The Benefits of Using Rapid Indirect Heating on Grain and Flour Products

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Don't beat up on the eggs—instead, fault the flour. This is essentially the conclusion of a study, published in late 2011 in the journal *Clinical Infectious Diseases*, that implicates untreated flour as the likely source of an *Escherichia coli* outbreak in 2009 that sickened dozens who ate uncooked, refrigerated cookie dough products.

Because flour at the time, unlike other commercial cookie dough ingredients, did not typically undergo any specific processes to kill pathogens, it was an obvious target for infectious disease researchers seeking a cause for the 2009 *E. coli* outbreak. As a result of findings similar to those reported in the 2011 paper, manufacturers of ready-to-cook or ready-to-bake foods that may be consumed without cooking or baking, such as cookie dough, are beginning to use heat-treated or pasteurized flour in their products.

Today, as food manufacturers continue to expand the use of whole-grain products in their foods, heat processing and treatment of grains are more important than ever. Suppliers and food manufacturers are using heat to address an increasingly complex variety of needs associated with grains and flour, ranging from new ingredient, flavor, and safety requirements to cost and productivity concerns.

This article describes how ingredient suppliers and manufacturers can take advantage of highly sophisticated and precise indirect heat treatment technologies to provide a variety of advantages, including higher product quality, a wider range of products and new products, and reduced maintenance and energy costs associated with manufacturing.

Background on Heat Treatment Technologies

Not all forms of heat treatment in manufacturing are the same. There are several different general categories of heat treatments: convective, radiant, and conductive. Table I illustrates the key characteristics differentiating heat transfer categories. Each of the three general types of heating covered in Table I (radiant, direct, and indirect) are reviewed.

Radiant Heating. Microwave, infrared, and radio frequency are all radiant methods of heating. Electron beam and gamma radiation are nonthermal methods used in pathogen reduction. Irradiative processing methods show promise for use in microreduction, drying, toasting, and roasting. Use of radiant and nonthermal methods is relatively new in commercial operations, and the methods are still being developed for use in many applications.

Microwave energy directly heats water molecules, providing pinpoint heating within products containing moisture. Manufacturers are continuing to improve the control of microwave energy, which will further expand its areas of application.

Infrared heating technology also has improved and is effective in directly heating dry products for toasting and roasting. However, the uniformity of treatment can be problematic because only the areas exposed to the infrared light are heated.

Electron beam radiation is an effective treatment for reducing microorganisms, and it has advantages over thermal methods for treating final packaged products, as well as in low-temperature processing because it minimizes any apparent negative qualities. Electron beam radiation is especially favorable for fresh products

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such as fruits and vegetables and very heat-sensitive products such as spices. However, the impact of irradiation on functionality for added processing and nutrition is not fully documented. Some negative public perceptions (particularly in the United States) remain attached to irradiated foods as well.

Direct Heating. Heat transfer by convection is commonly termed "direct heat" because heat is transferred directly from a hot medium, such as air, inert gases, or water vapor (steam), to material suspended in or otherwise in direct contact with the heated medium. Devices that use direct heat include flash and fluid bed dryers and jet zone or impingement ovens. Drying is a natural result of direct heating. In applications in which the control of time, temperature, and moisture are critical, such as enzyme inactivation, microreduction, and flour gelatinization, the natural drying effect of convection heating presents significant limitations. In general, operating costs and energy consumption are higher with direct heating methods compared with indirect heat treatments.

Indirect Heating. The third type of heat treatment, conductive or indirect heat transfer, is the focus of this article. The key operating characteristics of the various categories of indirect heaters are described in Table II. Specifically, we will focus on continuous and short-time indirect heat contact processing, such as the high-speed paddle processor shown in Figure 1. This thin-film, continuous, short-time processor offers simple yet sophisticated operation and control. Results are repeatable and consistent when process conditions are fixed, yet the processor is quick to respond to changes in process conditions when flexible manufacturing is required. Key process variables such as feed rate and jacket temperatures are easily monitored and controlled. Full automation further reduces labor costs, and a single process line can handle a range of products without retooling. Because thin-film processing results in efficiencies such as minimal utility costs and floor space requirements it presents distinct advantages to the cereal grains industry.

