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R.P. SINGH
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CONTENTS

BACK EXTRUSION AND SIMULATION OF VISCOSITY DEVELOPMENT DURING STARCH GELATINIZATION

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ABSTRACT

A generalized apriori theoretical model relating apparent viscosity of protein dough to several independent variables was used to model gelatinized starch dispersions. Independent variables in the original model were shear rate, temperature, moisture content, temperature-time history and strain history. The model is applied here to corn starch dispersions gelatinized using various temperature-time treatments. Apparent viscosity of a 13.7% gelatinized cornstarch solution at constant shear rate and strain history was measured at 20 C using a back extrusion technique. Activation energy of gelatinization was estimated as 210 kJ/mol (50 kcal/mol) over the range 81–95 C. The activation energy decreased in the range 95–105 C.

INTRODUCTION

The largest single food group in the human diet is cereal grains. Starch, the primary constituent of cereal grains, is used in different ways by the food industry (Lund 1984). Foods containing starch are processed over a range of temperatures and concentrations. Among these products, in order of increasing concentration, are soups and gravies, puddings, custards and doughs. Starch is used as a thickening agent and as a processing aid, such as corn starch used to dust work surfaces or in-process material to prevent sticking (Whistler *et al.* 1984).

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''Gelatinization'' is typically defined as the physicochemical phenomenon of swelling of starch granules as they imbibe water at temperatures sufficient to destroy the birefringence of the granules. The process occurs as the starch/liquid system is heated above a characteristic ''gelatinization temperature.'' Below this temperature, birefringence of the starch granules is preserved. For a population sample of granules, gelatinization temperature usually varies over a 10 °C temperature range, indicating distribution of different gelatinization temperatures. Viscosity of dilute starch suspensions in the early heating stages will increase mainly because amylose is released while, in later stages, viscosity increases further due to interaction of extragranular material and swelling of the granules (Lund 1984).

Apparent viscosity can be used to quantify the thickening effect of starch. One application is the prediction of minimum pressure or minimum wall shear stress for flow of a processed fluid. This information can aid in preventing plugging of pipes, a costly problem in industrial processing. Knowledge of the viscosity of starch-thickened foods is needed to design process systems with optimum operating performance as well as superior texture and product quality. Other applications include mixing systems, aseptic processing, and steam infusion.

Rheological Models for Starch Solutions

The Visco-Amylo-Graph (C.W. Brabender Instruments, Inc., 50 E. Wesley St., S. Hackensack, NJ 07606) is an empirical instrument used industrially to simulate effects of processing conditions on the rheological behavior of starch solutions. Thus, the ability of the instrument to predict flow properties depends upon the knowledge base of rheological behavior of solutions. This knowledge is usually unavailable when new products are being developed which involve changes in formulation or process conditions.

Several authors have presented models of the apparent viscosity of starch solutions. Christianson and Bagley (1983) and Bagley and Christianson (1982) found for dilute (less than 26%, g starch/g soln) corn starch and wheat starch dispersions, apparent viscosity/(C*Q) exponentially increased with C*Q, where C*Q equals the grams of swollen starch per gram of dispersion. Q, the grams swollen starch per grams initial dry starch, increased nonlinearly with increasing temperature, showing the dependence of viscosity on temperature.

Bagley, Christianson and Beckwith (1983) proposed an exponential dependence of intrinsic viscosity on the volume fraction of swollen corn and wheat starch granules for volume fraction between 0.6 and 1.0. Evans and Haisman (1979) suggested the viscosity was a function of volume fraction for gelatinized corn, potato, and tapioca starch solutions up to 10% starch.

A parameter related to apparent viscosity is yield stress. Bagley and Christianson (1983) found a yield stress existed for 11–13% gelatinized wheat starch dispersions measured at 23 °C, and found no yield stress for 10–14% dispersions measured at 60 °C. Christianson and Bagley (1984) reported yield stresses existed in 11 and 12% cornstarch solutions, and did not exist in 8 and 10% dispersions. They found that yield stress depended on temperature-time (T-t) history. Wong and Lelievre (1982) described yield stress of 1.6–8.2% wheat starch solutions as a function of starch concentration, swelling capacity, and the number fraction of large granules in the starch.

The dependence of viscosity and yield stress of starch solutions on T-t history can be inferred from the data of Bagley and Christianson (1982) and Christianson and Bagley (1983, 1984). However, in none of the above-mentioned models was the T-t history explicitly included. Other models for food doughs, discussed in the next section, clearly separate the opposing effects of temperature temperature-time history.

All of the previously mentioned studies modeled viscosity of starch based on variables measured at the end of the test, such as volume fraction and swelling capacity. The researchers did not correlate these variables with in-process conditions, such as temperature and time. The first-order modeling of Suzuki *et al.* (1976), Bakshi and Singh (1980) and Kubota *et al.* (1979) is different because it correlates end measurements to temperature and time during the test. Suzuki *et al.* (1976) reported $\triangle E_g$ for cooked rice as 80 and 37 kJ/mol for temperature ranges of 75–110 and 110–150 °C, respectively. Kubota *et al.* (1979) found $\triangle E_g$ equal to 59 kJ/mol between 70 and 85 °C for rice starch. Bakshi and Singh (1980) gave $\triangle E_g$ values of 78 and 44 kJ/mol for rough rice in the ranges 50–85 °C and 85–120 °C, respectively, and $\triangle E_g$ equal to 100 and 40 kJ/mol for brown rice in the ranges 50–85 and 85–120 °C, respectively.

Other Rheological Models Applicable to Starch

The molecular mechanisms acting in starch systems with excess water and in those with limited water are different. In the first case dispersed starch undergoes gelatinization, swells, and forms a thicker dispersion. In the latter case, starch undergoes melting and granules seldom swell; the latter material resembles more a glass, whereas the first system is a dispersion of deformable particles. Therefore the purpose of presenting dough viscosity models is not to suggest the phenomena are similar; rather, it is to propose that in both cases, temperature-time history and temperature may be treated as two separate independent process variables with opposite effects on viscosity.

Cuevas and Puche (1986) applied dimensional analysis to describe the apparent viscosity index (a relative indicator) and consistency of corn dough. They varied the speed and measuring temperature of a Brookfield viscometer, and the concentration of the corn dough (for 35 and 40% corn flour).

Harper *et al.* (1971) and Cervone and Harper (1978) predicted viscosity of cereal doughs and pregelatinized corn flour as a power law function of shear rate, an exponential function of 1/T and an exponential function of moisture content. Bloksma (1980) found that unless heating was "extremely slow," (less than .01 K/s) the viscosity of wheat flour doughs was a function of the actual temperature and thermal history.

In comparison to the effect of other variables, protein denaturation and starch gelatinization drastically increase solution viscosity. Both phenomena occur at temperatures above a certain level, and continue toward completion as long as that threshold is exceeded. Thus, there are two effects above the threshold: the "thinning effect" of higher temperatures which decreases viscosity, and the integral T-t kinetic history effect of gelatinization (or denaturation) which increases the viscosity.

Some researchers have separated these two opposite effects in their models. The development of Roller (1975) was used by Remsen and Clark (1978), who tested 22–35% MC (wet basis) defatted soy flour doughs. Janssen (1984) expressed apparent viscosity of an extruded food containing starch or protein as a function of shear rate, temperature and T-t history. Harper *et al.* (1978) presented a model for apparent viscosity as a function of T-t history and moisture content of bovine plasma protein suspensions.

MODELING APPROACH

General Mathematical Model

Morgan *et al.* (1988) proposed a mathematical model describing apparent viscosity of denaturing protein doughs as a function of shear rate, temperature, moisture content, T-t history, and strain history

$$\eta(\dot{\gamma},T,MC,\Psi,\Phi) = [(\tau_o/\dot{\gamma})^n+(\mu_r)^n]^{1/n}\; e^{[(\Delta E_v/RT)(1/T-1/T_r) + b(MC-MC_r)]}$$
$$\{1+A^\alpha(1-e^{-k\Psi})^\alpha\}\;\{1 - B(1-e^{-d\Phi})\} \tag{1}$$

Equation 1 was developed for this study by translating the approach of Morgan *et al.* (1988), from a protein denaturation-based phenomenon where water content is limiting (doughs) to a starch gelatinization model where excess water is available. Table 1 describes the analogy/physical meaning of each term in Eq. 1. Further explanation is reported by Morgan *et al.* (1988).

A number of assumptions were made in developing Eq. 1:

(1) No elastic effects,

(2) No compositional effects from materials other than starch and moisture content,

(3) No dependence upon maximum shear rate,

(4) No explicit volume fraction dependence,

(5) The effects of gelatinization on viscosity may be approximated by first-order reaction kinetics

(6) Homogeneous, isotropic medium.

The similarities and differences in the model with respect to starch versus protein are discussed in the following sections. The use of dough viscosity model for dilute systems has been justified by a review of literature for excess-water systems, not for water-starved systems. *The objective of this study is to determine the feasibility of applying the approach presented by Morgan et al. (1988) to the gelatinization behavior of raw corn starch solutions.*

TABLE 1.
PHYSICAL MEANING OF TERMS IN EQ. 1

Term	Physical Meaning
$[(\tau_o/\dot{\gamma})^n+(\mu_r)^n]^{1/n}$	shear rate effect
$e^{[(\Delta E_v/RT)(1/T-1/T_r)]}$	temperature effect
$e^{[b(MC-MC_r)]}$	moisture content effect
$\{1+A^\alpha(1-e^{-k\Psi})\}^\alpha$	gelatinization (T-t history) effect
$\{1-B(1-e^{-d\Phi})\}$	strain history effect

Shear Rate Effect. Christianson and Bagley (1983, 1984), Bagley and Christianson (1982), Wong and Lelievre (1982), Doublier (1981), and Evans and Haisman (1979) in separate studies investigated the effect of shear rate on the apparent viscosity of dilute wheat starch, corn starch, and tapioca starch solutions. All results showed shear-thinning behavior for the gelatinized solutions, but no attempt was made to quantify and/or correlate thermal history effects.

Christianson and Bagley (1984), Bagley and Christianson (1982), Lang and Rha (1981), and Evans and Haisman (1979) measured yield stresses of gelatinized corn and wheat starch dispersions in separate studies. Their findings indicate a model for starch dispersion viscosity must account for non-Newtonian behavior including the presence of a yield stress. The Herschel-Bulkley model describes both phenomena. However, at high shear rates this model approaches infinite or zero viscosity depending on the power law index. This behavior creates a problem if gelatinized starch solutions have a finite limiting viscosity, such as those experienced in high-shear processes. A simple model accounting for non-Newtonian behavior, yield stress, and finite limiting viscosity is the Heinz-Casson model, (Table 1, first term) used by Christianson and Bagley (1984), and selected for this study.

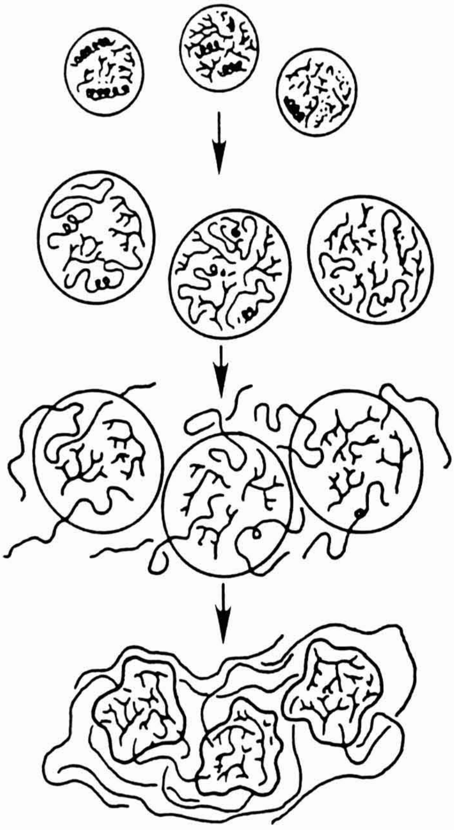
Temperature Effect. Within the starch literature reviewed, the work of Doublier (1981) with wheat starch pastes was the only one in which temperature effects were measured separately from thermal history effects, i.e., gelatinization was complete before measuring the change in viscosity with temperature. His plot of data shows adequate agreement (no measure of variance was given) with the viscosity model suggested by the Eyring kinetic theory (Eyring and Stern 1939). The Eyring model is the second term in Table 1.

