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Engineering: Heat Transfer in Extruders II—Simultaneous Heating and Cooling

In my last column (*Cereal Foods World*, November-December 2009), I began a discussion about heat transfer in extruders. The issue of heat losses was discussed and an approximate calculation of the relative heat losses in laboratory and commercial extruders was demonstrated. The calculations illustrated that the heat losses, as a fraction of the total mechanical energy input by the extruder, were negligible in the commercial scale extruder, but were quite significant in the laboratory extruder. The source of this difference was explained as the ever decreasing ratio of extruder surface area to throughput and the size of the extruder is increased.

In this column, I will consider a related problem that has been encountered by numerous people who design/operate extruders—the problem of cooking and cooling in one extruder.

The process to which I am referring is used to make a dense, unexpanded extrudate, which has been cooked prior to exiting the extruder. Such a process is used for making certain types of pet foods/snacks, ready-to-eat (RTE) cereal “pellets,” and snack pellets. The dense RTE cereal and snack pellets are subjected to further processing in order to get them to expand and form the desired texture. Processes used for this are commonly impingement-type air dryers (for cereals) and fryers (for snacks). For these products, it is essential that the pellets are very dense, so they must be extruded at a temperature below about 100°C, otherwise expansion and density reduction will occur by conversion of water to steam upon exit from the extruder’s die.

One way of accomplishing this production is by cooking in the back end of an extruder and then cooling the product to below 100°C before exiting the die. This could be done on single-screw extruders, but it is usually easier to accomplish on twin-screw machines. Since complete/significant cooking of the material requires heating the extrudate to a temperature significantly in excess of 100°C, the cooling presents a significant problem. This is usually accomplished with the process that is crudely illustrated below (Fig. 1).

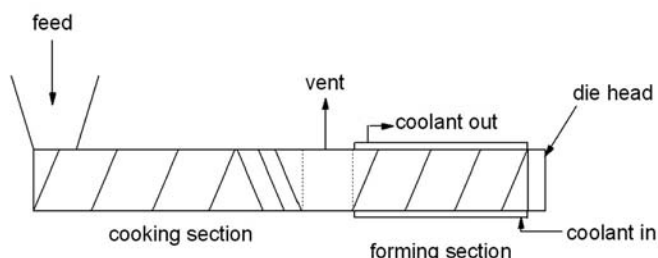


Fig. 1. Simultaneous heating and cooling in one extruder.

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The feed material is heated by the conversion of mechanical energy and the addition of thermal energy in the cooking section. The material exits the cooking section at some temperature in excess of 100°C; the actual temperature being determined by the degree of cooking required. Upon exiting the cooking section, the material enters a section of the screw that is incompletely filled and vented to the atmosphere (sometimes the vent is under a partial vacuum). Upon experiencing the drop to atmospheric pressure, the water in the extrudate, which is above 100°C, very rapidly approaches an equilibrium within the atmosphere, resulting in a flash-off of moisture and cooling to about 100°C.

The cooled extrudate must now be compacted and conveyed to the die in the forming section. Here, a problem occurs. The cooled, less moist material is usually very viscous. One cannot convey a material in an extrusion screw without generating significant shear, which results in the heat-up of the material. Of course, if there is any heat-up, the material reaching the die will exceed 100°C and will puff, which is not what we want. To overcome this problem—to keep the material at or below 100°C when it reaches the die—we cook the forming section of the extruder with water, or some other coolant, running through the jackets around the extrusion barrel. This is where the ever declining ratio of surface area per unit throughput with increased extruder scale causes a problem.

Let’s consider exactly removing heat at the rate it is being generated by the viscous shear. That is, the temperature of the extrudate entering the forming section is maintained at 100°C and the entrance to the die. Suppose we do this in a hypothetical 30-mm diameter laboratory extruder by cooling the barrel with the coolant at 20°C. We can say that:

$$\text{rate of heat removal by coolant} = \text{rate of heat generation by viscous shear}$$

The problem is that without pretty complicated calculations and/or measurements, we don’t know what the values used in the equation are. However, this is not a problem. The rate of heat removal by the jacket is given below.

$$q = UA(T_{\text{extrudate}} - T_{\text{coolant}})$$

In the above equation, “U” is called a heat transfer coefficient. There is limited data on estimating the value of the heat transfer coefficient, U, (this problem will be discussed in a future column). “A” is the area of the barrel. What is known is that the heat transfer coefficient does not change much with scale, so a designer will often measure a value in the laboratory and assume that value is the same for a commercial machine.

If we also follow the general scale-up rules described in the previous column, we know that the pumping capacity of the extruder goes up with the cube of extruder diameter, the energy input by viscous shear/unit capacity (SME) is constant, and the surface area of the barrel goes up with the square of extruder diameter.

Since SME is constant, the total energy which must be removed by the barrel is also proportional to the cube of extruder diameter. If we assume that the heat transfer coefficient, U , is independent of scale, and we want to maintain the same extrudate temperature (100°C), it is easily shown that:

$$\frac{(T_{\text{extrudate}} - T_{\text{coolant}})_{\text{plant}}}{D_{\text{plant}}} = \frac{(T_{\text{extrudate}} - T_{\text{coolant}})_{\text{laboratory}}}{D_{\text{laboratory}}}$$

As in my last column, I will assume that the commercial extruder is 130 mm in diameter, which means that:

$$\frac{(T_{\text{extrudate}} - T_{\text{coolant}})_{\text{plant}}}{130} = \frac{(T_{\text{extrudate}} - T_{\text{coolant}})_{\text{laboratory}}}{30} = 4.33$$

The temperature difference in the laboratory is $100 - 20^{\circ}\text{C} = 80^{\circ}\text{C}$. This means that to keep the extrudate below 100°C in the commercial extruder, the temperature difference must be $4.33(80) = 346^{\circ}\text{C}$. This converts to a required coolant temperature of $100 - 346 = -246^{\circ}\text{C}$! In other words, the required coolant temperature approaches absolute zero! I have done some calculations like this on a real process. The calculated coolant temperature actually came out less than absolute zero.

Obviously, this is not a practical process. It points out a problem which I've encountered a number of times. Laboratory researchers often produce test products which cannot ever be readily produced on a full scale. One conclusion from this is that laboratory products, which are targeted for eventual commercialization, should never be produced on a laboratory extruder if significant heating or cooling is required.

The second lesson from this example is that heat transfer and not pumping or shearing capacity is often the limiting factor on extruder scale-up. This means that, when significant heat transfer is involved, the extruder's capacity does not go up with the cube of the screw diameter, but at a slower rate. Most conservatively, to satisfy heat transfer requirements, the extruder's capacity may only go up with the square of the screw diameter. The actual solution is somewhere between these two extremes, depending on the heat transfer requirements and other factors.

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Preliminary Schedule

Wednesday, May 5

Golf Tournament – The Golf Club at Fossil Creek

Thursday, May 6

8:00 a.m. Meeting Convenes
10:30 a.m. Refreshment Break
12:00 p.m. Luncheon with Program
1:30 p.m. Meeting Reconvenes
3:00 p.m. Refreshment Break
5:00 p.m. Adjourn
Dinner is on your own.

Friday, May 7

8:00 a.m. Meeting Convenes
10:30 a.m. Refreshment Break
12:00 p.m. Adjourn – End of Conference

**Online registration and housing
will open in February 2010.**
Registration materials will not be mailed.

Questions?

Contact Nick Weigel at Nick.Weigel@adm.com



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