UNIVERSAL MELT TEMPERATURE DIAGRAM

Stephen J. Derezinski, Extruder Tech, Inc., Penfield, NY 14526

Abstract

The Universal Melt Temperature Diagram (UMTD) provides the developing melt temperature vs. length of an extruder based on four unique dimensionless groups. Factors included in the four groups are;

- the dependence of melt viscosity on shear and temperature,
- resin thermal properties,
- screw geometry, and
- process conditions.

Melt temperature vs. extruder length is provided in a succinct format that vividly illustrates the melt temperature development process.

Introduction

In the melt section of the extruder, the temperature of the molten polymer develops as it flows to the exit. At the exit, the temperature is defined as the product temperature, and it has a bulk average value and a distribution. With the UMTD accurate analysis of the melt temperature development and product temperature can be made to assess performance. This work is an extension of previous work for melt-temperature dimensionless functions [1,2] and melt-zone heat transfer coefficients [2-6]. The contributions of screw design, resin properties, and process conditions can be easily analyzed with this comprehensive diagram.

A few of the factors that can be investigated about the process are:

- Is there excessive heating or cooling of the resin?
- Is there excessive residence time?
- Is the temperature uniformity near optimum?
- Are the barrel zone temperatures set properly?

It will be shown how the UMTD, a single diagram of temperature vs. length, universally illustrates these conditions of importance to good product quality.

Basics Assumptions of the UMTD

The UMTD is based on the conservation of energy for the resin melt flow. These basic governing equations (See Appendix 1) equate the change in energy of the resin melt to the sum of viscous shear energy provided by the screw and of heat transfer with the barrel. Basic assumptions are:

- The change in energy is assumed to be proportional to the product of the resin melt specific heat and melt temperature change.
- The viscosity of the resin melt is assumed to follow the Carreau-Yasuda model for shear strain rate. See Appendix 2.
- The viscosity (Appendix 2) is assumed to follow an exponential function of temperature. The reference point is the viscosity modulus at the barrel wall temperature which ties the exponential function closely to the viscosity vs. temperature data curve.
- Heat transfer with the barrel is assumed to be a function of the heat transfer coefficient between the melt and the barrel, which is known to be a function of flight clearance and screw speed [2-6].
- A known fixed screw-geometry consists of a helical channel formed by a flight with a small clearance.
- Screw speed, fixed barrel wall temperature, and flow rate are known.
- Thermal properties of the resin melt are known constants.
- Thermally steady-state equilibrium and an adiabatic screw are assumed.

The melt section length of the extruder is divided into "melt zones". Melt zones are defined as any length of the melt section that has constant barrel zone temperature *and* fixed screw geometry. A change in either one of these constitutes the beginning of a new melt zone.

Unique Dimensionless Groups

The UMTD depends upon a set of four dimensionless groups for its universality as follows:

1. θ, Temperature
2. χ, Axial Position
3. N_h, Barrel Heat Transfer Coefficient
4. N_{CY}, Carreau-Yasuda Shear Strain

All four of the dimensionless groups are mathematically defined in Appendix 1 along with the governing equation.

Each group is defined as *uniquely* having a variable of the process as a factor and so named. For example, the first group is the temperature number, because it is the only group of the set that has temperature explicitly as a factor (equation 5). The temperature number is on the ordinate of the UMTD to solely represent average melt temperature. Similarly, the abscissa is represented by the uniquely defined axial position number, equation 6. Therefore, the UMTD axes are proportional to temperature vs. extruder axial position so as to appear in form and shape to data for temperature vs. axial position. Therefore, the UMTD is easily related to actual machine operation and interpretation.

The UMTD will be shown to have two domains. The first domain represents conditions for heating the melt, and the second for cooling the melt. Conditions for heating the melt are most common for plastic extrusion. They will always occur when the melt temperature entering a melt zone is less than the fully developed melt temperature for that melt zone.

UMTD (Melt Heating Domain)

Figure 1 shows the UMTD for the melt heating domain. Parametric curves based on the ratio of barrel heat transfer coefficient number, N_h, to the shear-strain number, N_{CY}, provide the average resin melt temperature number, θ, vs. extruder axial position number, χ. The heat transfer number is unique to heat transfer coefficient, and the shear-strain number is based on the Carreau-Yasuda equation for viscosity. See Appendix 1.