Moisture Content Effect. Doublier (1981) used a power-law model to describe the dependence of apparent viscosity of 0.1 to 2.5% wheat starch solutions on moisture content. Harper *et al.* (1971) used an exponential model. Bagley and Christianson (1982, 1983) and Christianson and Bagley (1983) presented plots showing the effects of moisture content on the viscosity of wheat starch and corn starch dispersions. The data suggest an exponential decrease of viscosity with increasing moisture content. Morgan *et al.* (1988) used the same assumption.

The last three studies, excluding Morgan (1988), investigated dilute solutions, where water did not limit gelatinization. Thus, the moisture term in Eq. 1 (Table 1, third term) describes the lubricating effect of water between the starch granules. If water were limiting (which may be the case with dough), moisture content would have a reverse effect upon viscosity, because gelatinization would depend on moisture content.

Temperature-Time History Effect. Thermal (T-t) history is distinguished from temperature in that the former depends upon the path. Thus, if the starch solution viscosity was dependent on only temperature, its value would be the same at 80 C, whether a sample had been brought to 80C in 30 s or in 5 min. In fact, the viscosity differs according to the temperature exposure over time. Furthermore, T-t history and temperature have opposing effects on fluid viscosity. Greater T-t histories increase viscosity to a limit, whereas greater temperatures decrease viscosity.

Remsen and Clark (1978) presented a simplified model of the gelatinization process (Fig. 1). The fact that gelatinization begins with separate granules and ends with a network of linked particles suggests a "pseudo" polymerization. After exceeding a threshold temperature, the viscosity of starch solutions increases to a maximum over time as gelatinization occurs. Conversely, as shown



Raw starch granules made up of amylose (helix) and amylopectin (branched).

Addition of water breaks up amylose crystallinity granules and disrupts helices. Granules swell.

Addition of heat and more water causes more swelling. Amylose begins to diffuse out of granule.

Granules, now containing mostly amylopectin, have collapsed and are held in a matrix of amylose forming a gel.

FIG. 1. MECHANISM OF STARCH GELATINIZATION (from Remsen and Clark 1978)

by the second term in Table 1 and increase in temperature causes a decrease in viscosity, as expected for most fluids.

Remsen and Clark (1978), Harper *et al.* (1978), Janssen (1984), and Morgan *et al.* (1988) have modeled the T-t history effect on the viscosity of cereal dough, bovine plasma, starch and protein foods, and defatted soy flour, respectively. Harper *et al.* (1978) and Morgan *et al.* (1988) assumed protein denaturation could be approximated by a "pseudo" first-order reaction, and made the process analogous to polymerization. Janssen (1984) assumed both protein denaturation and starch gelatinization could be approximated by first-order kinetics, and Suzuki *et al.* (1976) proposed a first-order model for the gelatinization of rice starch.

There is a major difference between protein denaturation and starch gelatinization. Denaturation is a chemical reaction, where a three-dimensional structure is lost as hydrogen bonds are broken. Gelatinization is both a physical and chemical process. The physical process is hydration and swelling of granules, with leaching of amylose and amylopectin molecules into the solution. The physicochemical process is water breaking intermolecular hydrogen bonds and replacing them with water-polysaccharide hydrogen bonds. However, the overall effect of both processes is similar. Full denaturation results in unravelled aggregated protein, and gelatinization results in a loose matrix of granules and long chain molecules. In both cases the net effect is an increase in viscosity.

Therefore, the gross effect of starch gelatinization on viscosity was made analogous to that of a first-order condensation polymerization. The same assumption was made by Morgan *et al.* (1988) for protein denaturation (Table 1, fourth term).

Strain History Effect. Starch granules were assumed to undergo irreversible damage due to mechanical degradation, solubilization of granules, and depolymerization of starch. Any reversible degradation caused by breakdown of starch flocculates was not considered. The shear (also called strain) rate was used as a measure of the degradation and subsequent decrease in viscosity (thixotropy). The strain rate-time effect (strain history term in Table 1) is prominent in high shear processes.

Shear rate and strain history are two separate effects, similar to temperature and T-t history. A given strain rate produces an instantaneous stress response, as shown by a rheogram (stress versus shear rate). However, while undergoing shear, the viscosity of a fluid may decrease asymptotically to a limit (thixotropy), showing the effect of strain history. As an illustration, Wong and Lelievre (1982) made measurements as quickly as possible because the viscosity of their starch solutions at higher shear rates drifted down with time. There are few models of starch solution viscosity as a function of strain history. Diosady *et al.* (1985) proposed a model describing intrinsic viscosity of raw starch solutions as a function of the fraction of starch fully cooked and the product of stress and time.

Since both protein and starch solutions show an asymptotic decrease in apparent viscosity as strain is applied, the strain history term (Table 1) proposed by Morgan *et al.* (1988) is also appropriate for starch.

Advantages of the Model

Simplicity of Form. Albert Einstein once said, ''Everything should be made as simple as possible, and no simpler.'' For example, a linear function to describe the temperature profile, in unsteady-state heat transfer is simple but unacceptably inaccurate. A higher-order polynominal may be accurate but unwieldy. A compromise can be made by using the simplest form still retaining acceptable accuracy: in this case, perhaps a parabola or exponential. The model used in this work was developed under the same concept, that the best model is simple yet accurate.

Predictive Nature. A general type of model is $y_n = f(x_n)$, where y_n are dependent variables and x_n are independent variables. However, some models are of the form $y_1 = f(y_2)$. The difference in words is that y_1 in the second model cannot be predicted; that is, y_1 is known only after the test when y_2 is measured. The current work distinguishes the two models by referring to the first as "predictive" and to the second as "dependent." An example of the difference between the two models is the directions for cooking a cake. Typical instructions are "bake the cake for 40 min at 350 °F, or until a knife placed into the center comes out clean." The time and temperature suggested are independent variables predicting the cleanliness of the knife (y_2), which in turn predicts that the cake is done (y_1). In this research, any independent variable which could not be measured before or during a process was discounted.

An example of a dependent rheological model is that of Bagley and Christianson (1982) and Christianson and Bagley (1983). They proposed apparent viscosity (y_1) as a function of the amount of swollen starch per dry starch (y_2) of the final product. Another example is the intrinsic viscosity model of Diosady *et al.* (1985), where he uses the fraction of starch fully cooked as an independent variable.

Generality. Independent variables with universally-recognized, objective definitions were used, rather than those created specifically for this work. For example, shear rate, temperature, time, and moisture content are used for any fluid and are strictly defined, whereas "degree of gelatinization" or "fraction fully cooked" (Diosady *et al.* 1985) are substance-specific and have various definitions.

Ease of Measurement. "Intensive" or "specific" properties (those independent of mass) were preferred over "extensive" properties (those dependent on mass), because measurement techniques were easier and more accurate for the former. The model also became more general because it was less substance-specific.

Shear rate, temperature, and time are intensive properties. Shear rate is calculated using the velocity profile of the substance. Temperature is measured by a thermocouple, and time by a clock. Although moisture content is an extensive property, it can be measured when formulating the sample. These measurement techniques of intensive variables are contrasted to those for extensive properties. The techniques for measuring volume fraction and swollen weight of starch seem to be more difficult (Bagley *et al.* 1983).

Simplified Model for Starch Gelatinization

For this study all variables in Eq. 1 were constant except the T-t history. Therefore, the simplified form of Eq. 1 is

$$\eta = \eta_{ug}[1 + A^{\alpha}(1-e^{-k\Psi})^{\alpha}] \qquad (2.0)$$

resulting in apparent viscosity as an exponential function of ψ, where

$$\Psi = \int_0^{t_f} [\; T(t)\exp(-\Delta E_g/RT(t)\;]dt \quad \text{if} \quad T \geq T_g$$

and

$$\Psi = 0 \qquad \text{if} \quad T < T_g \tag{2.1}$$

and

$$\eta_{ug} = [(\tau_o/\dot{\gamma}_1)^n + (\mu_r)^n]^{1/n}\, e^{[(\Delta E_v/RT_1)(1/T_1 - 1/T_r) + b(MC_1 - MC_r)]}\, \{1 - B(1 - e^{-d\Phi_1})\} \tag{2.2}$$

from Eq. 1, where $\dot{\gamma}_1$, T_1, MC_1, and Φ_1 are aribitrary. It is proposed that Eq. 2 be used to predict the relative increase in viscosity of a dilute starch solution at any point in the gelatinization process. There are three distinct features of Eq. 2:

(1) The gelatinization effect is additive.

(2) The value of the constant A is the relative increase in viscosity caused by gelatinization. For example, if $A^a = 1$, the final viscosity as ψ goes to infinity has increased 100% relative to the ungelatinized viscosity.

(3) The gelatinization effect has an exponential dependence upon T-t history, which in turn has an exponential dependence upon inverse absolute temperature. This ''double''-exponential dependence, simlar to first-order Arrhenius kinetics, describes the drastic increase of viscosity during gelatinization.

The value of ungelatinized viscosity and A give a range of the physically possible viscosity values. The integral T-t function and its coefficient (k) characterize the extent of reaction. In this research, the viscosity of the cornstarch solution increased 80 times (A^α equal to 80 in Eq. 2) after complete gelatinization.

MATERIALS AND METHODS

Choice of Variables

A parameter in a multi-variable model can be found by experimentally holding all variables constant except the one independent variable associated with the parameter. The dependent variable then varies and the parameter is fit statistically.

Equation 2 shows that k, α, and $\triangle E_g$ are the parameters and apparent viscosity is the dependent variable. However, the associated independent variable is not obvious because $\triangle E_g$ is within an integral (Eq. 2.1). Since an integral must be used for processes where temperature is a function of time, $\triangle E_g$ cannot not be solved for explicitly, but is approximated by an iterative procedure. The parameter k is lumped with $\triangle Eg$.

Experiments

Corn starch solutions varying from 13.2 to 13.7% starch were hand-mixed, to minimize strain history, using distilled water at 23 C. Moisture content was determined from sets of three 12 g samples oven-dried 24 h at 105 C.

The gelatinization threshold temperature was approximated by heating a sample at 3 C per min. between parallel plates in a Rheometrics Fluid Spectrometer, Model 8400. The gap was 0.8 mm and the steady shear rate was 100 1/s. A 30-gauge thermocouple (Omega Engineering, One Omega Drive, P.O. Box 4047, Stamford, CT 06907) lead was attached to the top plate with tape (Scotch) to press the tip against the plate. Silicone grease was applied to the tip to assure contact to the top plate. Another thermocouple monitored bath temperature at the bottom plate. The gelatinization temperature was approximated as a weighted average of the top plate temperature and bath temperature at the time when the viscosity began to continuously increase, as measured by the Spectrometer. Based on an estimate of thermal resistance, the bath temperature was weighted twice as much as the top plate temperature.

The starch solution was subjected to different T-t histories. Based on prior observations of the gelatinization and gelling phenomena, 125 × 13.5-mm (inner diameter) screw-top glass test tubes, one-third full of the solution were heated in an ethylene glycol/water (Aminco top-loading heating/cooling bath, Silver Springs, MD) at constant temperature. Seven temperatures were used: 81, 84, 85, 91, 95, 101, and 105 C. For each temperature, sets of two to three tubes were heated for various times ranging from 20 s to 20 min, depending upon the glycol bath temperature. The tubes were shaken in a container at at 250 rpm, a speed determined visually to prevent settling of starch granules. The temperature at the radial center of the solution and 12 mm below the solution surface was measured every 10 s by a needle-nose T-type thermocouple (Omega Engineering, one Omega Drive, P.O. Box 4047, Stamford, CT 06907) fixed in each of one to four representative tubes for each bath temperature. The average measured temperature at each time was used for T-t history calculations. At the prescribed cook time, the tubes were removed from the bath, and immediately placed in an ice bath at 0 C to reduce the temperature below T_g within 30 s.

Apparent Viscosity. The solutions were allowed to gel at room temperature, from 18 to 22 C. The apparent viscosity of each tube was characterized using a back extrusion device (Fig. 3), a technique described by Harper *et al.* (1978). A stainless steel plunger was forced through the gel at a constant rate of 50 mm/min over a distance of 25 mm, measured from the original surface of the gel. The force required to move the plunger was recorded graphically by an Instron (Model 4202) Universal Testing Machine (Instron Corp., Canton, MA).