Although batch heating may be the most commonly understood of the indirect heating methods, its relatively small heat transfer surface and typically lengthy heating time for large volumes of material limits its productivity compared with continuous processing heating methods. With batch processing, all of the material must move to the wall for heating, presenting a continuous opportunity for overheating of some materials and underheating of others. In Table II, this characteristic can be seen in the hot surface/volume ratio for the jacketed blender. This ratio directly impacts the heat scale-up rate of material in any processor. The higher the value, the shorter the process time required.

Table I. Time and uniformity of exposure to heat using radiant, direct, and indirect heating treatments

	Residence Time Capability					
Heat Treatment	**0–10 (sec)**	**10–30 (sec)**	**2–10 (min)**	**10–60 (min)**	**1–6 (hr)**	**Gradient[a] or Uniform Temp.**
Radiant		X	X			Gradient
Direct – Convection						
Flash dryer	X					Uniform
Fluid bed dryer			X	X		Gradient (time)
Rotary dryer				X		Gradient
Spray dryer	X	X				Uniform
Tray dryer (batch)				X	X	Gradient
Tray dryer (continuous)				X	X	Gradient
Indirect – Thin-film conduction						
High-speed paddle	X	X	X			Uniform
Flaking drum		X	X			Gradient
Tray dryer (batch)				X	X	Gradient
Tray dryer (continuous)				X	X	Gradient
Indirect – Deep-bed conduction						
Cone dryer (batch)			X	X	X	Gradient
Steam jacket rotary dryer				X		Gradient
Heated disc rotor			X	X		Gradient
Heated paddle rotor (slow speed)			X	X		Gradient
Heated screw			X	X	X	Gradient
Extrusion	X	X	X			Uniform

[a] Gradient refers to temperature gradient unless otherwise noted.

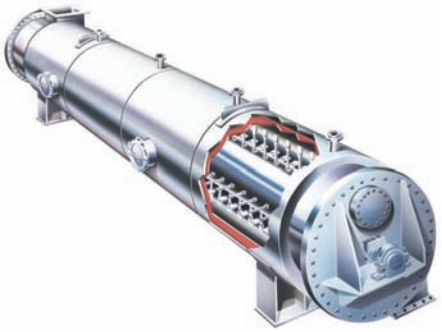

Fig. 1. High-speed paddle processor.

Table II. Indirect heat processor characteristics

Indirect Heat Processor Type	Operating Mode	Hot Surface/ Volume Ratio	Degree of Agitation	Scale-up Capacity
Thin-film conduction heaters				
High-speed paddle	Continuous vacuum pressure	65–82	High	High
Flaking drum	Continuous vacuum	164	None	Low, multiple units
Tray dryer (batch)	Batch vacuum	32–64	None	Low
Tray dryer (continuous)	Continuous vacuum	32–64	Low	Medium
Heated screw	Batch continuous vacuum pressure	32–64	Low	Medium
Extrusion	Continuous pressure	32–64	High	Medium
Deep-bed conduction heaters				
Jacketed blender (conical or horizontal)	Batch continuous vacuum pressure	1.6–8.2	Medium	High
Steam tube rotary dryer	Continuous	16–32	Medium	High
Heated disc rotor	Batch continuous vacuum pressure	19–26	Medium	High

Indirect heat exchangers are commonly used for gas and liquid heat transfer in all process industries. In the food and beverage industries, indirect heat exchangers that provide high-temperature short-time (HTST) processing are used for pasteurizing milk, juice, and other fluid beverages. HTST pasteurization is the industry standard because of the efficiency of its process.

