Transient Heat Conduction and Hotspot Development Prediction in a Flaking Roll with Revolving Heat Flux and Convection Boundary Conditions

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ABSTRACT: In the oilseed crushing industry, flaking rolls sometimes develop hotspots that cause high thermal stresses. Soybean flakes on contact with hotspots crumble to powder, which is unsuitable for oil extraction. Transient heat conduction equations with revolving boundary conditions were solved using the finite element method. Simulations demonstrated that hotspots arise due to heat flow in three dimensions from the source toward the roll ends and the curved surface. An estimated heat flux value of 56 kW/m^2 yielded surface temperature values near observed values. Perturbations performed to the base values showed that a 10% increase in thermal conductivity caused a 6–8% reduction in peak thermal gradient, whereas a 20% increase in heat-transfer coefficient caused less than 2% reduction in peak thermal gradient. Therefore, thermal conductivity is a more sensitive parameter affecting thermal gradients than the heat-transfer coefficient. A small change in heat-transfer coefficient caused by aspirating air through the flake outlet of the roll stands would not cause a significant reduction in temperature and thermal gradients in rolls. The higher thermal gradients observed near the outer surface of rolls suggest that casting rolls with subsurface layers of higher thermal conductivity would make rolls less prone to forming hotspots.

Paper no. J9802 in *JAOCS 78*, 787–792 (August 2001).

KEY WORDS: Convection, finite element, flaking, heat flux, hotspots, revolving boundary condition, transient heat conduction.

In the oilseed crushing industry, cracked soybeans are flaked by pressing and shearing them through a pair of smooth rolls rotating at the same speed or with a slight differential. In this process, cells are ruptured and oil pockets are exposed. In the next step, oil is extracted from the flakes by solvent extraction, screw pressing, or a combination of these two methods. The industry using shallow bed type extractors aims at producing optimal thickness of flakes in the range of 0.38–0.43 mm for maximal oil extraction (1). Often the thickness of flakes is greater than the optimal range. Pressing the rolls with a greater pressure reduces the flake thickness. For a given feed rate of cracked soybeans, the increase of roll pressure beyond a certain level causes hotspots to develop on the roll surfaces (1). Hotspots are bands or patches of very high temperature compared to the surrounding surface. Soybean flakes contacting hotspots crumble to fine powder, which is not suitable for oil extraction. Additionally, high-temperature gradients produce excessive stresses inside rolls, which damage the roll surface.

The phenomenon of hotspot development is not clearly understood in the soybean crushing industry. It would be expensive and impractical to study hotspots by conducting extensive experiments on the roll stands, because the attempt would damage the rolls. Therefore, the best alternative is to conduct numerical experiments with the help of computer simulations. It is hypothesized that the solution of the transient heat conduction equation for a cylinder with revolving heat flux and convection boundary conditions acting on the curved surface would demonstrate that the hotspot phenomenon arises due to the three-dimensional nature of heat flow.

The steady-state solution of heat conduction in rolls can be obtained analytically using the method of separation of variables. Such derivations can be performed easily only for simple boundary conditions (e.g., uniform heat flux along the entire curved surface and finite temperature at the roll ends). It becomes extremely tedious to obtain an analytical solution when the heat flux moves along the curved surface and convection takes place at the ends of a roll. In such cases the use of numerical methods becomes essential. Ootao *et al.* (2) performed a theoretical analysis of a three-dimensional transient thermal stress problem for a nonhomogeneous hollow circular cylinder subjected to a moving heat source in the axial direction at the inner and/or outer surfaces. Chen and Lin (3) investigated nonlinear transient heat conduction in a hollow cylinder with temperature-dependent thermal conductivity using the hybrid application of the Laplace transform technique and the finite-element (or finite-difference) method. Abu-Hijleh (4) used the finite-difference method to obtain the solution for heat conduction in a two-dimensional anisotropic cylinder subjected to a steady periodic and asymmetric temperature distribution at the outer wall. He identified that heat conduction across a cylinder was dependent on five parameters: Biot number, nondimensional outer radius, nondimensional frequency, orthotropicity factor, and anisotropicity factor. Along the contact line between a pair of flaking rolls, heat is generated due to particle deformation and friction against the roll surface. Heat is also conducted to the rolls from soybeans at a higher temperature. Owing to the rotation of rolls, the source of heat flux moves along the circumferential direction. At each instant, the curved surface not

