Using Preconditioners: The Thermal "Value"

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The use of steam preconditioners in front of cooking extruders has in recent years become quite common. In fact, from only one extruder manufacturer offering this option approximately 20 years ago, virtually all extruder manufacturers now offer this option.

There are a number of advantages to using preconditioners, including

1) Increased extruder capacity.
2) Increased thermal energy inputs with decreased specific mechanical energy (SME) input.
3) Reduced extruder wear.
4) Reduced degradation (dextrinization) of starch.
5) More uniform cooking of the raw material.
6) Improved development of "cooked grain" flavor.

The first four advantages are the result of replacing mechanical energy with thermal energy (item 2), because increased SME input correlates directly with molecular degradation of the starch and extruder wear. The last two advantages are probably the result of increasing the total residence time over which the cooking process takes place.

For a "typical" cooking process, the advantages of replacing mechanical energy input with the thermal input of the preconditioner can be readily quantified. This column will illustrate that quantification.

First, we must recognize that large commercial extruders are essentially adiabatic devices. That is, virtually all the heat input, when one is not using a preconditioner, comes from the direct conversion of mechanical energy into thermal energy by viscous dissipation. Let us consider what this means in terms of mechanical energy input requirements. First, assume we are cooking starch at 30% water level in the extruder. Furthermore, assume that to completely cook, gelatinize, and melt the starch requires raising the temperature to approximately 150°C. To calculate the energy required to perform this task, we must make several estimates of the thermal properties of starch and water and the enthalpy change (heat of gelatinization) associated with the process. For the purposes of this example, I will assume the following approximate values:

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 (Δh_s) = 17.5 J/g

The energy required per unit mass, which for the case of adiabatic extruder operation is identically equal to the SME input, is a function of final temperature (T_f) and initial temperature (T_i) and is given by

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

Assuming an initial temperature of the ingredients of 20°C, one computes the SME for the conditions stated above to be 0.089 kW·hr/kg.

Next, we put a preconditioner in front of the extruder. By injecting steam, we can theoretically raise the temperature of the extruder feed to 100°C and also achieve a significant level of gelatinization of the starch. To be conservative in our estimate of the preconditioner's contribution to cooking, we will assume that no gelatinization occurs in the preconditioner and the temperature of the product out of the preconditioner is only 90°C. The thermal energy (STE) input by the preconditioner is given by

$$\text{STE} = \text{fraction}_{\text{water}} Cp_w (T_f - T_i) + (1 - \text{fraction}_{\text{water}}) Cp_s (T_f - T_i)$$

Using the final temperature of 90°C and the same initial temperature (20°C) as before, we find thermal energy input of the preconditioner is 0.046 kW·hr/kg. This is more than one-half of the energy requirement for cooking (SME) with an adiabatic extruder (0.089 kW·hr/kg).

The implication here is that if one could feed higher rates to the extruder, which may require higher screw speeds and a change in screw configuration, one could roughly double the production capacity of the extrusion system. Because the preconditioner is a much simpler and cheaper device than the extruder, there is considerable economic incentive to do this.

Whether one can readily do this is subject to debate, however. As the moisture and temperature of the preconditioned material increases, the material can become sticky and difficult to handle. This may limit the total amount of water that can be introduced to the preconditioner and/or the temperature (quantity of steam added). Either will reduce the advantage of using the preconditioner.

If the feed zone of the extruder is already filled, or nearly filled, then one would have to roughly double the speed of the extruder to convey the increased feed material into the screw. Increasing the speed of the extruder would increase the power needed to convey the material and would have a small effect on SME. This means that one must first have an extruder that has the speed and power capabilities to increase the screw speed. The small effect on SME, as a result of simultaneously increasing screw speed and feed rate, means that preconditioning to the same degree will result in excessive total energy input, so the conditions in the preconditioner (exit temperature) would need to be adjusted, or the screw profile would need to be reconfigured to lower the screw fill and SME. It is obvious that some compromises are required to obtain the correct total energy input.

If the feed zone of the extruder is not the limiting factor in feeding more material to the extruder, then one is faced with a different set of problems. One would then probably need to adjust screw speed, screw configuration, or preconditioner conditions to balance the introduction of thermal energy and SME to obtain the correct exit temperature.

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How much of the theoretical doubling in feed rate one can obtain is obviously a function of how the screw operates without a preconditioner and what the moisture and extrusion requirements are. For example, heating the feed to 60°C would reduce the thermal energy input to around 0.026 kW·hr/kg, which is only approximately 30% of the total energy input required. Nonetheless, one can expect considerable improvements in the capacity of an extrusion system through the use of preconditioning.

Obviously, the efficacy of the preconditioning depends on the ability to introduce water to the extruder in the form of steam. If one is running a "dry" extrusion, such as that used for corn curls, then the benefits of preconditioning are minimal, because introducing significant amounts of water, in the form of steam, moves the process away from "dry" conditions. Conversely, if one is extruding at very high moistures, then the benefits of preconditioning increase because more steam can be added and it is difficult to obtain a high SME because viscous dissipation is limited by the low viscosity of the extrudate.

There is another possible advantage for using a preconditioner. On small-scale extruders there is often a significant quantity of heat introduced through barrel heating. Introducing heat this way is very problematic when using large extruders because of the reduced barrel surface per unit of throughput. One way around this problem is to use the preconditioner to provide the heat input typically provided by barrel heating when using a small-scale extruder.

There is another caution with respect to the use of a preconditioner. Because you will be substituting mechanical energy input for thermal input, one would expect less dextrinization of the starch. This if often desirable but may be observable as a difference in the quality of the products produced.