Figure 2 illustrates the HTST process for milk pasteurization. Fluid milk is pumped through a sanitary plate-frame heat exchanger. This provides a narrow (thin film) annulus surrounded by a heat transfer surface. This surface is then heated by hot water, steam, or other heat transfer fluid. Velocity and mixing are controlled in the exchanger by the flow rate and internal design of the flow path to achieve the uniform time-temperature profile required to pasteurize the milk. The typical standard for HTST pasteurization of milk is 72°C for 15–20 sec. Each drop of milk must be heated within this time-temperature range.

Typical Thin-Film Processor Design

HTST process technology is also available for solids handling. Instead of pumping through static, narrow flow channels, the material to be processed is metered directly into a cylindrical jacketed vessel that has a specially designed paddle rotor (Fig. 1). The rotor operates at speeds sufficient to suspend the material against the heat transfer surface by centrifugal force, creating a thin “film” or layer of solids that moves against the heated surface.

Within a thin-film solids processor, the rotor speed keeps materials suspended uniformly around the internal wall of the cylindrical vessel. Rotor elements are designed to create material mixing action to provide a continuous exchange of material against the heat transfer surface. The velocity and mixing action, with the relatively close proximity of rotor elements to the vessel wall, prevent material from accumulating on the heated surface. The rotor design allows for mixing against the heat transfer surface while maintaining uniform material flow from inlet to outlet, preventing back mixing, and, thus, providing a narrow residence time range for heat treatment. Figure 3 models material and vapor flow through the heater.

Heat exchangers are evaluated based on their total heat transfer capability (e.g., Btu/hr). This is governed by the equation $Q = U \times \Delta T \times A$, in which Q is the quantity of heat transferred from the vessel wall to the processed material (Btu/hr or kJ/hr), U is the heat transfer coefficient (Btu/hr·ft2·°F or kJ/hr·m2·°C), A is the area of the heat transfer surface (ft^2 or m^2), and ΔT is a measure of the thermal driving force, generally the difference between the jacket temperature and the material temperature as it changes from inlet to outlet conditions (°F or °C). The two major factors that govern the flow rate of heat to the process are the heat transfer coefficient (*U* value) and the thermal driving force (ΔT value). The greater these values are the smaller the heat transfer area required for a given heat treatment application, resulting in a smaller equipment footprint and lower capital costs.

The *U* value is a measure of the efficiency of heat transfer and is very dependent on the design of the heat exchanger. Table III shows the general relationship between tip speed and the heat transfer coefficient for a range of material types. Designs maximizing contact between a heated surface and processed material also optimize the *U* value. Table III shows the impact of tip speed and material characteristics on heat transfer. Higher rotor tip speed increases the *U* value, and higher material density improves surface contact. Fluids provide optimal contact with heat transfer surfaces, followed by very wet powders (wet cakes), damp powders, and low-density dry powders. The *U* value var-

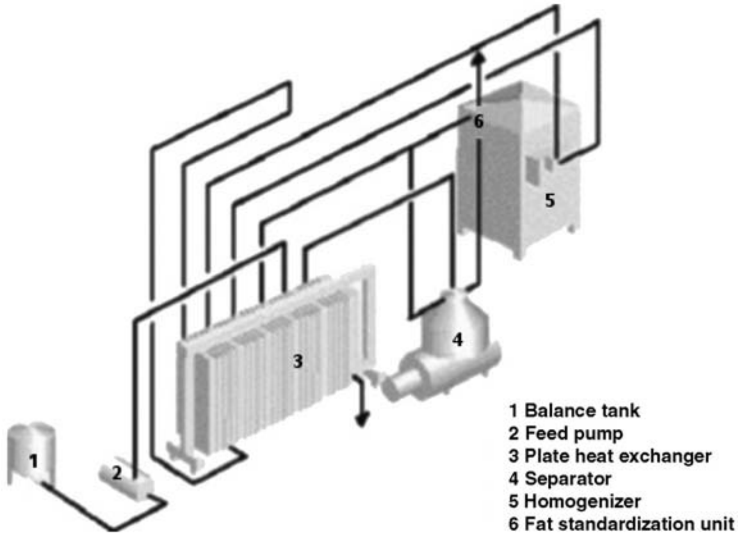

Fig. 2. High-temperature short-time milk pasteurization process (reprinted from www.apv.com).