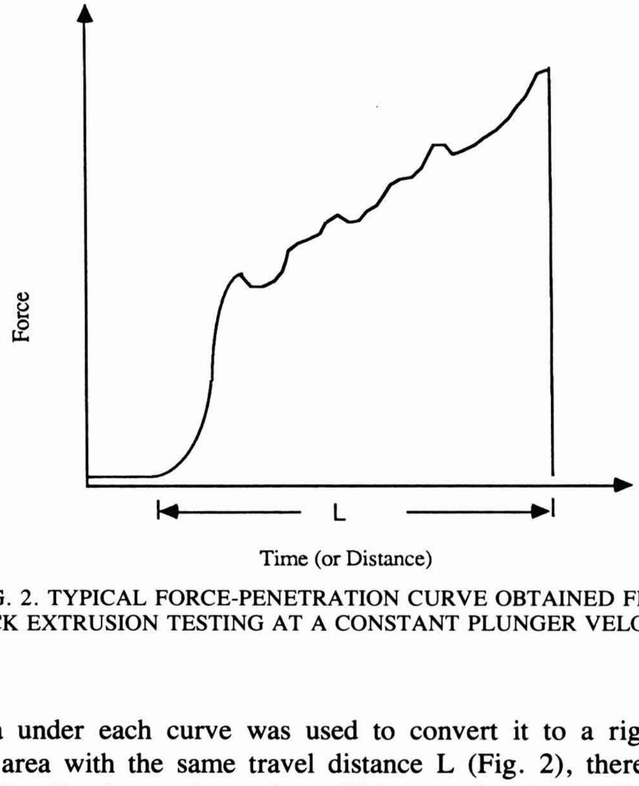


FIG. 2. TYPICAL FORCE-PENETRATION CURVE OBTAINED FROM BACK EXTRUSION TESTING AT A CONSTANT PLUNGER VELOCITY

The area under each curve was used to convert it to a right triangle of equivalent area with the same travel distance L (Fig. 2), thereby yielding a height equal to Fp, the maximum force. This procedure is a modification of that of Harper *et al.* (1978). The ratio of F to L times a constant was used as a relative value of viscosity (Hickson *et al.* 1982).

The dimensionless form of Eq. 2 is

$$\eta/\eta_{ug} - 1 = A^{\alpha}(1-e^{-k\Psi})^{\alpha} \tag{3}$$

As ψ goes to infinity,

$$\eta_{\infty}/\eta_{ug} - 1 = A^{\alpha} \tag{4}$$

Dividing Eq. 3 by Eq. 4 yields

$$\frac{(\eta/\eta_{ug})\quad -1}{(\eta_{\infty}/\eta_{ug})\quad -1} = \frac{\eta-\eta_{ug}}{\eta_{\infty}-\eta_{ug}} = y = (1-e^{-k\Psi})^{\alpha} \qquad (5)$$

Equation 5 was used for plotting the results. For each bath temperature, a curve of normalized viscosity $(\eta-\eta_o)(\eta_\infty-\eta_o)$ versus time was fit. The multiplicative form of Eq. 1 allows the effects of a varying temperature of measurement and moisture content to be cancelled by using normalized viscosity.

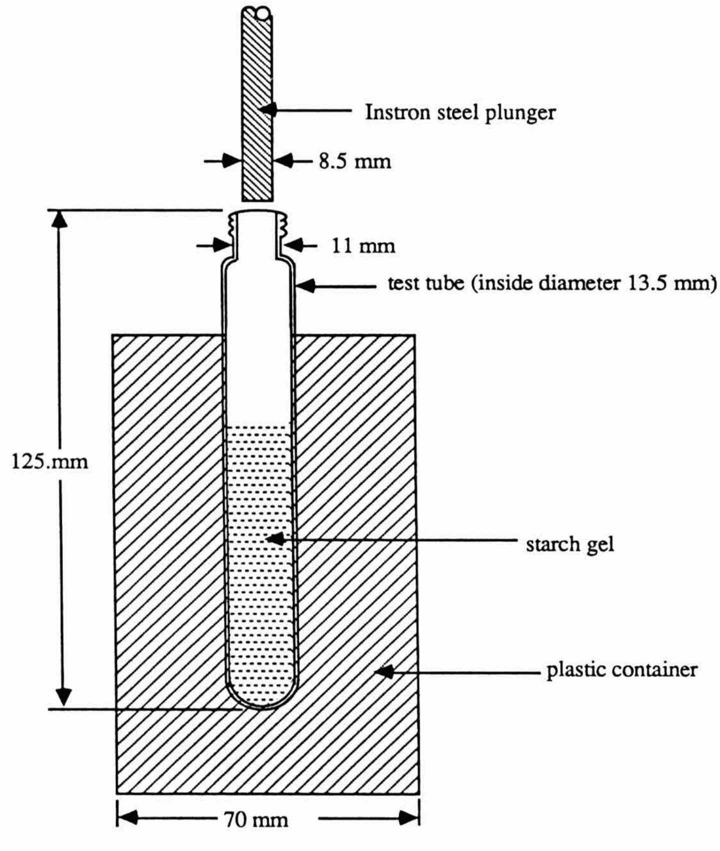


FIG. 3. SCHEMATIC OF TEST TUBE IN PLASTIC HOLDER DURING BACK EXTRUSION

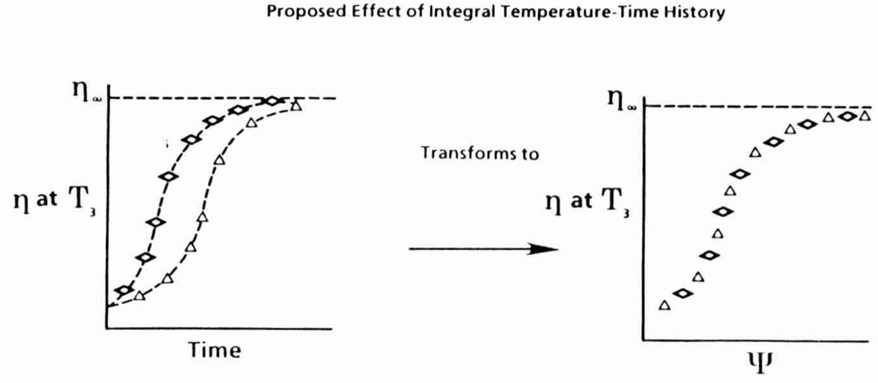

Proposed Effect of Integral Temperature-Time History

FIG. 4. USE OF TEMPERATURE-TIME HISTORY TO COLLAPSE A SERIES OF CURVES EACH AT CONSTANT TEMPERATURE TO ONE CURVE

Temperature-Time History. According to Eq. 5, all y versus time curves at different temperatures can be coverted to one master curve, y versus ψ. (Fig. 4), once the proper $\triangle E_g$ is determined. Because ψ was an integral, the following iterative procedure was developed:

(1) An estimate of $\triangle E_g$ was made, based on values reported in literature.

(2) By using the representative measured temperature-time history (T-t) and the estimate of $\triangle E_g$,ψ was calculated for each group of replicates taken out of the hot bath at a specific time and temperature.

First the "mass-average ψ" value was calculated. The gelatinized starch inside the tube was treated as an infinite solid cylinder at uniform initial temperature T_0, subjected to two step changes in environment temperature: first, an increase to the hot bath temperature, and second, a decrease to the ice-bath temperature at 0 °C. Heisler's chart (Holman 1976, Fig. 4–13) was used to calculate temperature at 10 different radii as a function of the measured center temperature. The combined thermal resistance of the glass tube wall and the heat transfer coefficient between the tube wall and bath fluid was estimated as at least 20 times less than the internal gelatinized starch resistance. Thus, at each time the mass average ψ value

$$\text{mass av. } \Psi = 2\int_0^1 T(r)e^{(-\Delta E_g/(RT(r))}(r/R)\,d(r/R) \qquad (6)$$

was calculated by Simpson's rule (Hornbeck 1975). Equation 6 is the integration over volume. These values were integrated over time using the trapezoidal rule (Hornbeck 1975), to obtain the integral temperature-time history ψ (Eq. 2.1) for each replicate group. y versus ψ were then plotted as points for each replicate group for all bath temperatures, using one value of $\triangle E_g$, estimated in 1.

(3) Using a computer routine, $\triangle E_g$ was varied and the procedure outlined in step 2 was repeated for each change. The coefficient k was lumped with $\triangle E_g$ because k was not varied independently, but forced to change with the fit of the equation every time $\triangle E_g$ was changed. The agreement between y and ψ was measured by a Marquardt nonlinear regression (Draper and Smith 1981) of all points using the statistical computer routine Plot-it (Eisensmith 1987). The $\triangle E_g$ yielding the greatest coefficient of determination (R^2) was used, as was the corresponding k for the fit to Eq. 5. A linear transformation on Eq. 5 was rejected because the resulting variance of residuals increased dramatically with ψ (discussed in Neter *et al.* 1985, p. 467–469).

The effect of different heating bath temperatures was shown by regression on successively smaller sets of data: (1) all points, (2) all points except those at 105 C, and (3) all points except those at 101 and 105 C.

RESULTS

Figure 5 shows the seven curves of average normalized viscosity versus time, and Fig. 6 shows the same curves transformed to one curve (normalized viscosity versus integral T-t history) with the regression line and 95% confidence band. The coefficient of determination was 0.843 for the regression of all values except those for 101 and 105 C (Fig. 6). The activation energy yielding the greatest coefficient of determination was $\triangle E_g$ equal to 210.kJ/mol (50.0 kcal/mol). The coefficient of ψ in Eq. 2.0, k, was equal to 0.846×10^{26} $(Ks)^{-1}$. The estimate of the exponent α was 0.494. Each point in Fig. 6 represents an average of two or three viscosity values at the same ψ value. The regressions on all points and on all points except those at 105 C gave lack-of-fit significance less than 0.0001. The regression on all points gave $\triangle E_g$ equal to 170 kJ/mol (40. kcal/mol) and a coefficient of determination of 0.755.

Figure 7 is a plot of residuals (measured value - predicted value) versus $\psi * 10^{26}$ for the regression line in Fig. 6. There were two to three replicates in each of 31 sets, giving 87 total observations. The standard deviation and absolute mean of residuals was 0.09 (9.0% of full-scale) and 0.076, respectively. In addition, the F value for lack-of-fit was 0.76 at a significance of 78.2%.

The weighted average "threshold" gelatinization temperature was 65C. The average moisture content of the raw starch varied form 8.0 to 12%. The average viscosity indexes at 99% gelatinization were estimated at 4300, 7300, 9600, and 7800 cp at 81, 85, 91, and 95 C, respectively.

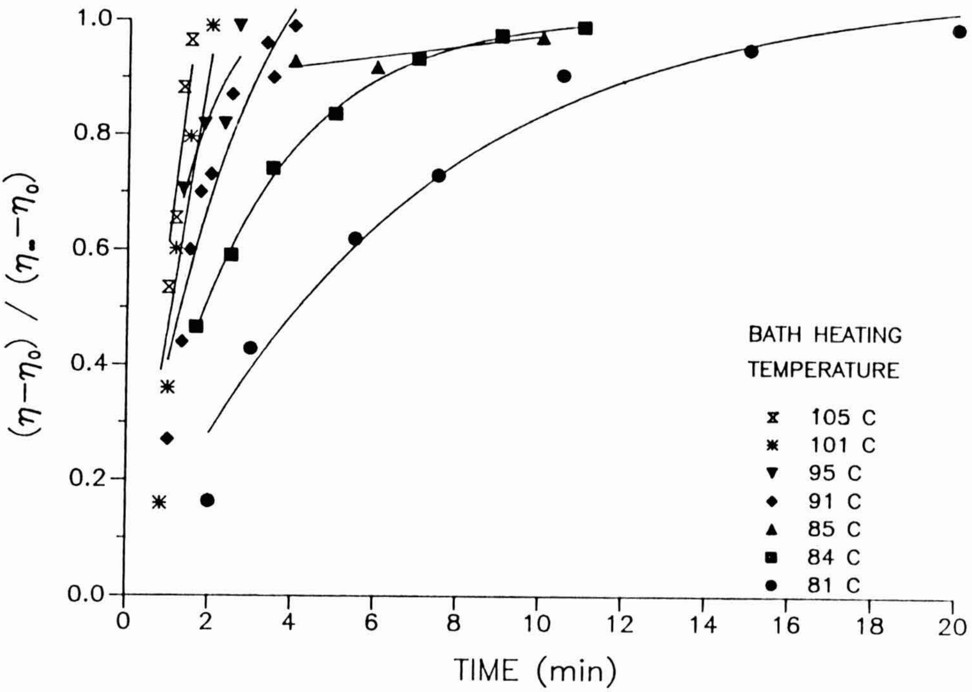


FIG. 5. AVERAGE NORMALIZED VISCOSITY VERSUS TIME FOR 13.7% (wb) STARCH SOLUTIONS AT 20 C AND CONSTANT SHEAR RATE AFTER HEATING AT 81, 84, 85, 91, 95, 101 AND 105 C

DISCUSSION

The regression on all points show that Eq. 5 is inadequate to include the full range from 81 C to 105 C. A better fit for all temperatures may be found by expressing $\triangle E_g$ as a function of temperature, or as a different constant within certain temperature ranges (Suzuki *et al.* 1976; Kubota *et al.* 1979; Bakshi and Singh 1980). This method is a concession for using first-order kinetics to describe what is probably a mixed-order reaction (Lund 1984). The three separate regressions revealed $\triangle E_g$ decreased at higher temperatures, in agreement with Suzuki *et al.* (1976) and Bakshi and Singh (1980). Most likely a different level of gelatinization, having a lower activation energy, is triggered at higher temperature.

