

Polymer Extrusion Cooling for the 21st Century

A white paper by:

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Considering all of the plastic produced and used every day, it is surprising that very little is documented on the cooling process for continuous profiles of extruded shapes.

The bulk of the cooling process is accomplished through the application of “rules of thumb” learned and used by cooling tank manufacturers, and through trial and error methods of individual processors. In spite of the desirability of processors to minimize space and elapsed time required to effectively cool profiles, the cooling process remains a “black art” as no tools exist that will accurately predict the time response of cooling plastics with liquids. This is remarkable in itself because the cooling puzzle can be solved through the simplification of the transient heat transfer equation for the materials involved.

Even more remarkable is that through the use of powerful personal computers, the process can be modeled and a solution derived through the use of finite difference methods.

The keys to accurately predicting the cooling response are:

1. Calculating the convection heat transfer coefficient from the plastic profile into the coolant
2. Knowledge of the mechanical properties versus temperature of the plastic

With these keys, required cooling times can be determined through the use of advanced computer models.

The challenge to this methodology is in obtaining accurate thermal conductivity and heat capacity of polymer compounds for use in predicting thermal response. Since there are literally thousands of compounds that are used in polymer extrusion, this paper concentrates on only six commonly used:

- Polyethylene (PE)
- Polypropylene (PP)
- Polycarbonate (PC)
- Polystyrene (PS)
- Poly Vinyl Chloride (PVC)
- Acrylonitrile Butadiene Styrene (ABS).

All of the analyses described in this paper assume isotropic forms with temperature dependent properties. Since the extruder is a fairly good mixer and the material is normally compounded prior to reaching the throat of the extruder. This is a reasonable assumption.

The Cooling Process

The goal of the cooling process is to bring the polymer from the molten state, leaving the die face, to a temperature that corresponds with the mechanical properties

TECHNICAL PRODUCT INFORMATION

required for post-processing (cutting and/or packaging) that will not leave permanent deformation of the final product.

Manufacturers would ideally like to have this occur as soon as possible, and in the shortest physical length attainable, for a given throughput of plastic. A third variable that should be considered is the energy (electricity) required for the cooling process – this should be evaluated so that any cooling improvements do not add production costs that would not significantly affect the manufacturer's ability to sell its product.

When plastic extrusion first came to popularity, cooling was accomplished by blowing ambient air over the profile. Later, water immersion in a static bath was introduced and was followed by moving water – cooling, that increased the heat transfer coefficient with a corresponding increase in manufacturing throughput. In the 1990s, cooling rates were again increased by the use of high velocity spray nozzles for forced convection cooling of the profile. Forced convection has become the state of the art as the energy required to move spray water is significantly less than that required to move an entire tank contents of water.

Forced convection cooling is the tradeoff between the energy required to spray the cooling water over the profile and the increased benefit of the cold water “wiping away” the warm insulating water layer, known as the boundary layer, next to the profile. The boundary layer is created by the heat transferred from the surface of the hotter profile to the cooling water next to the surface and tends to act as an insulator

between the profile and the sprayed cooling water. By using enough force, the sprayed water can effectively decrease the boundary layer enough to enable increased cooling through a higher Δt , ergo increased heat transfer. It should be noted here that there does exist a point of diminished returns where increasing the force of the water spray yields very little increase in the rate of cooling – at this point, increasing the spray flows results in dramatically increased energy costs per heat unit removed.

Polymer Properties Effect on Cooling Times

The principle material properties that affect the cooling time are plastic thermal conductivity and specific heat (heat capacity). The thermal conductivity is a temperature dependent property that defines how quickly heat can move through a compound versus the temperature difference within the compound. The thermal conductivity can be different for each compound with some having properties that are directly proportional to temperature and some that are inversely proportional to temperature. Heat capacity however, is the amount of heat that a compound can hold and often is described as the amount of heat necessary to add or remove from a compound to effect a discrete change in temperature of that compound.

For cooling plastic profiles, the thermal conductivity can be the limiting factor in determining the amount of time required for cooling. Since industry does not enhance (perhaps it should) the polymer properties to increase conduction, the time required to

TECHNICAL PRODUCT INFORMATION

cool a defined profile is largely governed by the size, thickness and general mass of the profile and the thermal conductivity of the compound, which incidentally, is usually low for polymers as they make good thermal insulators.

Heat capacity (specific heat) defines the amount of energy needed to change the temperature of a polymer. It can be expressed in heat rate per unit time per unit temperature. Since there is no clearly defined melting temperature for polymers, we will address the latent and sensible transfer lumped in together as heat capacity.