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*To whom correspondence should be addressed at Department of Agricultural and Biological Engineering, 1146 ABE Building, Purdue University, West Lafayette, IN 47907-1146. E-mail: maier@purdue.edu covered by the source of heat flux loses heat to air. Thus, the curved surface is subjected to revolving heat flux and convection boundary conditions. To our knowledge, the solution to such a problem has not been obtained in the past. We used the finite-element method to perform the analysis. The finite-element method can incorporate nonuniform roll properties and revolving boundary conditions. With the aid of a finite-element model, the effect of different combinations of roll materials, design, and operating parameters on the resulting temperature gradients can be studied. A suitable combination of these parameters will help roll manufacturers to design rolls with improved performance.

The specific objectives of this study were: (i) to develop a finite-element model of heat conduction in a roll with revolving heat flux and convection boundary conditions; (ii) to demonstrate hotspot development in a soybean flaking roll; and (iii) to study the effect of roll material and surface heat- transfer coefficient on resulting temperature and temperature gradient profiles inside a soybean flaking roll. Since rolls operate under a wide range of design and operating conditions, the accurate estimation of the heat-transfer coefficients at the curved surface is required. In a related paper, the equations of fluid mechanics have been solved using a commercial computational fluid dynamics (CFD) package to estimate heat transfer coefficients on the curved surface of a roll (Singh, P.P., and D.E. Maier, unpublished).

MATERIALS AND METHODS

Model development. The source of heat is the contact line between rolls where the beans are being crushed (Fig. 1). The heat entering each roll is dissipated through its curved surface and flat ends in contact with the ambient air. The phenomenon is three-dimensional and transient in nature because the heat flows in radial and axial directions, and the roll surface in contact with the heat source moves to a different angular location at the next instant, *t*. It is assumed that the thermal properties of the roll are isotropic. The equation of heat conduction for an isotropic solid is:

$$\nabla \cdot (K\nabla T) = \rho C \frac{\partial T}{\partial t} \qquad [1]$$

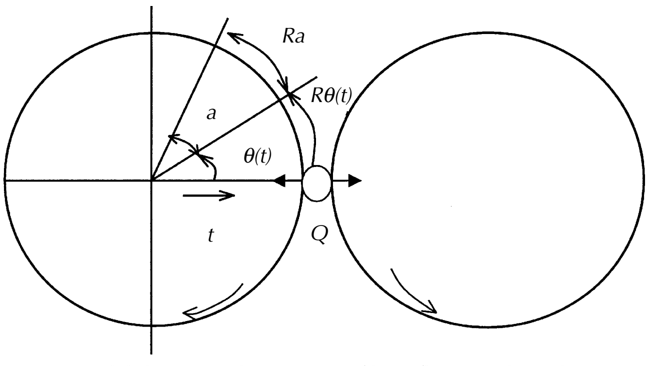

FIG. 1. Model diagram. The rotation of heat flux (*Q*) along the curved surface of a cylinder with radius *R*.

where ∇ is the gradient operator in cylindrical coordinates and $T(r, \theta)$ = temperature at location (r, θ) inside the roll (°C); $K(r, \theta)$ = thermal conductivity of the solid (W/m °C), $\rho(r, \theta)$ = density of the solid (kg/m^3); $C(r, \theta)$ = specific heat of the solid (J/kg °C); R = radius of the cylinder (m); a = angle projected by the heat source at the center of the roll (radians).

Isotropicity implies that at a spatial point the properties are independent of direction, but still the properties are allowed to vary from one spatial location to the other. To specify this, in spite of assuming isotropy, the properties K, ρ, and C have been written as functions of r and θ, which will make it easier to adapt the current code for the inclusion of layered roll materials with different thermal properties in the r and θ directions.