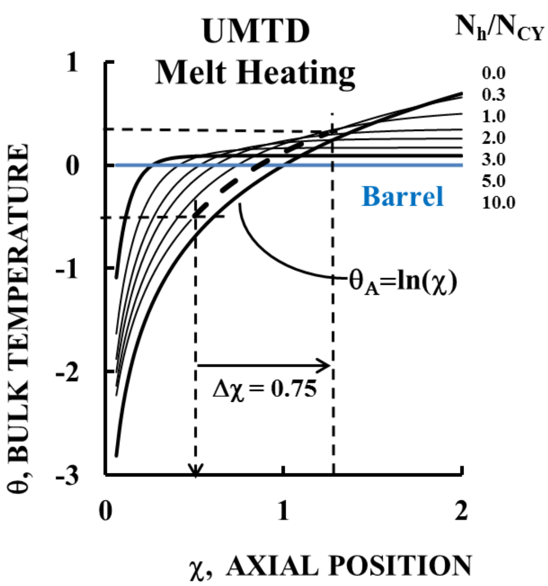

Figure 1. The basic UMTD for Melt Heating. Units are all dimensionless. An adiabatic barrel solution, θ_A, is shown as a limiting condition. An example for a single melt zone is shown by the dashed lines.

The beginning of a melt zone, χ_0, is defined by the melt temperature at the inlet to the zone, θ_0, and the prevailing ratio of heat transfer number and shear strain number, N_h/N_{CY}. For the example shown in Figure 1, a melt zone with a value of θ_0 of -0.5 and a value of N_h/N_{CY} of 0.3 gives an inlet position of χ_0 = 0.5 for this melt zone.

The end of the melt zone then occurs when the barrel zone temperature or the screw geometry is changed. In Figure 1 a change in axial position, $\Delta\chi = 0.75$, is shown that is calculated based on the actual length, L, of the melt zone. This change in axial position, Δχ, is then added to the initial position, χ_0, to determine the position of the end of the melt zone, χ_L, on the UMTD. Figure 1 shows for the example that a change in axial position of $\Delta\chi = 0.75$ would make the end of the melt zone, χ_L, occur at an axial position of 0.5 + 0.75 = 1.25. The curve along N_h/N_{CY} = 0.3 would be the path of the melt temperature development between axial positions 0.5 and 1.25. The diagram shows the approximate exit temperature number is $\theta_L = 0.3$.

Fully Developed Melt Temperature

Figure 1 shows that the temperature stabilizes to a constant value at some a point as axial position is increased. Above this point any additional length of the melt zone will not change the melt temperature. Therefore, this stable temperature is fully developed. For melt heating it represents a maximum value for the melt zone.

Figure 2 gives the axial position of the beginning of fully developed melt temperature as a function of heat transfer and shear strain numbers. The practical importance of this is that undue residence time will be added to the melt at greater axial length. Longer residence time is often associated with poor product quality, such as discoloring.

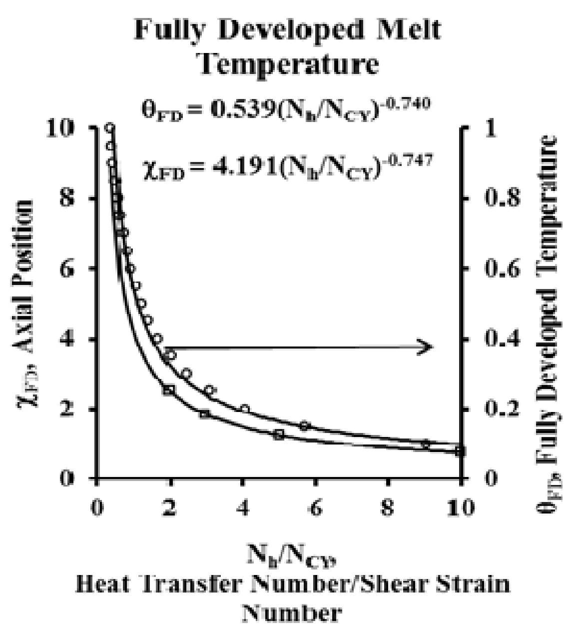

Figure 2. Axial Position Number at which Fully Developed Melt Temperature Begins and Fully Developed Temperature. They are a funtion of only heat transfer and shear strain numbers.