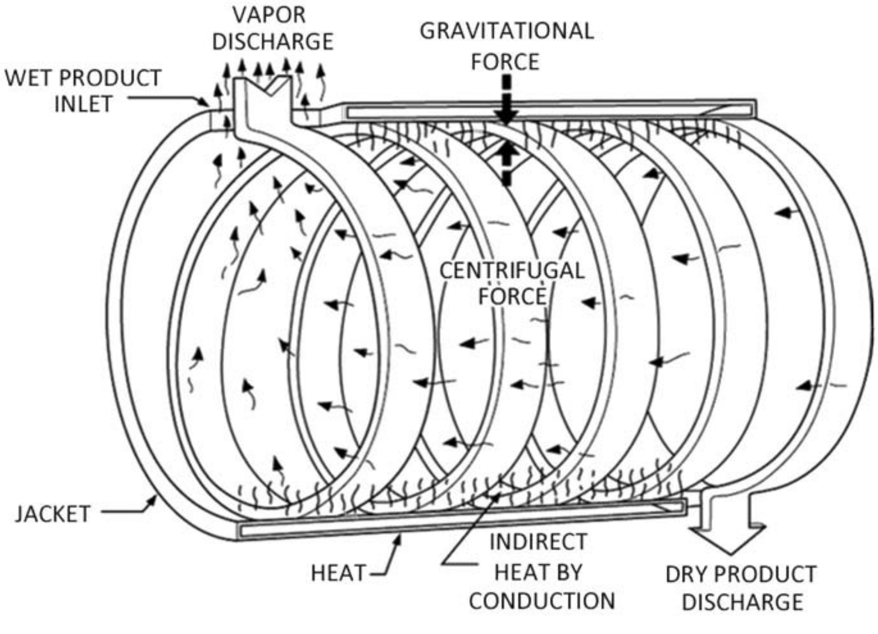

Fig. 3. Material and vapor flow through an indirect heater. Counter-flow sweep air pulls the vapor out at the inlet. Vapor is available for preheating the incoming product.

ies, therefore, between feedstocks on a given processor, and for a given feedstock, the value varies between heat transfer devices. The heat transfer coefficient is ultimately determined based on pilot-scale equipment for each application.

The ΔT value is the second variable affecting unit size for a given heat treatment application, measuring the difference between heated surface temperature and product inlet and outlet temperatures. Since inlet and outlet temperatures are typically fixed by an application, a higher surface temperature results in a greater ΔT value, thus maximizing heat input per unit of heat transfer surface. Maximum heat transfer surface temperature is influenced by processor design. Efficient and continuous movement of particles against the surface (mass transfer) allows for maximum temperature across the heated surface. The ultimate limitation is set by the material to be processed; however, a thin-film, short-contact processor may operate at higher temperatures than a filled bed, which is a slowly agitated process device.

Thin-film solids heat exchangers can be combined with direct heat transfer, e.g., direct steam injection. Condensation of water vapor transfers ≈1,000 Btu/lb of steam condensed. This occurs nearly instantaneously upon contact between vapor and solids. With fully jacketed vessels providing the possibility for all contact surfaces to be hotter than the temperature at which water boils, condensation occurs only on colder product particulate surfaces. This is especially important for gelatinization and sterilization or enzyme deactivation, where instantaneous heat-up can maximize capacity and minimize retention time (residence time). Figure 4 illustrates the vapor flow pattern for cocurrent direct-indirect processing.

Thin-Film Processor Applications

Due to the low shear inherent in thin-film processors, they can provide unique functionality in specific heat treatment processes, and they are used for a variety of applications. A thin-film processor is suitable for drying wet material cakes, slurries, and damp powders, especially if solvent recovery is required, such as in solvent extraction processes. These indirect driers use a minimum of sweep air or inert gas, resulting in efficient condensation and recovery of solvents with recirculation of the gas stream. Pasteurization can be accomplished with short contact times (10–30 sec) at high heat (≈160–190°F) in an appropriate moisture range to significantly reduce microbial counts, such as in flour pasteurization. Lipolytic enzymes in oats and other whole grains can be inactivated by heat treatment to extend shelf life and improve or preserve flavor. This increases the ability to incorporate whole grains, bran, and germ in more applications (2).