The rolls rotate with constant angular velocity, ω. The revolving heat source at time t will reach the angular position θ, which can be determined as:

$$\theta = \omega t \qquad [2]$$

The initial condition (IC) at time $t = 0$ is

$$T = T_i \qquad [3]$$

where T_i is the initial temperature inside the rolls before they start rotating. It was assumed that the rolls did not operate for a long time prior to the start of simulations, which allowed them to equilibrate with the ambient temperature. Thus, T_i can be assumed to be equal to the ambient temperature.

For boundary condition 1 (BC1), the length l of the curved roll surface along the circumferential direction in contact with the heat source Q is $R\ a$. This length is equal to the average flake diameter. At $r = R$,

$$-K\frac{\partial T}{\partial r} = Q \qquad [R\theta \le 1 \le R(\theta) + a)] \qquad [4]$$

The remaining portion of the curved surface is in contact with ambient air, T_a.

$$-K\frac{\partial T}{\partial r} = h_c(T - T_a) \qquad [R(\theta + a) < 1 < R(2\pi + \theta)] \qquad [5]$$

where h_c is the convective heat transfer coefficient along the curved surface of the roll.

For boundary condition 2 (BC2), the roll ends are in contact with the ambient air. At the roll ends $z = -L$ and $z = L$:

$$-K\frac{\partial T}{\partial z} = h(r)(T - T_a) \qquad [6]$$

where $2L$ is the roll length. The convective heat-transfer coefficient *h(r)* at the roll ends is a function of radius r owing to variation in linear velocity along the radial direction. For simplicity, one average value for the convective heat-transfer coefficient was used over the entire surface at the roll ends. Table 1 shows the base values of the material properties and other parameters used to perform the calculations.

METHOD OF SOLUTION

Equations 1 through 6 were solved using ANSYS (ANSYS Inc., Canonsburg, PA), a commercial finite-element software. Its THERMAL ANALYSIS module is a powerful package for solving heat conduction problems involving complex geometry and/or boundary conditions. The heat-transfer coefficient on the curved surface of the roll was obtained by solving fluid mechanics equations in the FLOTRAN module of ANSYS (Singh, P.P., and D.E. Maier, unpublished). The heat-transfer coefficient for the roll ends was obtained from a study on fluid flow in the vicinity of rotating disks (6).

Meshing of solid model. The cylinder was meshed using SOLID 70, a three-dimensional linear element with eight nodes available in ANSYS. The element predicts temperature and thermal gradient values. The element mesh was made of mapped type with increasing number of elements toward the outer surface where higher thermal gradients were observed (Fig. 2C). This helped to improve the accuracy of results. The linear elements were used because they consumed less computation time and storage space when a large number of calculations were involved.

Modifications. The finite element solution of the transient heat conduction equations (Eqs. 1–6) involved two numerical complications. The first complication arose because during flaking a soybean particle projects a small angle of 2.5° at the axis of the cylinder. To apply heat flux at this angular resolution, a very high-density mesh was required at the roll surface. This would have slowed the calculation process and required a huge amount of computer storage space. To overcome this complication, at each instant the revolving heat flux was distributed to a spanned angle of 30°. This required the application of 12 load steps in one revolution around the cylinder. The angular resolution of 30° was determined after several trial runs at different angular resolutions. This value yielded surface temperature values near to experimental values and provided data for a sufficient amount of simulation time. The second complication arose because the rolls being used in the soybean crushing industry have a high rotation speed. One popular make of flaking roll stand uses a rotation speed of about 5 rev/s (time period 0.2 s). At this rotation speed, a time step size of 0.017 s would be required to apply 12 load steps in one revolution around the cylinder. It was estimated that at this time resolution, each simulation for 1 h of heat conduction would have required about 3 mon on a Sun Ultra-X engineering workstation. Therefore, instead of changing the load continuously at a time resolution of 0.017 s, it was applied for 3.4 s (slowed by 200 times) at a 30° span of the roll and then moved to the next location. As will be shown, in spite of these modifications, surface temperature values near to experimental values were obtained. At these values of time and angular resolution, the software allowed simulations within 3,320 s of real time. This simulation time was sufficient for making useful deductions.