The fully developed temperature shown on the right axis of Figure 2 is a key value for each melt zone. The fully develped temperature will not change once this axial position given by Figure 2 is reached without changing process parameters or entering a new melt zone.

The hyperbolic shape of the curves of Figure 2 illustrates that heat transfer coefficient and shear strain have a point of diminishing returns as the heat transfer is increased and/or shear strain is decreased. That is, at high values of N_h/N_{CY}, change in it is less significant to temperature change. This would occur for high heat transfer coefficient and/or low viscosity and shear. These conditions are not typically found in plasticating extruders which have viscous flow with moderate or low heat transfer coefficients.

The fully developed temperature does occur in large metering extruders that are designed to only pump melt at contant temperature with the purpose of stabilizeing flow disturbances. The screw is normally of fixed channel dimensions and helix angle. Heat must be removed over the entire length of the extruder to maintain the constant melt temperature, and that energy is provided by the motor.

UMTD (Melt Heating) Temperature Limits

Figure 1 clearly shows that there are an upper limit to the melt temperature and a lower limit to the melt temperature. Figure 3 shows how melt temperatures will fall between these two limits for this domain of increasing the melt temperature. If they do not, then one or more of the assumptions of the UMTD is violated (such as steady state conditions) or the data are incorrect. This makes the UMTD a useful diagnostic tool.

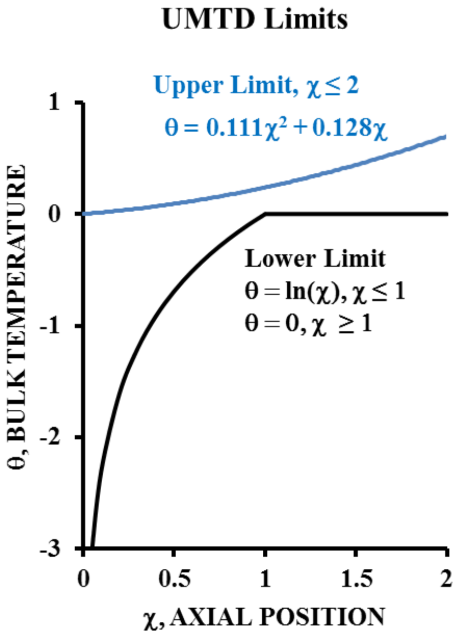

Figure 3. Upper and Lower Limits of Melt Temperature Heating

In Figure 1, the temperature function for an adiabatic barrel is shown as $\theta_A = \ln(\chi)$. This is an analytical solution to the governing energy balance, and it represents the limit of a fictitious adiabatic barrel (heat transfer coefficient = 0). All of the other curves are obtained through a finite difference solution to the governing equation, and they represent conditions that could actually occur. In Figure 3, the adiabatic solution provides a lower mathematical limit to the melt temperature for position value, χ, less than one.

Also, note in Figure 3 that there is a "narrows" between the upper and lower limit at $\chi = 1$. The significance is that at this point the variation in melt temperature is minimal. The consequence is that the melt temperature is least sensitive to variations of any of the other variables for χ at or near a value of 1. This would be a good condition to occur at the end of the extruder to minimize variations in product temperature uniformity. Figure 3 also shows that above a value of $\chi = 1$ the melt temperature will always be hotter than the barrel wall temperature ($\theta = 0$).

UMTD (Melt Cooling Domain)

Figure 4 shows the second domain, UMTD Melt Cooling, for temperatures always decreasing. This occurs when the melt temperature entering the melt zone is greater than the fully developed temperature given by Figure 2 since the fully developed values of temperature for the melt cooling are the same as for melt heating. Ultimately the fully developed temperature will be reached if the melt zone has enough length to reach axial position value given by Figure 2.