Table III. Typical heat transfer coefficients (*U*)

Equipment	Tip Speed (m/sec)	*U* Value (kJ/hr·m²·°C) for Different Materials		
		Light Density	Heavy Density	Damp or Wet
Slow-speed heated screw	0.1	40	60	75
Bed/disc dryer or heater	1	120	300	400
High-speed paddle dryer	10	300	600	900

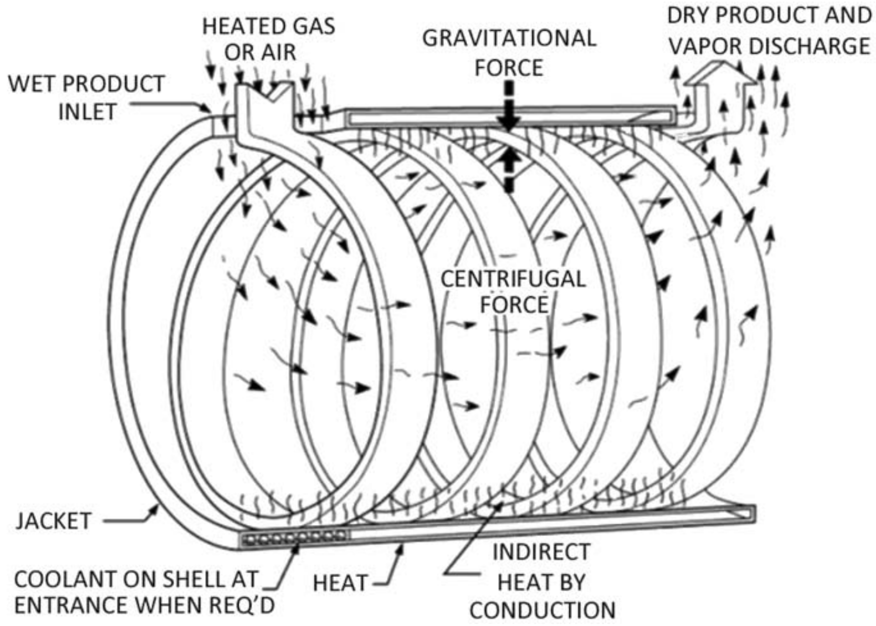

Fig. 4. Vapor flow pattern for cocurrent direct-indirect heat processing. Vapor exhausts at the discharge of the thin-film solids processor. The combination of indirect heat (jacket) and direct heat (live steam injection) within a single processor results in minimal moisture loss and provides instant preheating of incoming material.

Corn flour, cornmeal, and oat flours can be cooked to various levels of pregelatinization to increase water-holding capacity, reduce microbial counts, and improve operability for further processing, whether directly sheeting for extrusion or other processes. With sufficient humidity, gelatinization temperatures can easily be reached to partially gelatinize the starch component of a variety of flours. By controlling moisture and temperature, with and without direct steam addition, a wide range of heat-treated flours, starches, and pulses are possible. Moisture ranges from 20 to 40%, with temperatures ranging from 60 to 105°C, are possible in continuous atmospheric systems.

Thin-film heat treatment can be used to remove the raw flavor profiles of corn, soy, and other flours. Flavor notes (volatile components) are removed by the natural steam stripping inherent with indirect heat. The resulting bland flavor profile allows the flour to be used in delicately flavored products like yogurt, without the use of masking ingredients. Cocurrent flow is preferred.

Toasting of grains, wheat germ, or bran is accomplished with high-temperature heat treatment in a dry atmosphere. This accelerates Maillard reactions that affect color and flavor (1). Counter-current flow is preferred (Fig. 3) to minimize product moisture.

