# Using Injection in Extrusion: The Thermal "Value"

In my previous column (CEREAL FOODS WORLD, July-August, 2006), I discussed the use of steam preconditioners in front of cooking extruders. In this column, I will discuss a related method of adding thermal energy to extruders—steam injection. Although widely practiced, it is not as widely used as steam preconditioners. Unlike preconditioning, virtually nothing has been written about steam injection. The only reference that I am aware of that discusses this in any detail is Robert Miller's notes on heat transfer in the AACC International course on extrusion.

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Like preconditioning, steam injection offers the opportunity of significantly increased extruder capacity, and as far as I can tell, it gets around the problem of reduced heat transfer area per unit capacity that hampers the scale up of heat transfer through the extruder's barrel.

In my previous column, I pointed out that extruders are essentially adiabatic devices. That is, virtually all the heat input, when one is not using steam injection, comes from the direct conversion of mechanical energy into thermal energy by viscous dissipation. It was assumed that starch will be cooked at 30% water level in the extruder. Furthermore, it was assumed that to completely cook, gelatinize, and melt the starch requires raising the temperature from approximately 20°C ($T_i$) to approximately 150°C ($T_f$). Under these conditions, a mechanical energy input (SME) of 0.089 kW·hr/kg was required. The following thermal properties of starch and water were used for this calculation.

Heat capacity of water ($Cp_w$) = 4.177 kJ/kg·K

Heat capacity of starch ($Cp_s$) = 1.587 kJ/kg·K

Heat of gelatinization ($\Delta h_s$) = 17.5 J/g

Now, consider injecting steam directly into the barrel of the extruder. The steam condenses and gives up its heat of vaporization to the environment, in this case the extrudate. For this example, let us assume that the steam is saturated at 8 bar (absolute). The properties of this steam may be found in a standard steam table. The properties of interest are

Temperature ($T_v$) = 170.4°C

Heat of vaporization ($\Delta h_v$) = 2,048 kJ/kg

A simple energy balance provides the relationship between steam injection, SME, and the temperatures of interest. Let $M$ be the mass of steam injected per mass of extrudate before steam injection. The energy balance yields

$$\text{SME} + M[\Delta h_v + Cp_w(T_v - T_f)] = \text{fraction}_{\text{water}} Cp_w(T_f - T_i) + (1 - \text{fraction}_{\text{water}})[Cp_s(T_f - T_i) + \Delta h_s]$$

It's immediately obvious that if the flow of steam ($M$) is not zero, then the exit temperature will increase. We can plug in the appropriate values and find that for 1% steam injection ($M = 0.01$), the temperature of the outlet of the extruder will increase from 150°C to approximately 159°C. The relationship between temperature and the quantity of steam injection is linear, so one would expect this increase in temperature for each additional 1% increase in steam injection. The important thing to note is that relatively small amounts of steam will result in significant increases in extrudate temperature.

Of course the problem is not as simple as this. By injecting the steam, you have increased the moisture in the extrudate from 30% to approximately 30.7%. This would require reducing the feed moisture to compensate. Reducing the feed moisture would increase the viscosity of the paste and increase the viscous dissipation in the section of the screw where the extrudate is drier. This would require adjustment of the screw speed and/or the screw configuration.

Another way to look at this problem is to see how much mechanical energy input could be reduced by replacing some of the mechanical energy with steam injection. If the capacity of the extruder were limited by motor size or the drive train, this would be a way to squeeze more capacity out of the system. The equation above still applies, but not when the output temperature is fixed at the desired 150°C, and the required SME is recalculated. The required SME is only 0.083 kW·hr/kg, which is approximately a 6.7% decrease. So one could conceivably, under the right combination of conditions, obtain approximately a 6.7% increase in the capacity of the machine by simply injecting a small quantity of steam. Again, the problem is more complicated because injecting the steam may require adjustment of the screw profile and/or speed.

There is another issue about using steam injection, either directly into the barrel or into a preconditioner, which I have not mentioned. In the calculations used in this and the previous column, it was assumed that the steam being injected was of 100% "quality." Steam quality is defined as the percent vapor in steam. In other words, 100% quality implies that there is no condensate in the steam. A 0% quality means that you are injecting condensate and no vapor. The energy carried by steam is virtually all obtained from the heat of vaporization that is recovered when the steam condenses. As a result, poor quality steam will not convey much energy. It is important to design the steam supply system so that it provides "dry," that is, very high-quality steam. This is accomplished in a number of ways, including the use of steam traps, insulation, separators, heat tracing, etc.

The effect of steam quality is readily observable through modification of the basic equation given above. If we let $Q$ represent the quality of the steam, the energy balance becomes

$$\text{SME} + M[Q\Delta h_v + (1 - Q)Cp_w(T_v - T_f)] = \text{fraction}_{\text{water}} Cp_w(T_f - T_i) + (1 - \text{fraction}_{\text{water}})[Cp_s(T_f - T_i) + \Delta h_s]$$

If we redo the original calculation with a 70% quality steam, the temperature increase for 1% steam injection is now approximately 6.5 degrees instead of the previously calculated 9 degrees. A 70% steam quality is not as low as it sounds. With small, uninsulated steam lines and low steam flows, I have seen values significantly lower than this.

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