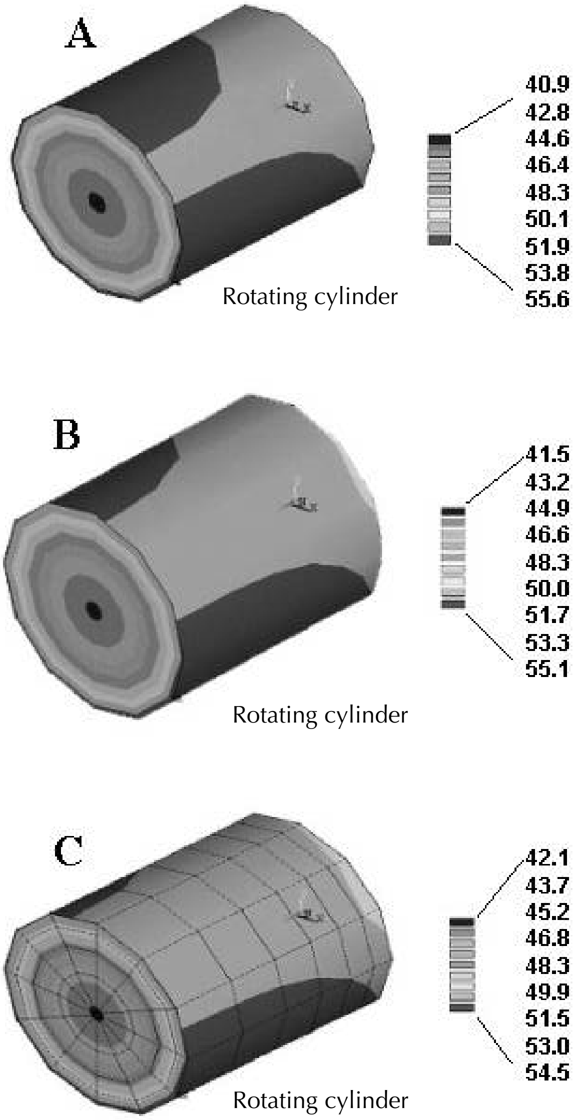

FIG. 2. Temperature profiles in a soybean flaking roll obtained for three values of thermal conductivity—(A) 51.3 W/m °C, (B) Base value, 57 W/m °C, (C) 62.7 W/m °C. The front surface displays the roll cross-section at the middle of the axis.

TABLE 1
Base Values of Material Properties and Other Parameters Used to Perform the Simulations

Material properties	
For gray cast iron:	
Thermal conductivity, *K*	57 W/m °C
Specific heat, *C*	0.452 kJ/kg °C
Roll density, ρ	7200 kg/m^3
Other parameters:	
Heat-transfer coefficient on curved surface, h_c	25 W/m^2 °C
Heat-transfer coefficient on roll ends, *h(r)*	25 W/m^2 °C
Roll length, 2L	1.57 m
Roll radius, *R*	0.3556 m
Ambient temperature, T_a	25°C

RESULTS AND DISCUSSION

Estimation of heat flux source. It is difficult to experimentally measure the heat flux, because it is composed of heat generation due to particle deformation, friction of particles against the roll surface, and conduction of soybean heat to the rolls. One soybean milling plant where we had conducted a previous study used flaking rolls with a maximum power rating of 110 kW (1). Data collection on a flaking roll in the plant provided the surface temperature of a set of rolls after starting them from an initial temperature of 35°C. The ambient temperature during this experiment was 25°C. For finite-element simulations, it was assumed that a fixed percentage of the maximum power (110 kW) was converted into heat. Simulations were performed using 10, 15, and 20% of maximum power as a heat source value.

Finite element method simulations performed using a heat flux value of 56 kW/m^2 (15% of maximum power distributed to a 30° span of the roll) caused roll surface temperature values closest to those observed during the experiment (Fig. 3). Therefore, 56 kW/m^2 was selected as the value of the source of heat flux for the parameter sensitivity analysis.