Roasting at very high product temperatures with extended residence time maximizes flavor impact. For example, heating products to temperatures higher than 150°C, even for a short period of time, results in intense flavor development, caramelizing, or carbonizing. Other terms associated with this level of treatment are torrefaction and low-temperature pyrolysis. Roasting applications range from sugar to nuts and beans. A predrying step may be required to avoid unwanted side reactions, such as gelatinization and protein denaturization, that occur at elevated moisture levels and high temperatures.

Heat treatment in combination with chemical addition (e.g., enzyme, acid, base, etc.) accelerates modification reactions, such as dextrinization. A combination cocurrent and counter-current flow is preferred—cocurrent at inlet and counter-current at discharge. Temperature and flow regimes are driven by the temperature and moisture requirements for reactions of interest.

Advantages of Thin-Film Processors

Thin-film processors provide more uniform heat history, with a relatively short contact time and low mechanical energy input, resulting in low shear. The only forces applied to the processed material are acceleration of the rotor tip speed from the initial entry velocity and sliding abrasion as the material is spun against the heat transfer surface. These factors are important because the resultant product performance will be uniform without the need to blend for improved performance. Low shear is important especially when considering the potential negative impact of starch damage in some applications.

Due to the low shear generated by thin-film processors, they can deliver unique functionality in precooked flour applications by providing increased absorption without the typical breakdown of the starch molecular structure. Figure 5 illustrates a typical fully gelatinized, highly sheared starch product that exhibits cold viscosity development and immediate breakdown of viscosity upon heating. Figure 6 shows a low shear, cooked corn flour with improved absorption and minimum cold viscosity development that retains its structure upon heating and has increased viscosity upon final cooling. This indicates that the flour is at least partially cooked and yet retains its structure, making it suitable for added processing (mixing) and cooking or baking and providing structure and body in the final product.

The market demands a continual stream of new ingredients and products to fuel the ongoing journey toward foods that are convenient, tasty, and nutritious and that present a clean label. Product developers look to meet these demands by requiring improved performance and functionality from their ingredients. If a more functional raw material can be used to displace more expensive additives, value is added to the developer and, therefore, to the ingredient. The third component in this supply chain is the technology supplier. With knowledge of the needs of both the raw material supplier and the retail product developer, the technology supplier can deliver customized solutions.

Thin-film indirect heat processing fits nicely into this supply chain niche, offering several advantages and breakthroughs. Advances in enzyme-catalyzed reactions and acid or base modifications, in combination with tight time, temperature, and moisture control, provide the opportunity to create new functional ingredients, such as gelatinization-resistant flours or specially modified flour components. Novel bench chemistry discoveries can be translated into pilot-scale and then commercial-scale applications. Thin-film indirect heat processors also offer higher product quality compared with bed-type indirect heat processors (blenders, disc, or screw heating units) due to the uniformity of heat input and even treating of all particles with respect to the time of exposure to the heat transfer surface. Finally, the technology allows processing of solutions or slurries, powders, and many transition products in between at high temperatures and for short controlled time intervals with low shear, which can impart new functionality to raw baseline ingredients (Fig. 6).

The market today is also faced with escalating energy costs and global competition. This is driving the need for increased energy efficiency, reduced labor through increased automation, and greater productivity. Thin-film indirect heat processing provides solutions to meet these demands.

Reduced Energy Costs. Energy costs can be reduced by minimizing heat losses. Nearly equivalent heat applied to heat required is typical, especially compared with direct methods.