What this leaves us with, from a practical standpoint, is that the heat within the extruded compound needs to be lowered to the maximum allowable temperature of the profile for post processing. We can begin to accurately predict how to accomplish the minimum cooling time possible knowing the:

- Maximum thermal conductivity rate
- Specific heat of the compound
- Starting temperature
- Required temperature after cooling

This information, coupled with the amount of energy expended to achieve the minimum cooling time, can be adjusted accordingly to maximize the process from a business standpoint.

Simulation of the Cooling System's Effect on the Profile

To add to the complexity of the calculation of cooling, it must be remembered that both of the primary considerations, heat capacity and thermal conductivity, are dependent on

the actual temperature of the polymer compound. This means that as heat moves from one location to another within the profile, these properties will vary. The variability of these properties needs to be accounted for in the calculation for cooling or serious inaccuracies in predicting cooling times will result. The ultimate means of accounting for this is a time-marching finite difference methodology. In other words, the profile cross section is divided into many small elements where the properties are "constant" for a given slice of time. The temperature is calculated across these elements for each time step and tabulated to closely approximate the temperature profile of the polymer at any given moment.

Here again is another tradeoff; this one being in computing power versus the time required to run the simulation. With today's personal computing power these simulations are quite precise with reasonable calculation times. Each simulation takes between 3 to 30 minutes to produce the profile's temperature versus time response to a cooling scenario.

Solving the Temperature vs. Time Problem

The computer simulation is set up by selecting the polymer, its shape and thickness and the initial starting (Die) temperature. To perform the simulation, the profile is sprayed with a virtual spray of water that promotes a heat transfer coefficient on the surface of the profile. This coefficient, together with the temperature of the cooling water predicts the surface convection heat transfer of the profile. It is a time dependent prediction as the amount

TECHNICAL PRODUCT INFORMATION

of heat transferred at any given moment is subject to the Δt between the cooling water and the surface of the profile which is continuously changing. The computer simulation calculates the local temperature marching through the cross section of the extruded profile taking into account the local polymer properties at that temperature. The simulation performs this calculation for each time period that is requested. The highest final allowable temperature is located where the profile is the thickest (the center for a solid profile). This is the critical temperature to understand because post processing of the profile out of the cooling tank needs to have a maximum allowable temperature to prevent poor profile ends or other heat related permanent deformation of the profile.

For a constant profile speed through the cooling tank, the time also represents a linear position in the cooling tank. Hence for a requested final temperature, there is a tank length that is associated with the amount of time the profile requires to be cooled. We have been able to fit a curve for standard profiles and polymers that we can predict the final temperature of the inside of the profile versus time. For example, if the producer knows that they need the polymer to be at 130°F to prevent post processing deformation, we can predict the amount of time needed to cool a specific product and maximum throughput in pounds per hour that a certain length of tank can support. There needs to be no additional length or “safety factor” because the process is completely calculated. This can create significant confidence in the throughput that can be supported by a given cooling

system. Without this calculation, the amount of unknowns to this process previously caused safety factor after safety factor to be added to the process – adding unnecessary capital expense to the downstream tank and operating expense to the cooling process for the producer. This calculation predicts the performance of the cooling tank without extensive empirical testing.

Future Work

The precision of this calculation could lead to some overconfidence in the accuracy of the results of these calculations. There are several areas where the accuracy can suffer, especially if trying to extrapolate the results to polymer compounds that were not considered in the development of the calculation – “average” compounds were used in the development of the model from which mechanical properties versus temperature were ascertained. If the polymer compound to be used has additional components or additives, the properties could vary and introduce error into the solution.

Opportunities for application of this model to additional profiles would be to model the internal foaming process. The present model uses a homogenous mixture across the cross section. To accomplish this, the profile would need to be radially segmented into solid layers, and foamed layers (probably lower in thermal conductivity, but also lower in density and mass), the different material properties of these foamed layers would have to be tested and input into the perspective layers for the model. The finite difference calculation would

TECHNICAL PRODUCT INFORMATION

require more processing time, but not necessarily more computing power.

Conclusion

We know that polymer properties of density, thermal conductivity and heat capacity vary significantly with the temperature of the polymer as it cools and hence must be accounted for in any cooling calculation. Today's computers are able to calculate the transient temperature profile for plastic as it cools and these results have been assembled into a final temperature vs. time equation for a given profile. Using this, it has been demonstrated that Forced Convection (Spray) Cooling has the benefit of high velocities of cold water applied to the profile resulting in increased throughput and lower operating costs compared to

submerging and moving the profile through a tank of water. Spraying maintains the minimum thermal boundary layer (resulting in maximum heat transfer) while only moving a fraction of a full tank of water over the profile. This process, using the finite difference equations and thermal / mechanical properties, has been analyzed and developed for several common profiles and compounds and your Novatec representative can assist you in your extrusion cooling application system sizing. The sizing program available will eliminate the need for multiple safety factors and a close approximation to the actual physical system performance by accounting for polymer compound properties variation with temperature.

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