Effect of thermal conductivity. Finite-element simulations were performed by perturbing the base value of thermal conductivity (57 W/m °C) by ±10%. The roll temperature began to increase from an initial temperature of 25°C (Fig. 4). A 10% increase in thermal conductivity reduced the peak temperature by only 0.5°C at 3320 s of simulation time (Figs. 2A–C). However, the high-temperature patch receded to a significantly smaller portion of the curved surface. This indicates that thermal conductivity is a sensitive parameter affecting the size of the area covered by high-temperature patches in flaking rolls. Therefore, a slight increase in thermal conductivity incorporated into the metal matrix during the casting of rolls could result in rolls that are less prone to forming large hot spots.

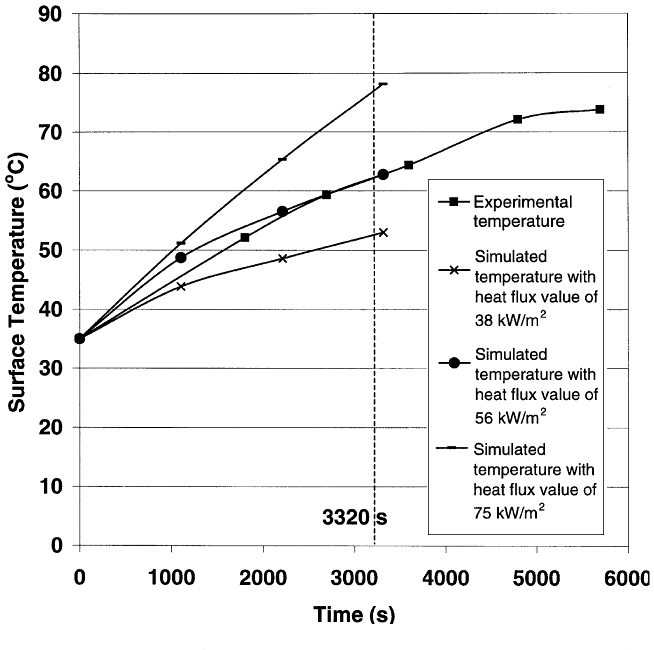

FIG. 3. Comparison of experimental and simulated temperatures at the center position of the roll surface.

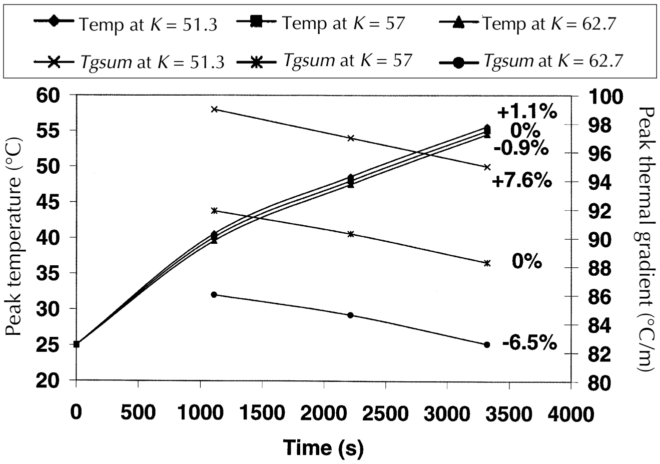

FIG. 4. Variation in peak temperature and peak temperature gradient (*Tgsum*) over time in a soybean flaking roll as a function of thermal conductivity. *K* = thermal conductivity (W/m °C).

Thermal gradient at each spatial location inside a roll was computed by summing thermal gradient values in r, θ, and z directions. Thermal gradients inside rolls decreased with time (Fig. 4). This is expected because when rolls are started from room temperature, very high thermal gradients are formed due to sudden exposure to the heat flux. As the inside of rolls starts heating up, these thermal gradients decrease. A 10% increase in thermal conductivity caused a 6–8% reduction in peak thermal gradient (Figs. 5A–C; Fig. 4). Flaking rolls used in the industry are made of concentric layers of materials with different mechanical strength and thermal conductivity (6). Figures 4A–C show that greater temperature gradients are formed near the surface of rolls than the center. Thus, casting of flaking rolls with outer layers of higher thermal conductivity would make them more effective in avoiding large hot spots and dissipating extreme thermal gradients more readily. The developed finite element program could be used to perform simulations by adding concentric layers with different thermal conductivity values. However, these simulations were beyond the scope of our present study.

