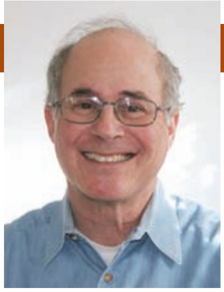

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Engineering: Heat Transfer in Extruders—The "Adiabatic" Extruder and Heat Losses

I hope this column will be the first in a series about heat transfer in extruders. Heat transfer in extruders presents a considerable problem for the successful scale-up of extruders.

Many analyses of extruders begin with one of two assumptions. First, one can consider that the material in the extruder is isothermal, which is, of course, is not usually a realistic condition. Second, one can consider that in an adiabatic extruder, the only heat transfer to the system is via viscous dissipation and there is no heat transfer from or to the wall of the extruder. Either of these assumptions makes the mathematical prediction of extruder performance relatively straightforward. Adiabatic operation is sometimes confused with what the polymer literature refers to as "autogenous" operation. Autogenous operation is when the only heat source is viscous dissipation, but there are heat losses from the extruder barrel. True adiabatic operation can never be obtained, because there are always heat losses. One extreme limit of autogenous operation is adiabatic operation.

The question arises as to how close to adiabatic operation an extruder can operate. Any deviation from true adiabatic operation, in the absence of external heating of the extruder barrel, will result in a lower extruder exit temperature than adiabatic operation would predict. This would be reflected in the final properties of the extrudate, such as in the degree of expansion and amount of moisture flashed upon the exit from the die.

Consider the sketch of the cross-section of a twin screw extruder (Figure 1). We wish to estimate the heat losses that will be encountered. An exact analysis of the heat losses that will be encountered is extremely complicated. One must know the temperature within the barrel as a function of barrel length, the temperature profile within the screws, the composition and geometry of the barrel itself, and the environmental (room) conditions around the extruder. Such an analysis is very far beyond the capacity of this column to explain and perform. In fact, as far as I can ascertain, such a complete analysis has never been done. There are individual pieces of research about the temperature profile within the screw and heat transfer between the extrudate and the barrel walls. One paper, authored by M. V. Karwe and S. Godavarti (1), which I shall use for a "gross" engineering analysis, describes the heat losses from the barrel's surface to the environment. The paper gives correlations for the heat loss from the barrel surface in terms of the surface and environmental temperatures. However, the barrel surface temperature (which was close to the barrel set point temperature) was measured and not calculated from first principles, which would require the analysis that I describe above.

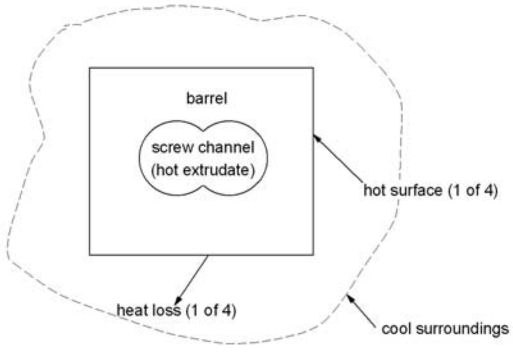

Fig. 1. A sketch of the cross-section of a twin screw extruder.

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To analyze this problem, I will use a "gross" analysis that engineers often resort to when they can't completely analyze a problem. Such analyses often give useful and informative, semi-quantitative descriptions of the exact answer. First, I will assume we are considering a situation that is of interest to a "typical" cooking extruder and use operating conditions and parameters that apply to this situation. From Karwe and Godavarti (1), I will choose a "typical" or "average" constant rate of heat loss from the barrel surface. Note that, in reality, the heat losses vary down the length of the barrel and even the heat losses from the top, bottom, and sides of the extruder barrel vary at a lengthwise location.

I will first use conditions (Table I) that are reasonably representative for making an expanded extrudate on a 30-mm ZSK extruder (Coperion Werner & Pfleiderer, Germany) used by Karwe and Godavarti (1).

A simple heat balance yields the temperature expected at the extrusion die:

$$T_{\text{die}} = T_{\text{feed}} + \text{Specific Mechanical Energy (SME)}/C_{\text{p}}$$

Table I. Representative conditions

Variable	Value
Flow rate	15 kg/h
Barrel heat loss rate	1,500 W/m^2
Extruder length/diameter	15
Screw energy input (SME)[a]	0.1 kWh/kg
Extrudate heat capacity (C_p)[b]	0.5 cal/g°C

[a] Specific mechanical energy.
[b] Heat capacity at constant temperature.

Using the conditions above calculates a die temperature of 197°C, which is in the ball park, or perhaps a little higher, than what's been reported for direct expanded snacks. Now let us consider the effect of the "average" heat loss rate of 1,500 W/sq m that's been reported.

Another simple heat balance allows us to calculate the effect of heat loss.

$$T_{\text{die}} = T_{\text{feed}} + (\text{SME–STE})/C_{\text{p}}$$

Where the specific thermal energy (STE) is the energy lost per unit mass, STE is readily calculated with barrel heat loss rate multiplied by the barrel area.

Ed Beecher, Coperion Werner & Pfleiderer, was kind enough to provide me with dimensions of the barrel (width = 130 mm, height = 90 mm). With this data, one can easily calculate the STE and the die temperature. One obtains a die temperature of 163°C! There is no way that one could consider this small laboratory extruder as being, even approximately, adiabatic. If you break down the calculations further, you find that on a small lab extruder the heat losses are about 20% of the mechanical energy input. This is consistent with a value of 30% heat loss that I've observed on a similar lab extruder.

In order to approximate adiabatic, information, or, as I will demonstrate, approximate the performance of a commercial extruder, the lab extruder will require a considerable input of heat to compensate for the heat loss.

Now, let's consider a larger extruder in the same model series, a 130-mm ZSK machine.

The barrel dimensions are 314 mm in width and 205 mm in height. First, we must estimate the capacity of this machine. Using the generally used design criteria that power an output increase with the cube of the diameter at the same length/diameter, we obtain the production rate of 1,220 kg/h and the same SME for the smaller extruder. Assuming that the heat loss rate is similar on both machines, which is reasonable because the environmental conditions are similar, we obtain the following very different results (Table II).

Table II. Comparison of lab and commercial extruders

	Value	
Variable	**Lab**	**Commercial**
Diameter	30 mm	130 mm
SME[a]	0.1 kWh/kg	0.1 kWh/kg
T_{die}[b]	163°C	193°C
STE[c]/SME	20%	2.5%

[a] Specific mechanical energy.
[b] Temperature of the die.
[c] Specific thermal energy.

It's clear that the heat losses from the surface of the plant extruder are very small. The large machine is a pretty good approximation for an adiabatic machine. Very little barrel heat would have to be introduced to approximate an adiabatic machine. Why do we observe such a large difference between the two machines? The difference is related to a simple fact: the surface area of the extruder does not increase with the diameter of the machine as quickly as the volume (pumping capacity) does. The area/unit throughput of the commercial machine is about one-seventh of the area/unit throughput in the lab machine, so a much larger quantity of heat/unit mass is lost on the small machine. The relative loss of surface area on larger machines presents a problem in almost every scale-up.

Reference

1. Karwe, M. V., and Godavarti, S. Accurate measurement of extrudate temperature and surface heat loss on a twin-screw food extruder. J. Food Sci. 62(2):367, 1997.

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