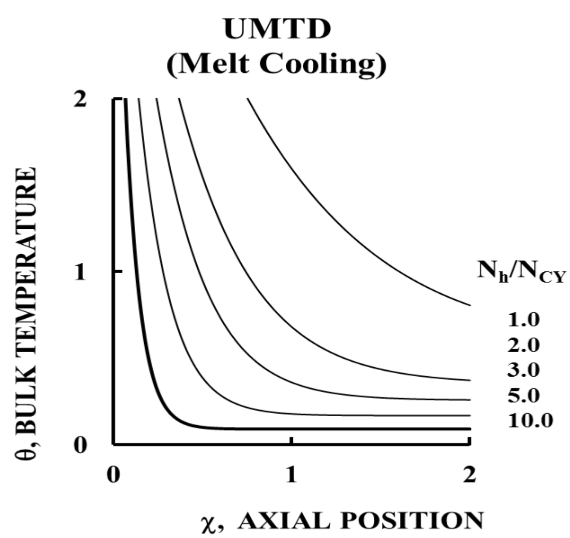

Figure 4. Melt Cooling The temperature of the melt entering the melt zone is greater value than the prevailing fully developed melt temperature.

Cooling of the melt is not typically done in plastic extrusion since this would be needed as a result of overheating the melt. Overheating is avoided as it would lead to degradation of the resin. Cooling the melt stream is also very inefficient because viscous heating requires substantially colder barrel zone temperature, and this would lead to excessive temperature gradients and possible resin freeze-out on the barrel walls. Melt zones can be established so as to avoid needless melt cooling with the aid of the UMTD.

Total UMTD

Figure 5 shows the full UMTD consisting of both heating and cooling domains for comparison. The cooling domain (upper in blue) is noticeably inefficient as compared to the heating domain (lower in black). Viscous heating will hinder cooling the melt in the cooling mode, but it aids heating of the melt in the heating mode. This makes cooling of the melt inefficient compared to heating of the melt, and this is quantifiably evident by the UMTD.

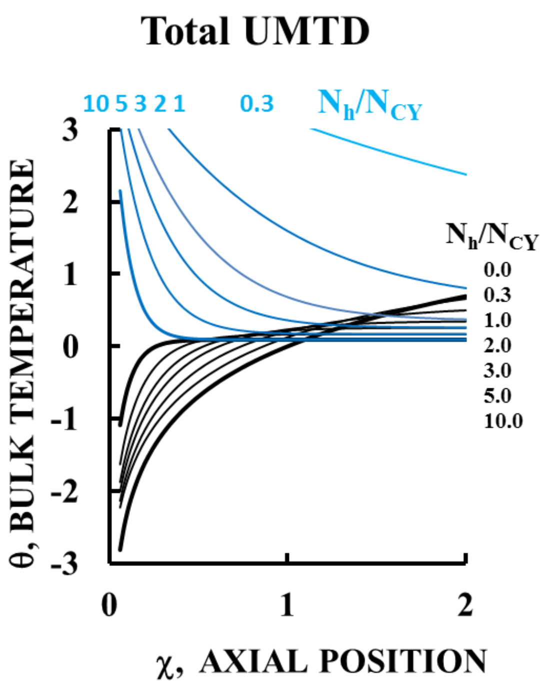

Figure 5. The Complete UMTD Melt heating and melt cooling shown for comparison.

Temperature Distribution

The temperature distribution of the melt between the barrel and the screw can be calculated based on the data for the bulk temperature used by the UMTD. Known values of

1. bulk temperature,
2. barrel wall temperature,
3. heat flux at the barrel wall, and
4. the assumption of an adiabatic screw

provide four independent parameters used to calculate the temperature distribution of the melt with a cubic function. See Appendix 3 for details.

Data for the exit melt temperature distribution for a 31.75 mm, 16/1 L/D extruder were measured [7] with a thermocouple bridge spanning a 25.4-mm diameter exit pipe. The resin was LDPE, and Figure 6 shows the data [7]. Also shown is the exit melt temperature cubic profile calculated from the UMTD analysis as described above, and good agreement is noted. The prediction compares well with an iterative approach used later for the same test setup [8].