Reduced Labor Costs. Simplifying au-

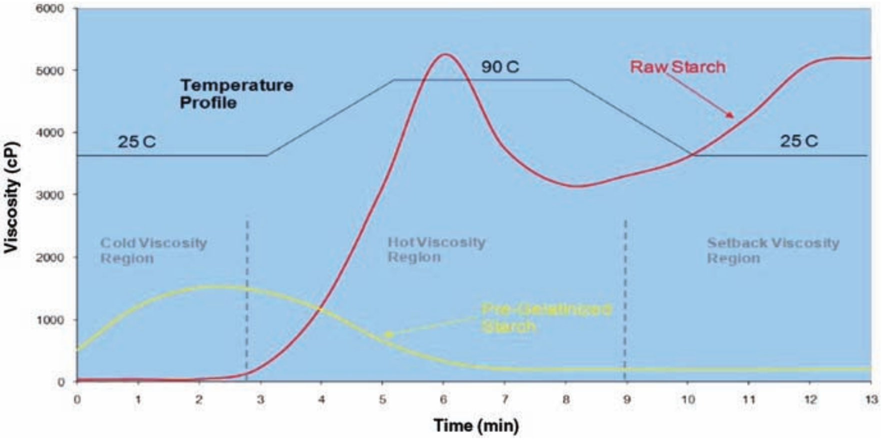

Fig. 5. Typical fully gelatinized, highly sheared starch product exhibits cold viscosity development and immediate breakdown of viscosity upon heating, as measured by rapid viscosity analysis.

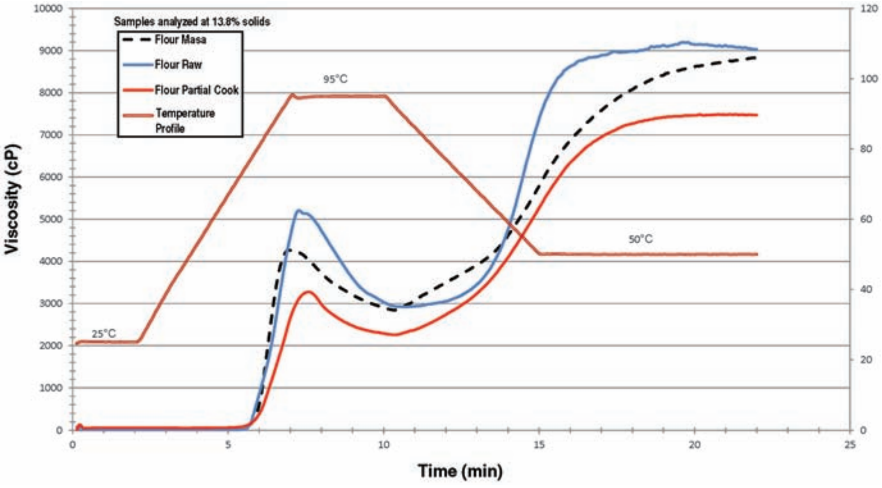

Fig. 6. Rapid viscosity analysis profiles (atmospheric versus pressure) of whole-corn flour products. Typical low-shear, cooked corn flour shows improved absorption and minimum cold viscosity development, retains its structure upon heating, and has increased viscosity upon final cooling.

tomatic control systems provides maximum, reliable "up time" with minimal operator attention. Systems can often be integrated into existing facilities without adding personnel.

Reduced Maintenance Costs. With most food products wear and abrasion are minimal, reducing maintenance costs. With low mechanical energy input, the lifetime of the rotating shaft, mixing elements, and bearings is maximized. The unit lifecycle may be longer than 20 years, providing long-term productivity. This may exceed product lifecycles. However, the flexibility to work under a range of process conditions often allows conversion of the system for new products with minimal changes to the basic unit.

Increased Productivity. The efficiency of heat transfer (high U value and large ΔT value) and the simplicity of operation, with minimal components requiring minimal plant space, help increase productivity. Providing single units capable of stream flows of 25 tons/hr for heat treatment applications creates a favorable economy of scale.

More Tools for Cereal Processing

A lesser known, but highly versatile and effective processor, thin-film solids heat exchangers provide a valuable tool for the cereal processing industry, transforming the theory of heat treatment reactions into economical processing performance. These devices are especially valuable in light of the movement toward clean labels, improved natural raw material functionality, and use of all components of whole grains. With the continued rise in energy costs, this efficient heat transfer method provides additional value. Further development of this technology could enable heat treatments above or below atmospheric pressures, provide further extensions in the functional performance of treated products, improve process economics, and enable treatment of more temperature-sensitive materials.

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