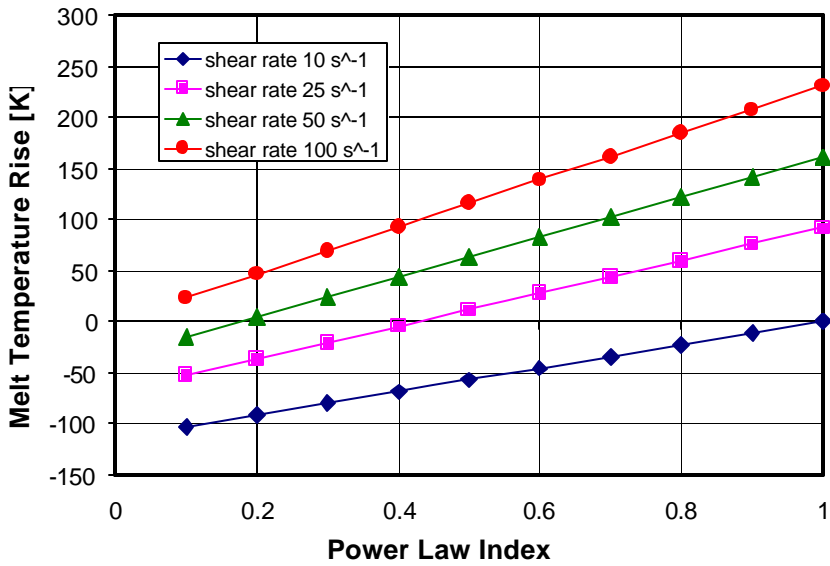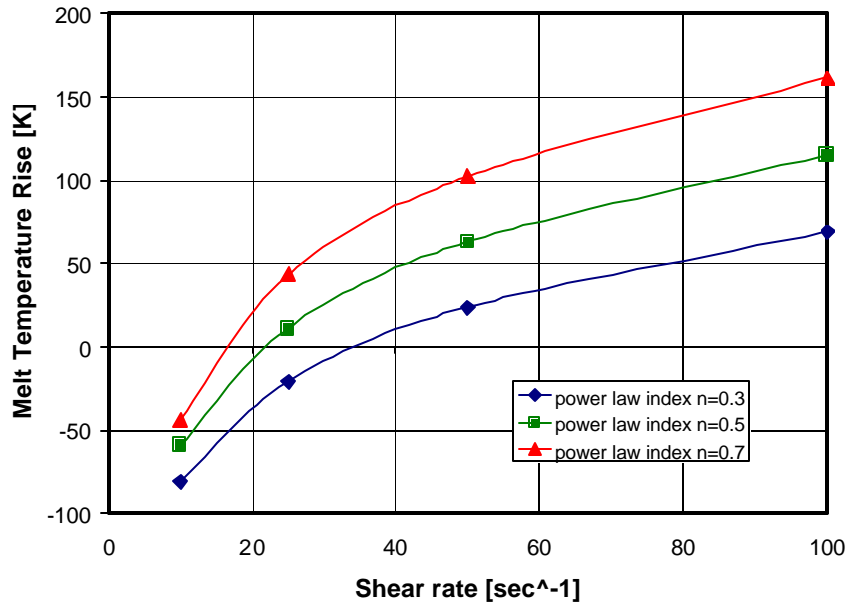

Figure 2, Equilibrium melt temperature rise versus power law index.

Figure 3, Equilibrium melt temperature rise versus shear rate.