Effect of heat-transfer coefficient. In some flaking roll stands, the surface heat-transfer coefficient can be slightly changed by aspirating air through the flake outlet. CFD simulations showed that a 32% increase in roll surface velocity relative to the turbulent boundary layer would cause a 20% increase in the surface heat-transfer coefficient. Simulations were performed by perturbing the base value of the heat-transfer coefficient at the curved surface and the roll ends by ±20%. At 3,320 s of simulation time, the temperature profiles and thermal gradients are shown in Figures 6A–C and 7A–C, respectively. Increasing the heat-transfer coefficient did not cause the peak temperature patch to recede to a smaller portion of the curved surface. The perturbation caused a 0.5°C

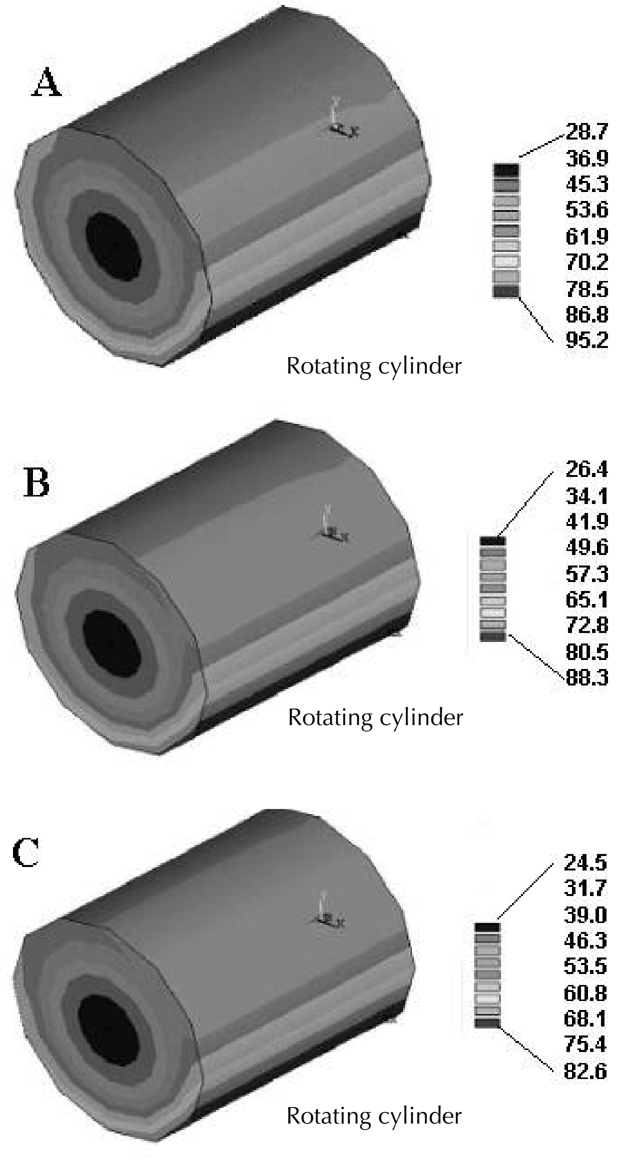

FIG. 5. Profile of temperature gradient, *Tgsum* (sum of temperature gradients in *r*, θ, and *z*-directions), in a soybean flaking roll obtained for three values of thermal conductivity—(A) 51.3 W/m °C, (B) base value, 57 W/m °C, (C) 62.7 W/m °C. The front surface displays the roll cross-section at the middle of the axis.