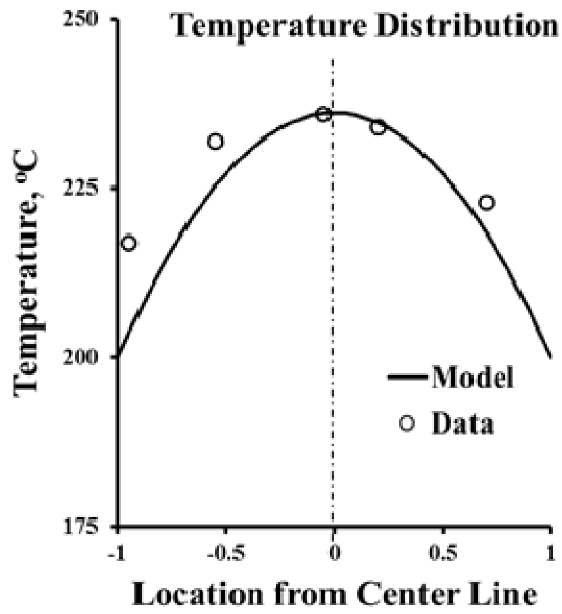

Figure 6. Temperature Distribution for LDPE Model based on UMTD analysis of bulk temperature distribution.

The cubic function used here to model the temperature profile will demonstrate a known variety of melt temperature profiles. The UMTD predicts the average temperature, but for a given average temperature dramatic differences can occur in the melt temperature profile predicted by the cubic function.

For the above example a hypothetical doubling of the viscosity modulus, η_w, can be studied for its effect on the temperature profile. To maintain dimensionless similarity, the heat transfer coefficient, h, would be doubled (see equation 8, Appendix 1) and the melt section length, L, would be halved (see equation 7, Appendix 1). The same values for the dimensionless groups result in the same predicted average temperature. However, the exit temperature profile as predicted by the cubic function used here is dramatically different. Figure 7 shows the temperature profile to be an "M" shaped profile [9] for this hypothetical case. Other profiles [8,10], such as "U" shaped and "inverted M" or "moustache" profiles all result with the cubic function when proper conditions exist.

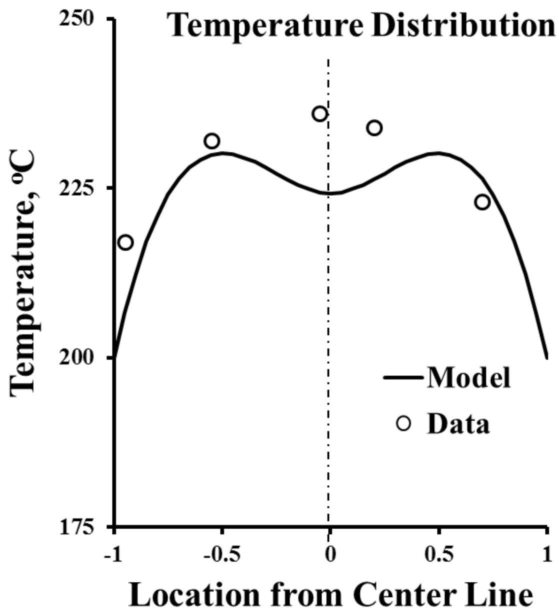

Figure 7. An "M" Shaped Profile The average product temperature for the model is the same as for the data.

The practical significance is that an average product temperature is subject to a large variety of exit temperature profiles. Using the UMTD to model the average temperature leads to calculation of the temperature profile with the cubic function. A large thermal profile difference in two processes can be identified even though they have the same average product temperature.

It is also notable that the melt temperature distribution so calculated is a constant (uniform) for values of axial dimension, χ, where θ=0. Therefore, thermal uniformity is optimized for these values of the axial position.

Summary

The UMTD (See Appendix 4 for enlarged version) is a single diagram created to model the melt temperature development in a single screw extruder in detail. Only four dimensionless groups are needed to include viscosity dependence on shear and temperature, process conditions, screw design, and resin melt thermal properties. Each group is singly associated with a single process variable to make the results easily and meaningfully interpreted in terms of an actual melt temperature profile.

Conclusions

1. The Universal Melt Temperature Diagram (UMTD) graphically shows the melt temperature changes as the melt flows to the exit. Various characteristics of the curves are given that define what is needed for good processing.
2. Finite temperature limits are established for the melt with the UMTD.
3. The UMTD shows the melt can be either heated or cooled with an extruder.
4. Cooling of the melt with an extruder is demonstrated to be very inefficient by the UMTD.
5. Conditions for optimum product temperature uniformity are clearly defined by the UMTD.
6. Data show melt temperature distribution can be accurately calculated with the results of the UMTD.
7. Conditions for fully developed melt temperature are identified.