The 0.843 coefficient of determination and 78.2% significance of F lack-of-fit (Fig. 6) indicate the usefulness of the model form $y = (1\text{-exp}(-k\psi))^{\alpha}$ for the temperature range 81–95 C. However, the 0.98 rather than 1.0 coefficient in the regression line (Fig. 6) indicates the difficulty of deciding what value of viscosity is the limiting value.

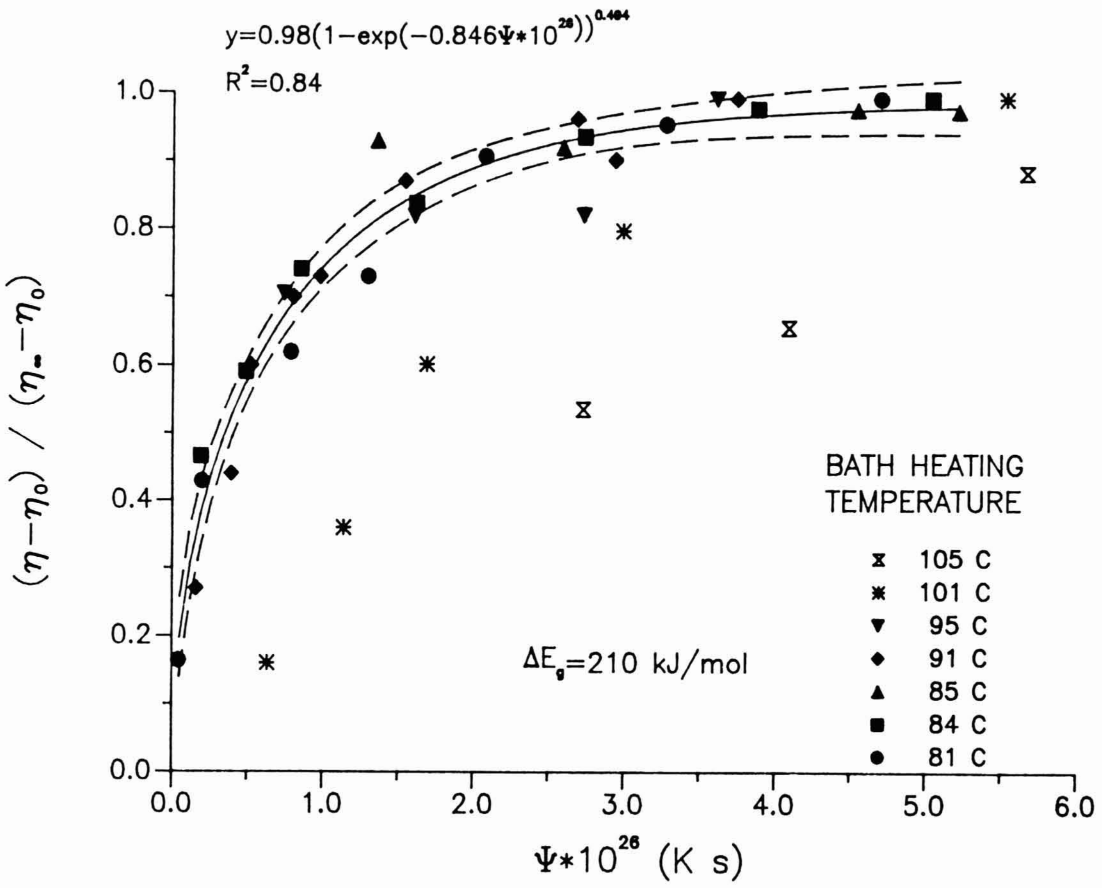


FIG. 6. FIGURE 5 WITH THE ABCISSA REPLACED BY TEMPERATURE-TIME HISTORY
(Regression does not include values at 101 and 105 C)

Data for 101 and 105 C (Fig. 6) were not included in the regression, but were plotted to show how far they lay from the rest of the data. This excessive deviation may have been caused by the increased error at high temperatures, specifically in the calculation of T-t history. Errors in temperature measurement are magnified in ψ as temperatures increase, because of the exponential dependence of ψ on inverse temperature (Eq. 2.1).

At a given T-t history, the viscosity is lower when heated at higher temperatures (Fig. 6). This result suggests there is a limit to how quickly water can enter and hydrate the starch granules. Although the calculated T-t history may be greater, the diffusion of water in and the diffusion of amylose out cannot proceed any faster. Another limiting factor is the increased amount of water vapor produced as temperatures approach 100 C. Not only is heat lost to vaporize liquid water, but the vaporized water cannot enter and swell the granule as liquid water can.

In addition, the values at 101 and 105 °C may have been affected by the more complete disintegration of granules and the increased solubility of the starch. Christianson and Bagley (1983) also mention the increased amount of solubles at temperatures greater than 94 °C.

Figure 7 shows the residual for every observation in the Fig. 6 regression. The standard assumptions (Beck and Arnold 1977) are that errors are additive, have zero mean with constant variance, are uncorrelated, and have a normal probability distribution. Randomness and lack of trends (Fig. 7) suggest that the errors are additive. An absolute mean of .068 does not seriously violate the assumption of zero mean, and the number of positive and negative residuals is 47 and 40, respectively. The "band" of residuals is approximately horizontal and of constant width, showing a constant variance with ψ, unlike the results for the linear form of Eq. 5. The number of changes in sign (48) is more than half the total observations (87). According to Beck and Arnold (1977, p. 409) the errors are uncorrelated. In summary, the standard assumptions for residuals are valid.

Problem for Calculating the Cook Time of a Steam Infusion Process

The model developed in this study can be used to solve process engineering problems. One example is provided in this section. Assume that a steam-infusion process requires a final apparent viscosity (η) of 700 cp, and the material has an ungelatinized viscosity (η_{ug}) of 20 cp. The following fundamental information is provided from prior rheological measurements: $k = 2.3 \times 10^{19}$ (K min)$^{-1}$, $\triangle E_g = 150.$ kJ/mol, $\alpha = 1.0$, and $A = 49$. Calculate the required cook time considering a sequence of steps:

1. Make sure desired η (700 cp) is less than maximum $\eta_\infty = \eta_{ug}(1+A) = 20(1+49) = 1000$ cp
2. Calculate the normalized viscosity (Eq. 5): $y = (700-20)/(1000-20) = 0.69$

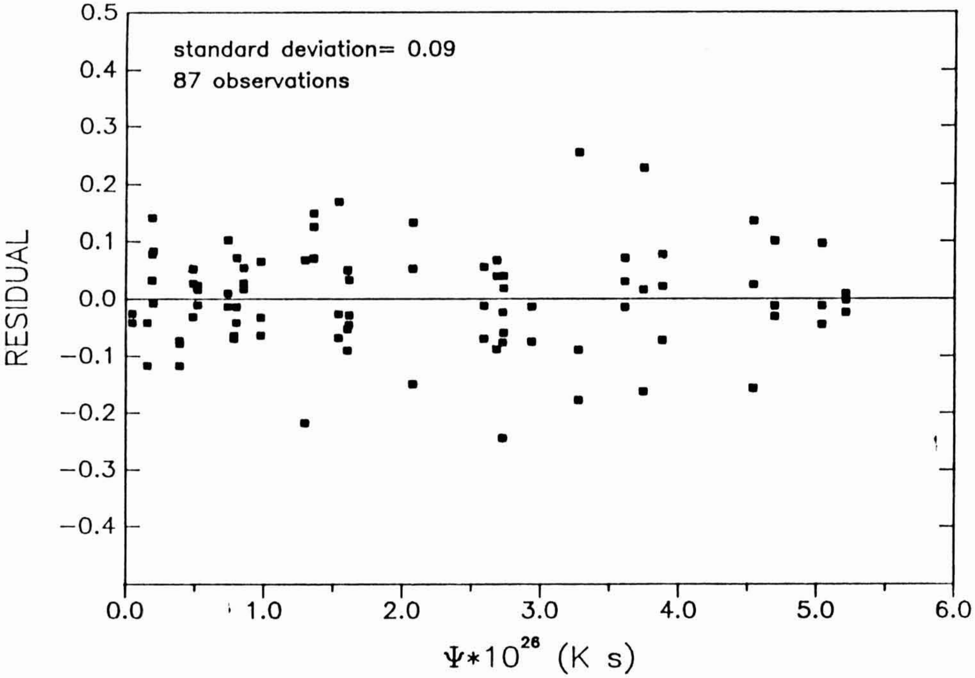


FIG. 7. RESIDUAL (MEASURED VALUE-PREDICTED VALUE) VERSUS TEMPERATURE-TIME HISTORY FOR REGRESSION LINE IN FIG. 6.

3. Rearranging Eq. 5,

$$\psi(.69) = -\ln(1-y)/k = -\ln(1-.69)/(2.3 \times 10^{19}) = 5.1 \times 10^{-20}$$

4. Calculate cook time for a constant cooking temperature 85 C = 358 K
Rearranging Eq. 2.1

$$\Delta t = \psi\, e^{(\Delta E_g/RT)}/T =$$

$$(5.1 \times 10^{-20})\text{K min} \exp[(15 \times 10^{4}\ \text{J/mol})/(8.314\ \text{J/mol K} * 358\ \text{K})]/358\ \text{K}$$

$$= 1.1\ \text{min} = 66\ \text{s} = \text{cook time}$$

This type of analysis would be appropriate for steam infusion problems involving starch-thickened fluids, such as many baby food products.

SUMMARY AND CONCLUSIONS

A general model was used to simulate starch viscosity development during gelatinization. Only the thermal history effect of gelatinization was experimentally verified. However, the authors propose a comprehensive model, including independent variables of shear rate, temperature, moisture content, T-t history, and strain history, for describing viscosity of dilute starch solutions. The shear rate dependence is described by the Heinz-Casson model, including a yield stress and finite limiting viscosity at high shear. The temperature effect is modeled using the Arrhenius relationship, and the influence of moisture content is assumed to be exponential. The gross effect of gelatinization on viscosity is modeled using first-order kinetics, leading to a temperature-time history term. The effect of strain history is approximated as exponential.

Evaluation of the T-t history effect indicates the relative influence of gelatinization upon apparent viscosity can be modeled as a function of one parameter only, temperature-time history. Expression of ''activation energy'' as a functions of temperature will improve the model.

Unlike starch viscosity models in the literature, this model does not require measurement of the end product. The model is general in that it can be used for any system geometry, process, or equipment, and can predict apparent viscosity at high shear rates. The form of the model (Eq. 1) allows each term to represent the complete effect of one variable (Table 1). Therefore, any one term may be easily replaced by another suggested form. For example, the Heinz-Casson model can be directly replaced by the power-law form for apparent viscosity.

The model can be tested and modified by estimating the parameters for several types of starch. Future research should be directed towards a verification of each term to assess which are most influential and which may be neglected. The assumption of independence of variables should also be investigated. The model can then aid in full-scale simulations of the processing of any starch-thickened fluid, if gelatinization is the overriding cause of viscosity increase.