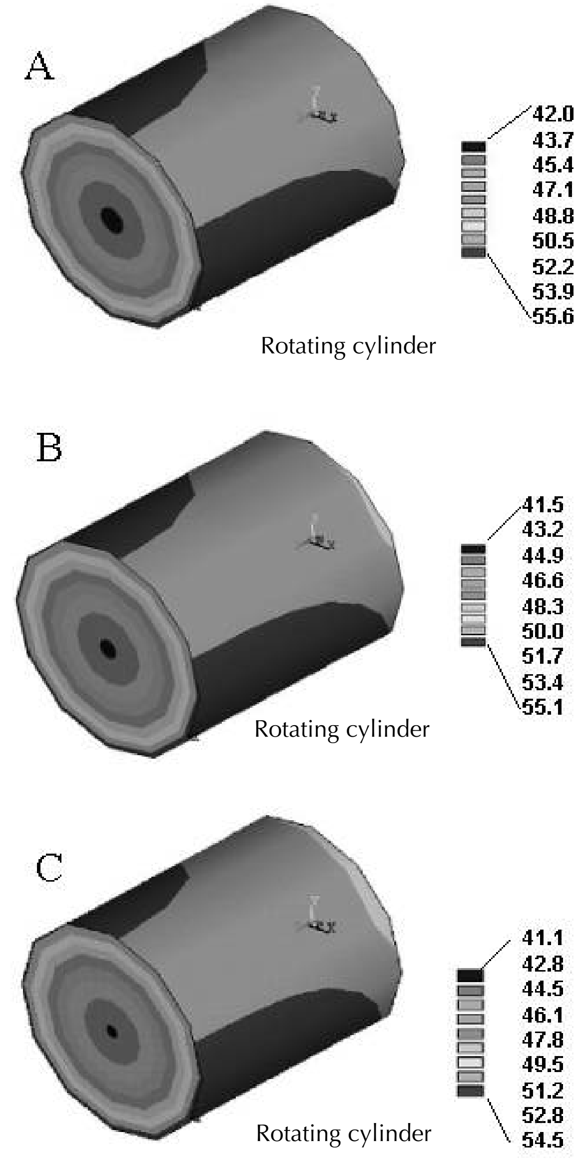

FIG. 6. Temperature profiles in a soybean flaking roll obtained for three values of convective heat-transfer coefficient on the curved surface and roll ends—(A) 20 W/m^2 °C, (B) base value, 25 W/m^2 °C, (C) 30 W/m^2 °C. The front surface displays the roll cross-section at the middle of the axis.

decrease in the peak temperature but less than a 2% change in the peak thermal gradient value (Fig. 8). This indicates that the surface heat-transfer coefficient is a less sensitive parameter than roll thermal conductivity to affect thermal gradients and high-temperature patches. This result is in agreement with experience of plant personnel in the soybean crushing industry, who have attempted to aspirate roll stands but did not observe its benefit.

Temperature profiles and gradients. Figure 3B shows a high-temperature patch of 55°C extending from the middle of the roll toward its edges. This patch was formed due to heat-flow in three dimensions. Even though surface heat flux was evenly distributed at a 30° span of the roll, the heat moved toward the roll ends and curved surface in contact with the ambient air. At each instant, rotation of the roll to a new position slightly changed the direction of the heat-flow path lines. The temperature profile at each instant resulted from a complex effect of twists in heat flow path lines at all previous times. Temperature gradient profiles at 3,320 s of simulation are shown in Figure 5B. The figure shows a much higher value (88.3°C/m) of temperature gradient at the roll surface than at the center (18.7°C/m). The temperature gradient profiles were not uniform in the circumferential and axial directions. Higher temperature gradients at the roll surface and uneven gradient profiles will result in thermal stresses. If thermal stresses exceed the ultimate strength of the material, failure might occur. This could be a possible cause of roll spalling,