Nomenclature

a Yasuda exponential term for shear strain
B exponential factor for melt viscosity vs. temperature
C_p Melt specific heat
h Heat transfer coefficient, melt to barrel
H Channel depth (constant)
H_R Ratio of channel depth to flight clearance
k Thermal conductivity of melt
L Melt section length
n Exponential term for shear strain
N_{CY} Carreau-Yasuda dimensionless strain group
N_h Heat transfer dimensionless group
T Temperature
$\overline{T}$ Bulk temperature
T_W Temperature of barrel wall
v Average melt velocity, axial direction
V Screw surface speed
Vo_c Channel volume fraction
Vo_f Flight volume fraction
x Location between barrel wall and screw channel
z Axial position
γ Shear rate
$\Delta\chi$ Melt section dimensionless length
η Viscosity
η_W Viscosity modulus at barrel wall temperature data
θ Dimensionless temperature
θ_A Temperature for an adiabatic barrel
θ_{FD} Fully developed temperature
θ_L Axial temperature at of end of melt zone
θ_0 Temperature at start of melt zone
λ Carreau factor
ρ Melt density
χ Dimensionless axial position
χ_L Axial position at end of melt zone
χ_0 Axial position at beginning of melt zone

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Appendix 1

Dimensionless Variables

Dimensionless Energy Equation

$$\frac{d\theta}{d\chi} = -\frac{N_h}{N_{CY}}\theta + e^{-\theta} \quad (1)$$

$$\theta = \theta_0 \quad (2)$$

$$\chi = \chi_0 \quad (3)$$

$$\chi_L = \chi_0 + \Delta\chi \quad (4)$$

Dimensionless **Temperature**

$$\theta = \frac{(\bar{\mathbf{T}} - T_w)}{B} \quad (5)$$

Dimensionless **Axial Position**

$$\chi = N_{CY}\frac{(\eta_w V^2)}{(\rho B C_p H^2 v)}\mathbf{z} \quad (6)$$

Dimensionless Melt Zone **Length**

$$\Delta\chi = N_{CY}\frac{(\eta_w V^2)}{(\rho B C_p H^2 v)}\mathbf{L} \quad (7)$$

Dimensionless **Heat Transfer Coefficient**

$$N_h = \frac{\mathbf{h}HB}{V^2\eta_w} \quad (8)$$

Dimensionless **Shear Strain Function**

$$N_{CY} = Vo_c(1+(\lambda\dot{\gamma})^a)^{(n-1)/a}(1+12(v/V)^2) + Vo_f H_R^2(1+(\lambda\dot{\gamma}H_R)^a)^{(n-1)/a} \quad (9)$$

Adiabatic Barrel Condition, set $N_h = 0$ in equation 1.

$$\theta_A = \ln(\chi) \quad (10)$$

Fully Developed Temperature, Implicitly Defined
Set $d\theta/d\chi = 0$ in Equation 1. Then,

$$e^{-\theta_{FD}}/\theta_{FD} = N_h/N_{CY} \quad (11)$$

Appendix 2

Viscosity

The viscosity is assumed to follow the Carreau-Yasuda Equation for shear combined with an exponential function for temperature as follows:

$$\eta(\dot{\gamma},T) = \eta_w e^{-(T-T_w)/B}(1+(\lambda\dot{\gamma})^a)^{(1-n)/a}, \quad (12)$$

where the value of the viscosity modulus η_w, at the known barrel wall temperature, T_w, is obtained from actual viscosity vs. temperature data. The value of exponential constant, B, can also be adjusted according to the wall temperature or shear rate.

Appendix 3

Cubic Temperature Distribution

The four factors that result from the temperature analysis are used to estimate the melt temperature distribution as follows.

The distribution is assumed to follow a cubic function as

$$T(x) = ax^3 + bx^2 + cx + d \quad (13)$$

Bulk melt temperature is known, so

$$\bar{T} = (1/H)\int_0^H T(x)dx = \frac{aH^3}{4} + \frac{bH^2}{3} + \frac{cH}{2} + d\,. \quad (14)$$