ACKNOWLEDGMENTS

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NOMENCLATURE

A	relative amount of viscosity increase due to gelatinization, dimensionless
B	relative amount of viscosity reduction due to thixotropy, dimensionless
b	exponent quantifying the lubricating effects of moisture on dough viscosity, dimensionless
C	dry weight of starch per unit weight of dispersion, decimal
d	rate constant quantifying thixotropy effects, dimensionless

F	maximum force for ideal back-extrusion, Fig. 3 (N)
k	reaction transmission coefficient (K s)$^{-1}$
L	distance traveled by plunger, Fig. 3 (m)
MC	moisture content, wet basis, decimal
MC_r	arbitrary reference moisture content, wet basis, decimal
n	power law flow index, dimensionless
Q	weight of swollen starch per unit weight of dry starch, decimal
R	universal gas constant (8.314 J/mol K or 1.986 cal/mol K)
T	absolute temperature (K)
T_g	threshold temperature for gelatinization (K)
T_o	initial temperature (K)
T_r	arbitrary reference temperature (K)
t	time (s)
t_f	total time of experiment (s)
y	normalized apparent viscosity, defined by Eq. 5, dimensionless

Greek Symbols

α	exponent describing molecular weight effect on viscosity, dimensionless
$\dot{\gamma}$	viscometric shear (strain) rate (s^{-1})
$\triangle E_g$	"activation energy" of gelatinization (J/mol or cal/mol)
$\triangle E_v$	viscous activation energy of temperature effects (J/mol)
η	apparent viscosity (Pa s)
η_o, η_{ug}	apparent viscosity at zero time, equal to ungelatinized apparent viscosity, Pa (s)
η_∞	apparent viscosity as $\psi \rightarrow \infty$ or $\Phi \rightarrow \infty$, (Pa s)
μ_r	Heinz-Casson high-shear limiting viscosity at reference temperature T_r and reference moisture content MC_r (Pa s)
τ_r	Heinz-Casson yield stress at reference temperature T_r and reference moisture content MC_r (Pa)
ψ	integral temperature-time history function, defined by Eq. 2.1, (K s)
Φ	integral strain history, dimensionless $= \int_0^{t_f} \dot{\gamma} dt$

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CONDUCTION HEATING OF HIGH MOISTURE ROUGH RICE III. CHANGES IN MILLING AND COOKING QUALITIES

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ABSTRACT

The effects of high temperature conduction heating on the milling and cooking qualities of rough rice having moisture in the range 18–30% wet basis were investigated. The results showed an increase in head rice yields of heat-treated samples accompanied by a reduction in milled rice whiteness and improvement in cooked-rice texture. Heat treatments of rough rice corresponding to fungal inactivation level of 95% gave the highest head rice yields and acceptable level of reduction in the whiteness of milled rice. The observed increase in the firmness of cooked-rice kernels and a reduction in their stickiness due to conduction heating appeared to resemble the natural aging of fresh rough rice.

INTRODUCTION

It has been recently reported that conduction heating of high moisture rough rice could effectively arrest fungal growth and hence its spoilage during temporary storage prior to drying (Reyes and Jindal 1988a, 1988b). However an understanding of changes in milling and cooking quality of rough rice during the conduction heating process is essential for its successful practical applications. Other studies on high-temperature short-time conduction heating of rough rice for accelerated drying have shown an increase in the head rice yields due to gelatinization of starch in the grain (Khan *et al.* 1974; Raghavan and Harper 1974; Ali and Bhattacharya 1980; Acasio and Belonio 1983). However, there is no presently available information on the effects of high temperature heating of rough rice on the appearance and cooking qualities of milled rice. Therefore, the main objective of this study was to investigate the changes in head yields, whiteness and cooking qualities of rice due to conduction heating carried out for fungal inactivation.

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MATERIALS AND METHODS

Heating Experiments

Freshly harvested high moisture rough rice samples of variety RD-23 were heated in the experimental rotary conduction heating unit. The details of the equipment and experimental procedure are given by Reyes and Jindal (1988a). The rough rice samples used in this study had moisture contents of 18, 22, 26 and 30% w.b. The heat treatments consisted of conduction heating of high moisture rough rice samples, each weighing 3 kg, using predetermined heating surface temperature and exposure time and then cooling to room temperature. Five heating surface temperatures of 75, 100, 150, 175, 200 °C and exposure times up to 100 min were used. Aluminum trays about 30 cm in diameter and 10 cm deep with perforated cover were used for cooling the heat-treated samples. This cooling method resulted in a cooling rate of about 0.7 °C/min.

Milling Tests and Moisture Content Determination

All rough rice samples (heat-treated and control) were air-dried to 14% moisture content prior to milling. The quantity of head rice which comprised of kernels three-quarters in size and longer was determined by using a standard laboratory procedure (USDA 1977). A precleaned rough rice sample weighing 125 g was passed twice through a rubber roll testing husker (Satake model THU35A) and the resulting brown rice was whitened for 1 min, using a McGill type laboratory testing mill. A testing length grader was operated to separate the head rice from brokens. Percent head rice yield was calculated as the mean of three replications, each determined with a 125 g rough rice sample.

The degree of whiteness of milled rice samples was measured using a whiteness meter (Kett model C-300). At least three readings were made for each sample. Head rice yields and whiteness readings were later expressed in terms of head rice yield ratio (HYR) and whiteness ratio (WR), respectively, to reflect the changes in heat-treated rough rice samples relative to the control sample.

The moisture of rough rice samples was determined by drying whole rough rice grains for 16 h at 130 °C in an air oven (Matthews 1962).

Evaluation of Cooked Rice Texture

The texture of cooked rice samples was evaluated in terms of the firmness and stickiness determined with an Instron Universal Food Tester Model 1140, equipped with a 50 kg capacity compression load cell. A back extrusion test cell similar to one reported by Cagampang *et al.* (1984) was used for firmness measurements. The stickiness was determined using the modified single kernel techniques of Okabe (1979). The cooked rice samples were prepared using the adequate water method (Perez and Juliano 1979).

The back extrusion test cell consisted of a 80 mm long stainless steel cylinder having an internal diameter of 16.3 mm and a spherical plunger with annular gap of 1.8 mm (Fig. 1). A removable base could be attached at the lower end of the test cylinder. A 12 g sample of cooked rice was placed into the test cell by gently packing 2-3 g of sample at a time with a wooden rod. This method resulted in about 67.0 mm long packing with its upper level about 7.0 mm below the top of test cylinder. The downward stroke of the plunger ended about 6.4 mm from the bottom of the test cell. The force-distance curve during compression of cooked-rice was recorded using a crosshead speed of 10 cm/min and a strip chart operating at a speed of 20 cm/min. Firmness was defined as the total compression energy or the area under the force-distance curve until the point of extrusion. A digitizer was used for integrating the area under the experimental force-distance curves.

For measurement of stickiness, three kernels of cooked-rice were placed apart with the dorsal and ventral side lying horizontally. The sample was compressed with a 3.6 cm diameter plunger at a speed of 0.5 cm/min to a fixed clearance of 0.2 mm. After 10 s, the plunger was pulled up at the same speed. Stickiness was measured as the total energy required to lift the plunger. Stickiness and firmness values were later expressed in terms of stickiness ratio (SR) and firmness ratio (FR), respectively to reflect the changes relative to control samples. The reported values of the texture parameters are the average of 5 determinations. Other details of the experimental procedure are given by Reyes (1986).

RESULTS AND DISCUSSION

Moisture Removal During Conduction Heating

A typical plot showing the change in the moisture content of rough rice during conduction heating is illustrated in Fig. 2. The bulk grain temperature of rough rice samples during conduction heating in the experimental unit could be estimated by a relationship reported in a previous study (Reyes and Jindal 1988a). Rapid moisture removal from rough rice was obvious in all experiments especially at higher heating surface temperatures. A simple logarithmic model which represented the drying behavior of rough rice having moisture in the range of 18 to 30% w.b. during conduction heating follows:

$$Mt = Mo \exp(-k\,t) \tag{1}$$

where Mt = instantaneous grain moisture content during heating, % w.b.
Mo = initial grain moisture content, % w.b.
t = drying time, min
k = drying constant, (1/min)

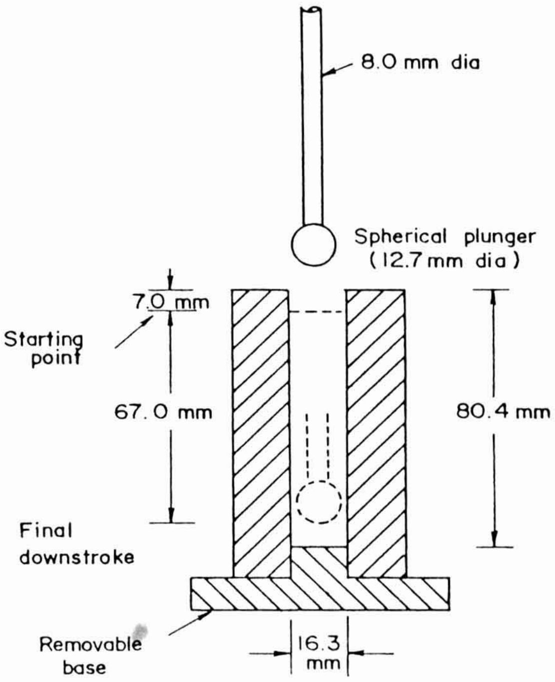

FIG. 1. SCHEMATIC DIAGRAM OF BACK EXTRUSION TEST CELL FOR MEASURING THE FIRMNESS OF COOKED-RICE

The dependence of drying constant k on the experimental conditions was adequately described by the following equation:

$$k = -7.8460 \times 10^{-5}\,Ts + 1.4114 \times 10^{-6}\,Ts^2 \qquad (2)$$

$$(R^2 = 0.930;\ SEE = 0.004)$$

where Ts = heating surface temperatures, °C

Eq. 2 revealed the strong dependence of drying constant only upon the heating surface temperature.

Since heating of high moisture rice to achieve at least 90% or higher fungal mortality level (FML) was recommended by Reyes and Jindal (1988b) for safe temporary storage, corresponding exposure times could be estimated using bulk grain temperature history and a general procedure also proposed by Reyes and Jindal (1988a) in a previous study. The final moisture contents corresponding to

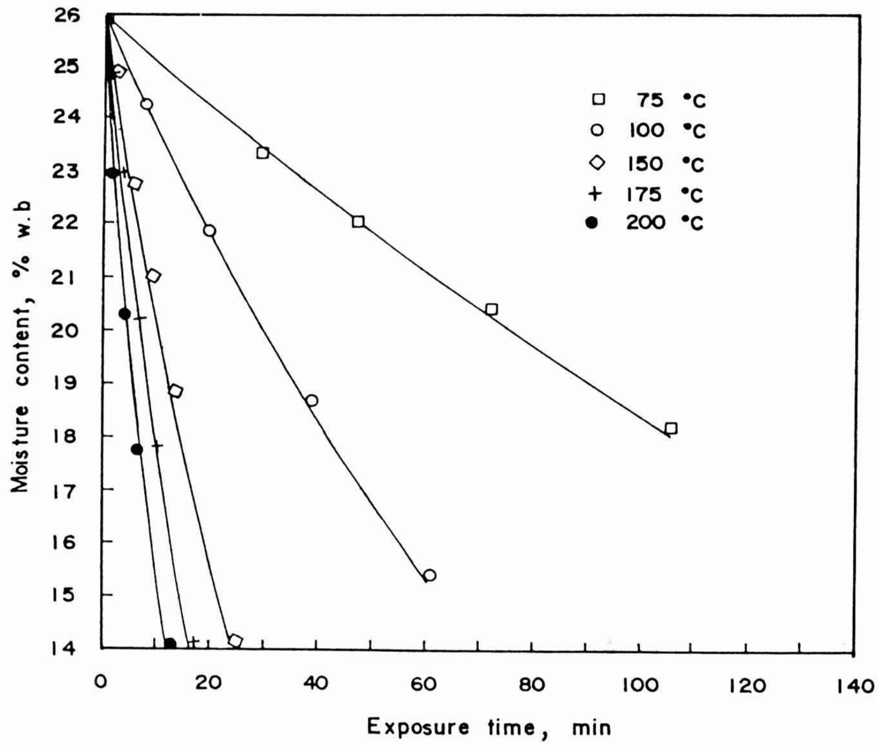

FIG. 2. A TYPICAL PLOT OF MOISTURE CONTENT OF ROUGH RICE AS A FUNCTION OF EXPOSURE TIME FOR VARIOUS HEATING SURFACE TEMPERATURES

these exposure durations could be computed using Eq. 1 and 2. Heating time corresponding to 90% FML resulted in about 3% moisture reduction in rough rice when using a heating surface temperature in the range of 150 to 200 °C.