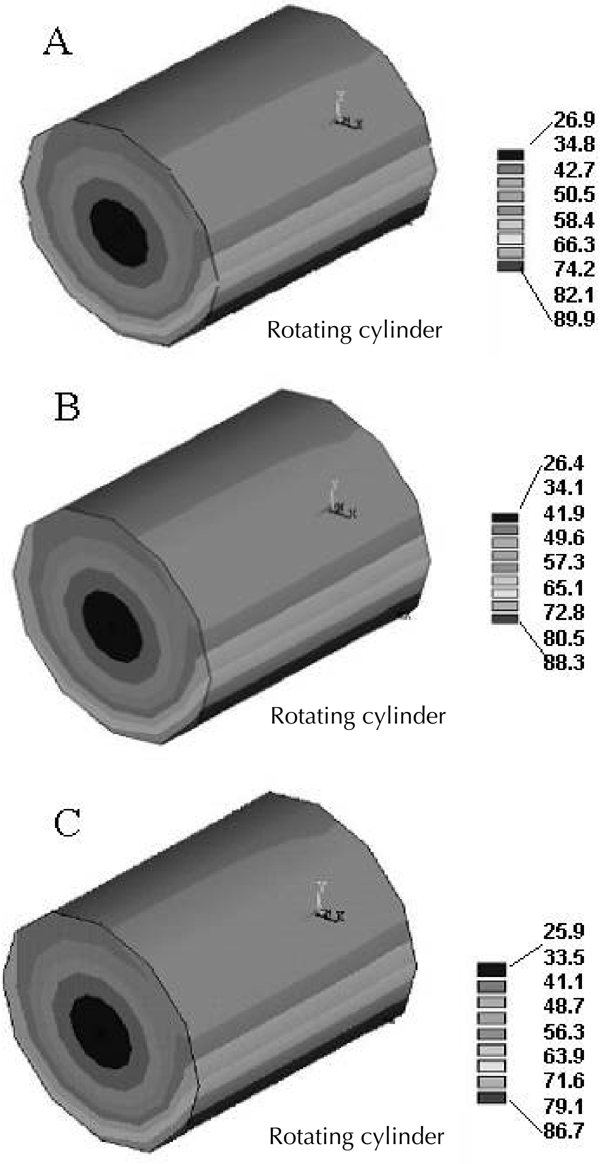

FIG. 7. Profile of temperature gradient, *Tgsum*, (sum of temperature gradients in *r*, θ, and *z*-directions) in a soybean flaking roll obtained for three values of convective heat transfer coefficient on the curved surface and roll ends—(A) 20 W/m^2 °C, (B) base value, 25 W/m^2 °C, (C) 30 W/m^2 °C. The front surface displays the roll cross-section at the middle of the axis.

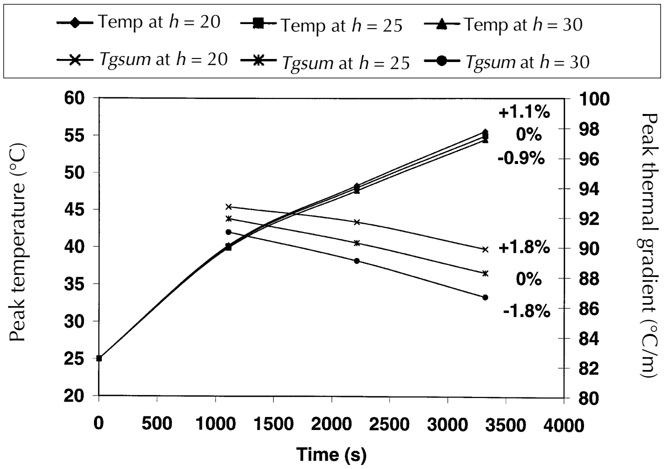

FIG. 8. Variation in peak temperature and peak temperature gradient (*Tgsum*) over time in a soybean flaking roll as a function of the convective heat-transfer coefficient, *h*.

which is a phenomenon observed in the industry that involves chunks of metal breaking off the roll surface unexpectedly.

Due to limitations imposed by the software, it was not possible to conduct simulations for uneven surface heat flux in the axial direction. The peak temperature and temperature gradient values are expected to become even larger when the heat flux in the axial direction is uneven due to nonuniform feed distribution by feeders (1). Uneven feeding will also cause concentration of high temperature patches around areas of high surface heat flux, thus forming hotspots.

ACKNOWLEDGMENTS

Cooperation of a soybean crushing plant, where the real-time experiments were conducted, is hereby acknowledged. Engineers from this company provided critical discussion and feedback. Purdue University Agricultural Research Program, Manuscript No. 16513.

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[Received November 3, 2000; accepted May 11, 2001]