Barrel wall temperature (x=0) is known, so

$$T_w = T(0) = d\,. \quad (15)$$

Heat flux at the barrel wall (x=0) is known, so

$$dT(0)/dx = -h/k(\bar{T} - T_w) = c\,. \quad (16)$$

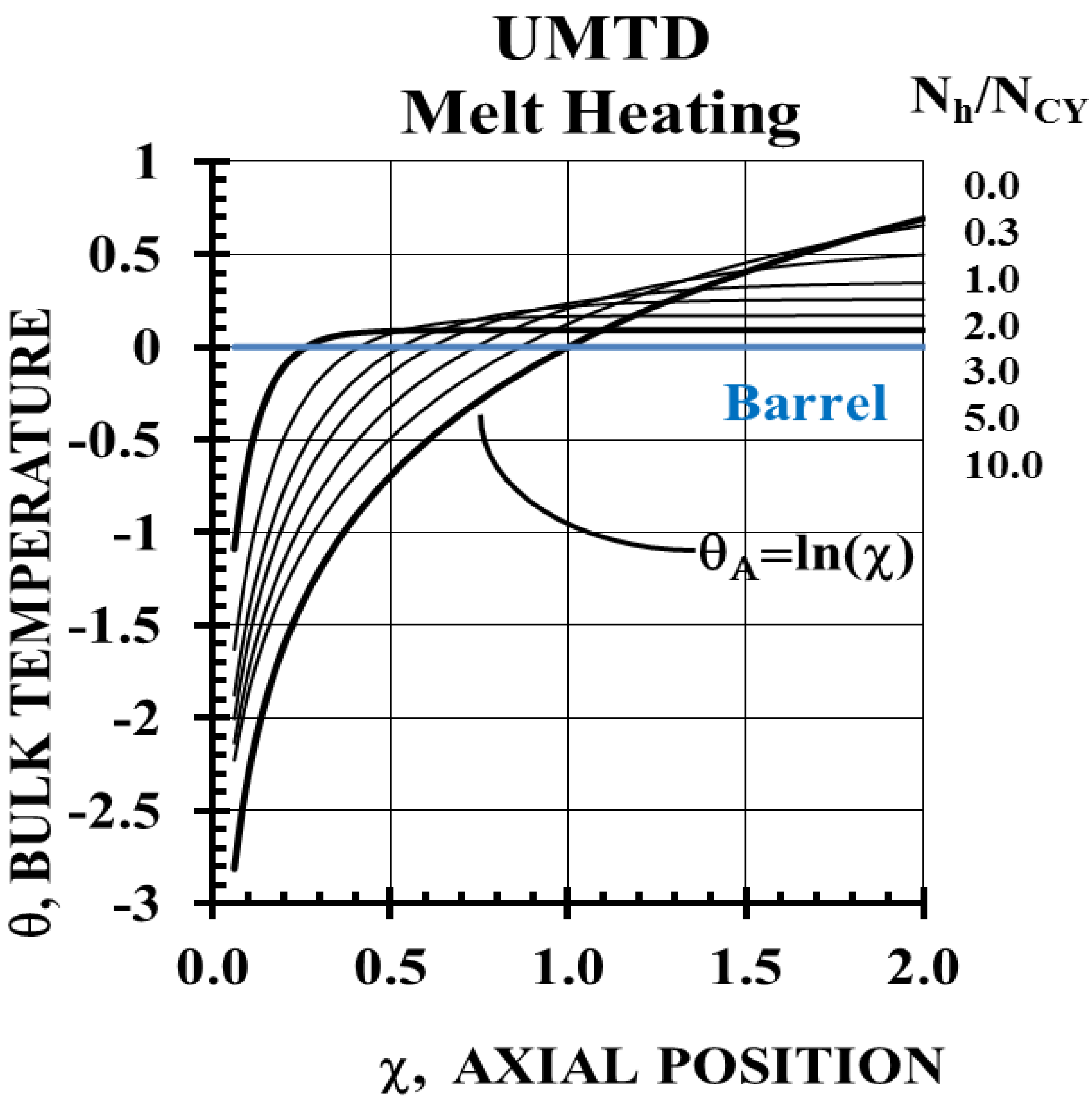
An adiabatic screw is assumed (x=H), so

$$dT(H)/dx = 0 = 3aH^2 + 2bH + c\,. \quad (17)$$

Equations 14-17 are solved for the 4 coefficients of the cubic equation 13 (a, b, c, and d) to give the temperature profile.

Appendix 4

Enlarged UMTD



Key Words

Temperature, melt, metering, pumping, model, analysis, plastic, resin, flow, extruder, single-screw