Effects of Heat Treatments on Head Rice Yield

A typical plot showing the effect of exposure duration on head rice yield during conduction heating of high moisture rice samples at 150 °C surface temperature is presented in Fig. 3. Similar trends were observed during heat treatments with heating surface temperatures of 75, 100, 175 and 200 °C. The heat-treated rough rice samples clearly showed an increase in their head yields with increasing exposure time initially. However, a reduction in head yield was observed during prolonged heating. The dependence of head rice yield on the exposure duration was expressed by the following quadratic equation:

$$\mathrm{HYR} = 1 + \mathrm{A}\,t - \mathrm{B}\,t^2 \qquad (3)$$

where HYR = head yield ratio, decimal
t = exposure duration, min
A, B = regression coefficients

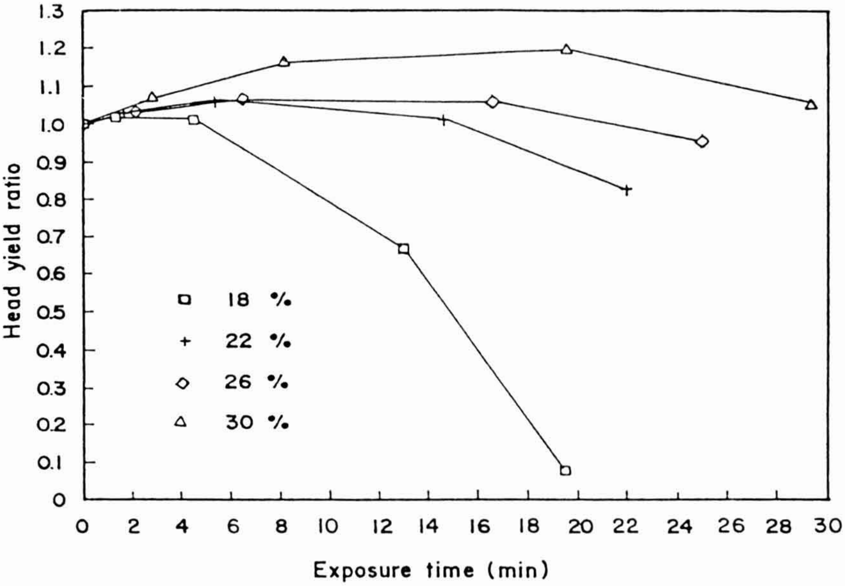

FIG. 3. A TYPICAL PLOT OF HEAD YIELD RATIO AS A FUNCTION OF EXPOSURE TIME FOR HEATING SURFACE TEMPERATURE OF 150 °C AND VARIOUS INTITIAL MOISTURE CONTENTS OF ROUGH RICE

The regression coefficients A and B were related with the experimental conditions by the following equations:

$$\ln A = -17.8816 + 0.079694\,Ts + 0.35658\,Mo - 0.001961\,(Ts * Mo) \quad (4)$$

$$(R^2 = 0.927;\ SEE = 0.73)$$

$$\ln B = -7.7149 + 0.11835\,Ts - 1.03754\,Mo + 0.02849\,Mo^2 - 0.002699\,(Mo * Ts) \quad (5)$$

$$(R^2 = 0.942;\ SEE = 1.00)$$

Equations 3, 4 and 5 were used to quantify the effects of high temperature conduction heating of rough rice on its head yield.

The heating time corresponding to the highest value of head rice yield was estimated by taking the first derivative of Eq. 3 and equating to zero to give the following relationship:

$$t_H = A/2B \qquad (6)$$

where t_H = heating time for highest value of HYR, min
A,B = constants of Eq. 3

The increase in head rice may be attributed to the partial gelatinization of the starch granules and cementing of the fissures present in kernels leading to reduced breakage during the milling process. The increase in head yield ranged up to 27% relative to the control sample depending upon the moisture content of the rough rice and the heating surface temperature (Fig. 4)

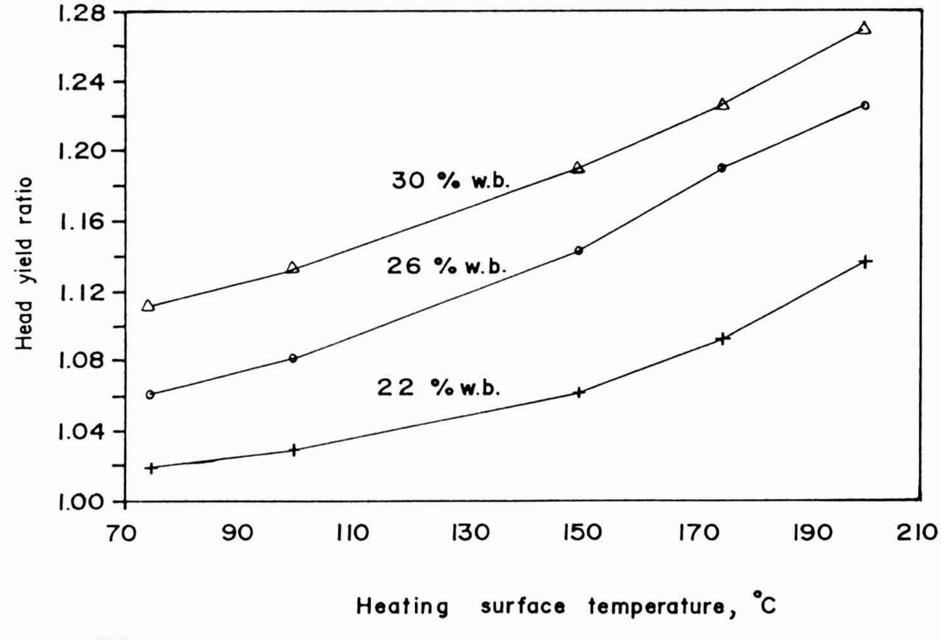

FIG. 4. HIGHEST VALUE OF HEAD YIELD RATIO AS A FUNCTION OF HEATING SURFACE TEMPERATURE OF ROUGH RICE HAVING DIFFERENT INITIAL MOISTURE CONTENTS

The heating time corresponding to the higher value of head rice yields were compared with the fungal inactivation times required for 90 and 95% mortality levels as shown in Fig. 5 for all heating surface temperatures. It was obvious that treatments resulting in 90% FML did not lead to a possible maximum increase in the values of head yield ratios. However, heating times corresponding to 95%

FML appeared to result in the highest value of head yield ratios on the average. These results clearly indicated that thermal inactivation of fungi in high moisture rough rice using heating surface temperatures ranging from 75 to 200 °C could be carried out with a distinct improvement in its milling quality.

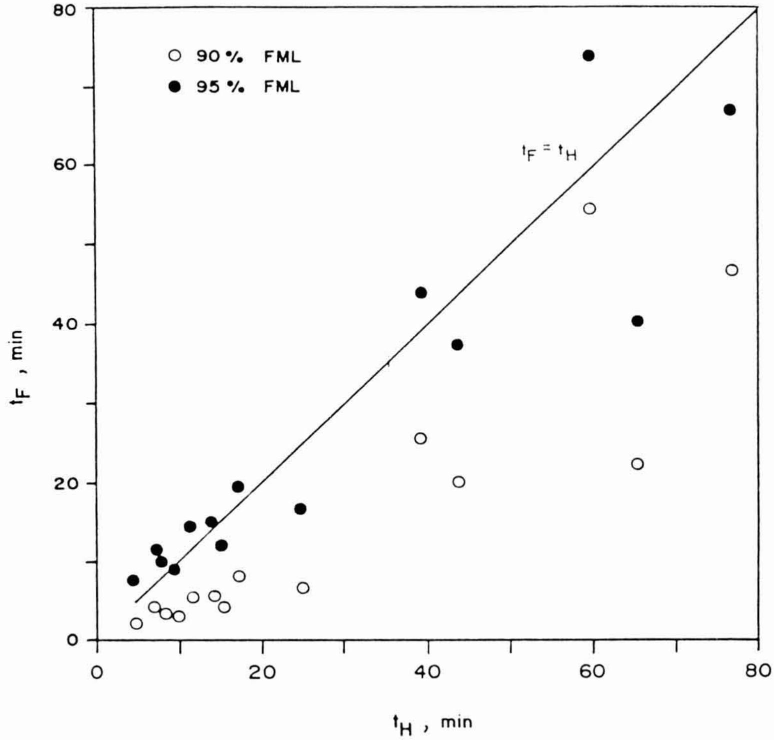

FIG. 5. HEATING TIMES (t_F) REQUIRED FOR 90 AND 95% FUNGAL MORTALITY LEVELS VERSUS HEATING TIMES (t_H) CORRESPONDING TO THE HIGHEST VALUE OF HEAD YIELD RATIO

Effects of Heat Treatments on Milled Rice Whiteness

Heat-treated rough rice samples yielded milled rice which was slightly yellowish-brown in appearance in comparison with the unheated control sample. This change in color could be due to the non enzymatic browning and/or the diffusion of coloring pigments of the hull and bran to the endosperm caused by the exposure of the grain to very high temperatures. Generally, the change in color was less severe for milled rice produced from rough rice samples having lower initial moisture content as well as from samples exposed to lower heating surface temperatures. Whiteness ratio (WR) of milled rice and heating duration appeared to be related in the following equation form:

$$WR = \exp(a' t^{b'}) \tag{7}$$

where WR = whiteness ratio, Ws/Wc
Ws = whiteness units of milled rice obtained from heated rough rice sample
Wc = whiteness units of milled rice obtained from the control sample
t = heating duration, min
a′, b′= regression coefficients

Equation 7 was considered satisfactory since the average value of the coefficient of determination for all experimental tests was found to be 0.84 with a standard deviation of 0.073. The dependence of regression coefficients a′ and b′ on the moisture content of rough rice and heating surface temperature in the range of 18 to 30% w.b. and 75 to 200 °C, respectively, was given by the following equations:

$$\ln a' = -43.4066 + 0.2177\,Ts + 1.2208\,Mo - 0.006737\,(Ts * Mo) \tag{8}$$
$$(R^2 = 0.900;\ SEE = 1.250)$$

$$b' = 8.3793 - 0.03905\,Ts - 0.2593\,Mo + 0.001357\,(Mo * Ts) \tag{9}$$
$$(R^2 = 0.800;\ SEE = 0.310)$$

The average whiteness value of milled rice samples produced from unheated rough rice was about 31.8 units. Since the change in the whiteness of milled rice detectable to human eye yielded whiteness meter readings between 25 and 26 units, a minimum acceptable level of whiteness ratio was approximately selected to be 0.8. Based on this consideration, allowable heating times were computed using Eq. 7, 8 and 9 for each combination of heating surface temperature and initial moisture content of rough rice and compared with heating times required for attaining highest head rice yields (Fig. 6). These results showed that the conduction heating of high moisture rough rice to 95% FML approximately corresponded to the highest head yield without a significant reduction in the whiteness of milled rice.

Effects of Heat Treatments on Cooked-Rice Texture

An improvement in both cooked-rice firmness and stickiness was observed following the conduction heating of fresh rough rice samples using surface temperatures ranging from 75 to 200 °C. Unheated control samples exhibited a characteristic soft and sticky texture of freshly harvested rice. In comparison, the heat-treated samples produced firm and less sticky cooked-rice grains. The

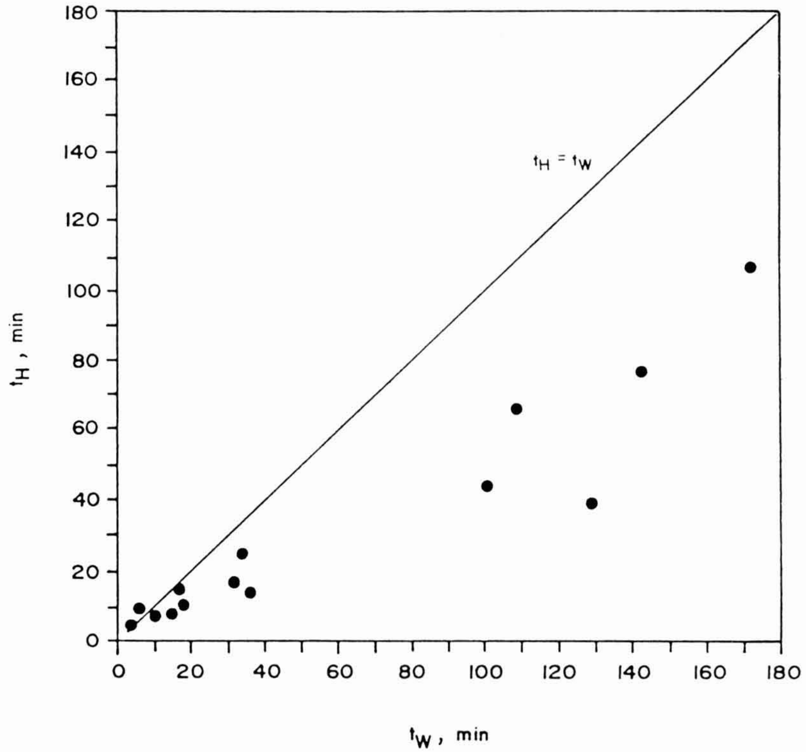

FIG. 6. HEATING TIMES (t_H) CORRESPONDING TO THE HIGHEST VALUE OF HEAD YIELD RATIO VERSUS HEATING TIMES (t_W) REQUIRED FOR MINIMUM ACCEPTABLE WHITENESS

firmness of cooked-rice as measured by the total energy needed in the back extrusion tests increased approximately from 3 to 9% depending upon the duration of heating (Fig. 7 and 8). Stickiness, on the other hand, was reduced in the 6 to 18% range in heat-treated samples. This improvement in cooked-rice texture may be viewed as an added advantage of the heat treatment aside from a definite increase in the head rice yields since most people prefer less sticky and moderately firm cooked rice. The changes in cooked-rice texture observed in this study are apparently similar to those occurring in the artificial aging process due to heat treatment of freshly harvested rough rice reported by Normand *et al.* (1964).

SUMMARY AND CONCLUSIONS

This study showed that high-temperature conduction heating of freshly harvested rough rice could result in a definite improvement in its milling and

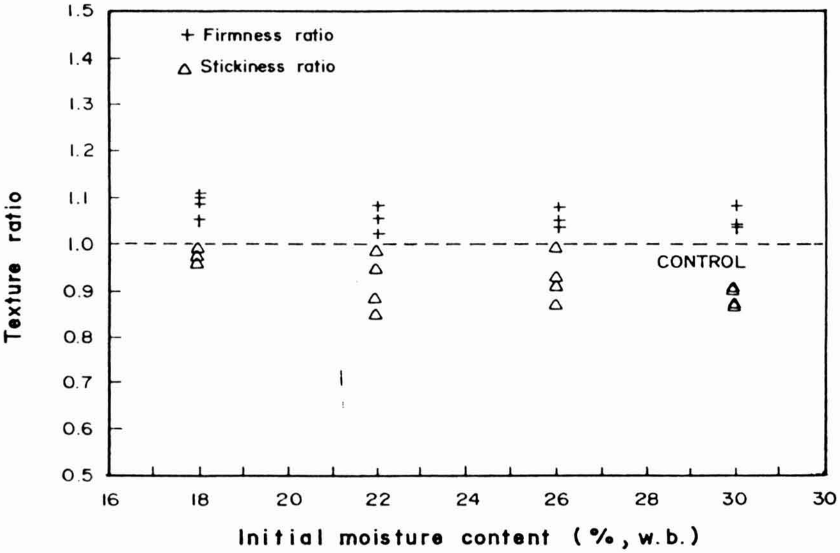

FIG. 7. TEXTURE OF COOKED-RICE SAMPLES AS A FUNCTION OF INITIAL MOISTURE CONTENT OF ROUGH RICE FOR HEAT TREATMENTS RESULTING IN 90% FUNGAL INACTIVATION

cooking qualities. A slight decrease in the whiteness of the milled rice may be offset by the advantages gained in terms of improved head yields and cooked-rice texture. Heat treatments corresponding to at least 90% and higher FML may be beneficial in attaining higher head yield and improved eating quality without marked reduction in the whiteness of milled rice.

The following specific conclusions were drawn based on the results of this study:

(1) A simple logarithmic model adequately described the moisture removal from high moisture rough rice during conduction heating. The drying constant depended upon the heating surface temperature only.

(2) The head yield of high moisture rough rice increased during conduction heating at first and then decreased with prolonged heating time. It was possible to maximize the head rice yields during the heating process by careful control of exposure times.

(3) The whiteness of the milled rice obtained from the heat-treated rough rice appeared to be the most limiting factor in its acceptability. However, the changes in milled rice whiteness could be within acceptable limits if the heating times were limited to those corresponding to the highest value of head rice yields.

(4) Milled rice obtained from heat-treated rough rice showed a definite improvement in its cooking quality in comparison with fresh rice. There was a desirable charactersitic increase in the firmness of cooked rice kernels and a decrease in their stickiness resembling the artificial aging process.

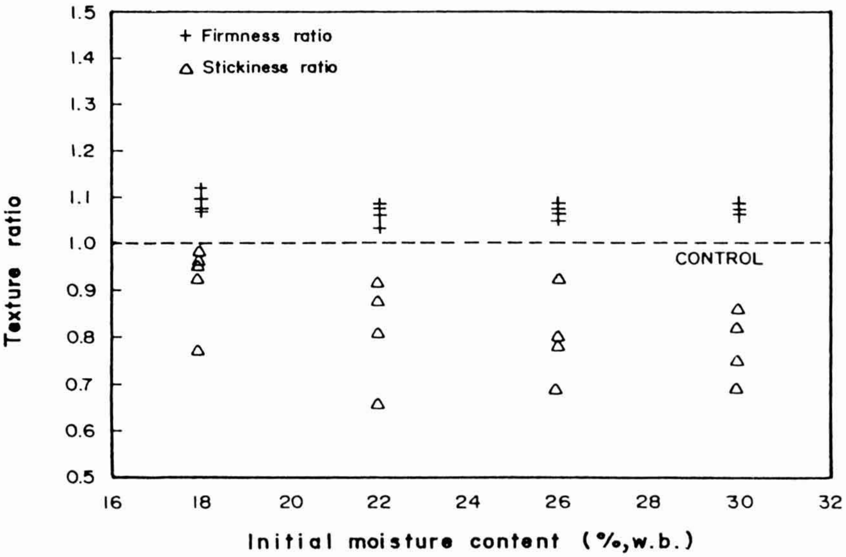

FIG. 8. TEXTURE OF COOKED-RICE SAMPLES AS A FUNCTION OF INITIAL MOISTURE CONTENT OF ROUGH RICE FOR HEAT TREATMENTS RESULTING IN 95% FUNGAL INACTIVATION

ACKNOWLEDGMENTS

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OPTIMAL ROASTING

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ABSTRACT

In this paper we discuss the application of numerical optimization techniques to the process of roasting, which essentially is heat treating meat under a variety of ambient temperature conditions. The doneness of roast, as measured by the distribution of maximum temperatures achieved through the meat, is taken to be the objective for optimization, using cooking temperatures and times as the process variables. Cooking beef roasts of varying weights and shapes are the examples considered. Additional considerations for optimization, such as minimum cooking time and energy used, have also been considered. Direct search methods were found to be most suited for objective functions with a highly varied topology, as were encountered in this problem. The optimal results, compared with the conventional cooking recommendations, show that superior heat treatment can be effected by using numerical modeling and optimization techniques.

INTRODUCTION

In the companion paper (Townsend *et al.* 1989) a model of roasting meat was developed and tested. Essentially, cooking a roast is heat treating the meat under a variety of ambient temperature conditions to achieve some desired properties. For the roast, doneness at a point is measured by the maximum temperature reached there. The model is non linear, containing variable surface and element properties and phase changes for thawing and boiling. The model can be

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generalized to other applications where the desired properties are related to the model parameters; e.g., in heat treating steel, grain structure could be related to its time - temperature history. Townsend *et al.* (1989) also surveyed the relevant literature.

In (Townsend *et al.* 1989) the model was validated with classical solutions and tested against cooking recommendations. The differences from the classical solutions were consistent with the nonlinearities and the finiteness of the actual system. However, the cookbook recommendations tend to be both very conservative and very broad, to account for the ranges of sizes, shapes and doneness, so that they barely provide extreme limits for cooking times and temperatures. Most recommendations are to cook at 325 °F or 350 °F at "X" to X+2" min/lb. Using such values, we found that long and flat roasts tended to overdoneness, and equidimensional roasts (length over diameter ratio around 1.0) tended to overly rare.

The model is limited in that local inhomogeneities (e.g., fat, bone) are not included, although they could be in a more detailed model. The assumption of constant transition temperatures is not really severe; however, a more detailed model could include the temperature dependence of local properties. The particular choice of properties' values appears to be an open question, especially for specific heat and thermal conductivity. The values used (see Appendix) are something of a compromise. Other aspects of the model are discussed in (Townsend *et al.* 1989).

Experimentation to any appreciable extent which would give useful results would be extremely costly and wasteful of both time and food, and the results might end up being a hodge-podge of tables and empirical factors and therefore difficult to use. Hence, in this paper we employ the model of (Townsend *et al.* 1989) and numerical optimization techniques to identify cooking programs which will give desired doneness profiles. Comparisons of the various optimal procedures for cooking roasts of different shapes and sizes are presented. The use of such models and techniques can yield superior results, save money, effort and much full scale experimentation, and give insight into such heat treatment problems.

MODEL

In (Townsend *et al.* 1989) the roast is modeled as a right circular cylinder divided into finite elements of rectangular cross-section toroids (see Fig. 1). Accordingly, each roast can be characterized by its weight (or mass) and length to diameter ratio (LOD). Axially the roast model is divided in half by an adiabatic mid-plane, and one half is the mirror image of the other due to the symmetry. It was found that good model behavior was obtained with a hybrid finite element,

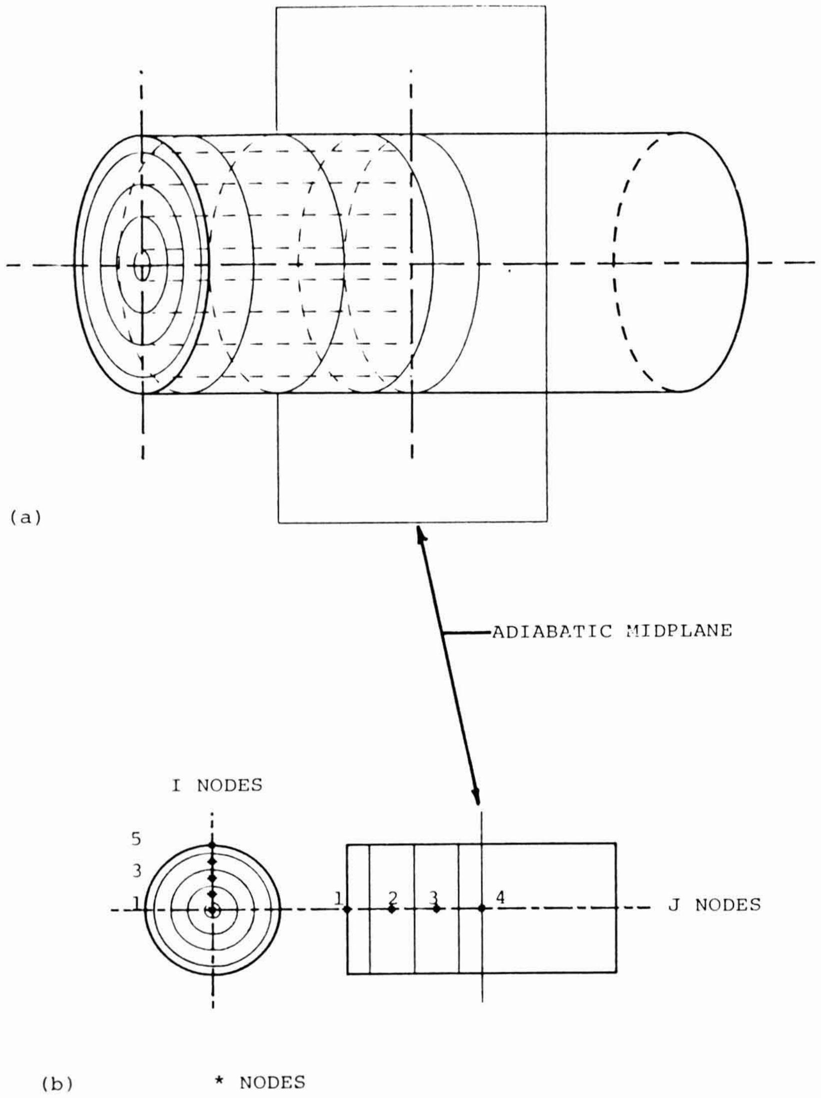


FIG. 1. SCHEMATIC OF ROAST

(a) General view
(b) Orthogonal view showing nodes

finite difference model of five radial concentric annuli and four axial segments per half. Finite difference and energy balance equations across each of the toroids thus formed are solved for new temperatures from the known old temperatures and appropriate heat flows and inputs for each increment in time.

Conduction, convection and radiation heat flows can occur in the surface elements, whereas heat transfer in the interior of the meat is due to radial and axial conduction. Phase change transformations are considered as absorption of adequate latent heats in the elements at specified temperatures: the latent heat of fusion (or vaporization) is absorbed at each element before the element temperature goes past the freezing (or boiling) point. The roast is assumed to be 60% saline water, homogeneous with constant density, thermal conductivity, specific heat and uniform initial temperature distribution, although these properties can be variable. Surface heat transfer properties and moisture content are variable. In all of the numerical experiments in (Townsend *et al.* 1989), boiling occurred only at the surface. For an edible roast, interior boiling need not be considered, since boiling within would occur only after the surface is charred. Complete details of the model and the nonlinear equations are given in (Townsend *et al.* 1989). The Appendix briefly presents the model equations and parameter values.

In this paper, the model is restructured for manipulation by an optimization search algorithm.

OPTIMIZATION

Objective

The principal purpose of the objective function is to penalize deviations of the actual temperature profile from a specified desired profile. The optimization algorithm then seeks to minimize a suitable weighted combination of those differences. Subsidiary criteria include accomplishing this in a reasonable time, minimum energy usage, reasonable expectations of the oven, etc. (These are discussed later).

Doneness at a point in a roast is usually assumed to be established by the highest temperature reached at that point. In this study we will be considering beef (roasts). The relationship between roast doneness and internal temperatures for beef is given in most cookbooks (e.g., Crocker 1969; Rombauer and Becker 1973) as:

Rare	--- 140 °F
Medium	--- 160 °F
Well done	--- 170 °F

(English units are used throughout in accordance with present conventional usage.)

An objective function which penalizes deviations from a desired profile in a convenient form is

$$U = \sum_{i=1,j=1}^{I,J} (Ts(i,j) - T(i,j))^2 \tag{1}$$

where T(i,j) is the maximum temperature achieved at node i,j;
Ts(i,j) is the maximum temperature desired at node i,j corresponding to the desired doneness.

Specification of all points in the roast is probably unduly detailed and unnecessary. Based on numerical experiments, the doneness is adequately quantified by specifying the temperature profile along the axis of the cylinder, such as Eq. (1) becomes

$$U = \sum_{j=1}^{J} (Ts(1,j) - T(1,j))^2 \tag{2}$$

For the present model, $J = 4$.

Numerous temperature profiles could be specified, depending on the doneness distribution desired. In conventional cooking, the oven temperature is controlled and heat is transferred to the interior of the meat by conduction through the outer layers, as per the model. This results is a natural temperature (and hence doneness) gradient across the sections of the meat. If the objective is to have a uniformly rare (or other doneness) roast, then an optimal solution in one sense would be to set the oven at that temperature (or slightly higher) and wait --possibly for an infinite time. However, most people really prefer a gradiation of doneness, say to a medium or rare center, and a roast usually must satisfy a variety of preferences. For purposes of this paper, we have opted for a ''universal'' profile with a slight emphasis on a rare center, as follows:

Exterior end T (1,1) = 230 °F
T (1,2) = 170 °F
T (1,3) = 160 °F
Center T (1,4) = 140 °F

Thus, instead of requiring a uniform or unreasonable temperature distribution, we define a desirable temperature profile along the axis of the cylinder, and the optimal cooking schedule is the one that most nearly produces this profile. This profile can be approached quite accurately by a reasonable cooking process in a reasonable time and will produce a roast for all tastes without invoking additional penalties or constraints on the problem. The surface temperature is the boiling point; this recognizes the reality that the outer surface will tend to char some and does not penalize that. Indeed, many people like this. Other objectives and modifications to this function are addressed in the **Results** section.

Variables in the Roasting Process

Most of the roasting process consists of heating the meat in an oven. Each oven stage involves two independent variables for otpimization: oven temperature and cooking time. A simple cooking process consists of only one cooking stage, hence two design variables. A complex cooking process would have a series of cooking stages, presumably with different oven temperatures and times for each stage. There are two special stages, both normally occurring at room temperature: thawing and aftercooking. Both are found useful in optimizing the roast doneness. Thawing may be partial or useful in optimizing the roast doneness. Thawing may be partial or complete and will usually give a nonuniform temperature profile when actual oven cooking begins. Aftercooking is letting the roast stand at room temperature for some time after the oven cooking is completed; this can result in a more even distribution of the internal meat temperature to yield better roast doneness. The interior cooks more while the exterior cools, so aftercooking affects the doneness of the interior only. Since thawing and aftercooking occur at room temperature, time is the only independt variables in these stages.

Hence, the number of independent variables in the optimization is twice the number of oven cooking stages plus one for each of the thawing and aftercooking stages. Number of stages, thawing and aftercooking stages are specified explicitly in the optimization. The values of stage temperatures and times are then returned.

Optimization Procedure

A Hooke-Jeeves direct search algorithm (coded as FORTRAN Subroutine PATSH (Hooke and Jeeves 1961)) has been employed for the unconstrained nonlinear optimization of the roast doneness. The optimizations were run on a PRIME 850.

This algorithm is quite suitable to complex models involving a lot of computation for each evaluation of the objective function (a complete simulation) such as this. It is very systematic, avoids derivatives and minimizing searches, makes minimal assumptions about continuity of the model and objective function, and entails minimal storage requirements. Indeed, since the model is quite complicated, and the derivatives are discontinuous at the control points, such a robust algorithm which converges to a minimum more than compensates for possible slower performance.

The objective function of Eq. (2) has a varied topology for this model. Apparently there are numerous local minima and extended relatively flat regions, valleys and near optimal plateaus. The latter occasionally allowed the optimization alogorithm to converge at values far from the optimal value. Sometimes the objective change was small, and other times it was significant. Thus, optimizatins were carried out a number of times with different starting values, usually varying the initial guess for oven temperatures from 250 °F to 500 °F in 50 °F increments. The minimal value of U, denoted by U*, obtained from these results is assumed to be the globally optimal value.

RESULTS

Results are presented in order of increasing complexity of the cooking program. Two sets of initial conditions are used: room temperature (70 °F throughout) and a roast taken from the freezer (10 °F throughout).

The oven temperatures were not constrained explicity. In a few cases the optimization procedure produced very high or very low (even negative) oven temperatures. In such cases, instead of constraining the optimization problem, the next best value of the objective function with temperatures within the feasible range of a domestic oven are also given. In general, the feasible results were not significant worse. In assessing the quality of the optimal profile, the mean temperature error is on order the (U/number of points in U)$^{0.5}$.

Optimal Simple Cooking

Optimizations for one oven cooking stage with no thawing or aftercooking stages were performed for roast weights of 4.4 lb, 5.6 lb and 7.8 lb and length over diameter ratios (LODs) of 0.5, 1.0, 2.0. This case has only two independent variables — the cooking time and the oven temperature, for minimizing the objective function.

Cooking from room temperature (70 °F), all three roast weights show very similar trends for the three shapes (reading across Table 1). The proportionate (LOD = 1.0) and slender (LOD = 2.0) roasts of the same weight cook at about the same temperature for best roast doneness; cooking temperature for the flat roast (LOD = 0.5) is higher. The quality of cook, or roast doneness profile (value of U*), improves with slenderness. The optimal times increase with the roast size for a given LOD, as would be expected; obviously, the larger roast requires more heat and therefore, at comparable oven temperatures, takes longer to cook. This suggests that for this objective and cooking cycle, oven temperature is more critical to the doneness profile. The larger roasts require lower oven temperature over a longer period of time to cook optimally. The times for cooking show a consistent result: proportionate roasts take longer to cook than either of the other two shapes. This is logical since, as is easily shown (Townsend *et al.* 1989) LOD = gives the minimum surface area to volume ratio and hence, minimum heat admission for a given mass.

In simple cooking of frozen meat (from 10 °F we are ''power thawing'' as well as cooking the meat, all in one cooking stage. In Table 2 the trends are similar to

TABLE 1.
RESULTS OF OPTIMAL SIMPLE COOKING FROM 70 °F

Weight (lb)	LOD = 0.5	LOD = 1.0	LOD = 2.0
4.4	1.45 hrs at 355° F $U^* = 192$	1.83-1.87 hrs at 320-325° F $U^* = 162$	1.57-1.59 hrs at 320-325° F $U^* = 137$
5.6	1.68-1.7 hrs at 347-350° F $U^* = 193$	2.15 hrs at 315° F $U^* = 163$	1.84 hrs at 315° F 1.76-1.84 hrs at 320-325° F $U^* = 137$
7.8	2.09 hrs at 338-339° F $U^* = 194$	2.64 hrs at 308-309° F $U^* = 164$	2.25 hrs at 308-309° F $U^* = 137$

TABLE 2.
RESULTS OF OPTIMAL SIMPLE COOKING FROM 10°F

Weight (lb)	LOD = 0.5	LOD = 1.0	LOD = 2.0
4.4	2.05 hrs at 355°F U^*= 194	2.49 hrs at 327° F U^* = 194	1.69 hrs at 403°F U^*= 12.4
5.6	2.45-2.49 hrs at 345-347°F U^*= 196	3.0 hrs at 315°F U^* = 184	2.58 hrs at 313°F 2.13 hrs at 362°F 1.81 hrs at 466°F U^*= 123
7.8	3.05 hrs at 335.5°F U^*= 197	2.84 hrs at 433° F U^* = 250	2.21 hrs at 482°F U^*= 122

those observed for cooking from room temperature. However, due to the thawing phase, higher temperatures are needed for longer times, since heat is needed to melt the ice. The flat roasts of all sizes converge to nearly the same U* as cooking from 70 °F (U* = 196 here versus U* = 193). The slender roasts of all roast weights given slightly lower values of U* than cooking from 70 °F. However, the proportionate roast results are quite variable. Indeed, the flat and slender roasts cook relatively well from a frozen initial state compared to optimal cooking from room temperature, but the proportionate roast cooks relatively poorly when frozen, as measured by U*. This is probably becaue of the minimum surface area to volume ratio, which tends to restrict the heat flow and subsequent temperature gradients for thawing and cooking to this objective.

The optimal oven temperatures are comparable for the flat roasts of the three sizes for both initial conditions although the times are naturally longer for frozen meat. The remaining results show a tendency for higher oven temperatures and longer times for cooking frozen meat as compared to cooking from room temperature.

Optimal temperature-time profiles are shown in Fig. 2 for both initial conditions. The thawing phase is clearly seen in Fig. 2b.

Optimal Simple Cooking with Aftercook

An aftercook stages adds one independent variable to the optimization problem, the aftercook time (at room temperature, 70 °F). The optimizations for cooking frozen meat and cooking from room temperature were carried out for the same threeee roast sizes and shapes as above.

As in the case of simple cooking without aftercook from room temperature, all three roast sizes show similar trends for the three roast shapes (Table 3). However, in this case, the proportionate roasts have a minimum value of the objective function substantially lower than either the flat or slender shapes. Oven temperatures tend to be significantly higher and increase both with weight and LOD. Slender roasts returned very high oven temperatures, well beyond the range of most domestic ovens. Feasible alternate results are shown; these are considerably poorer in this cycle. Simple cooking without aftercook for slender roasts gave as good roast quality (U* = 137) as with aftercook and at feasible oven temperatures (about 315 °F). Hence, aftercooking does not improve roast doneness in the case of slender roasts.

However, for flat and proportionate roasts, roast quality is improved quite appreciably with aftercooking; the objective function was more than halved by the addition of aftercooking. Aftercooking disrupts the gradient of oven cooking, since the interior meat is still being heated while the outer layers cool (see Fig. 3a). Thus, the maximum temperatures reached in the inner parts can be much closer to the desired values, so that lower objective function values are obtained.

In this cycle there are regions of optimal values rather than unique optimal values. Figure 4a shows these regions for different shapes of the 5.6 lb roast. Figure 4b shows regions for different weights with LOD = 1.0. Slightly longer than optimal aftercook times do not significantly affect the roast doneness since the maximum temperatures have already been reached and the entire roast is starting to cool. Hence aftercook times do not appear on Fig. 4. The oven temperatures for flat and proportionate are within the range of conventional ovens. Table 3 shows that flat roasts require slightly higher temperatures for a shorter time whereas the proportionate roasts cook better at somewhat lower temperatures for a longer time.

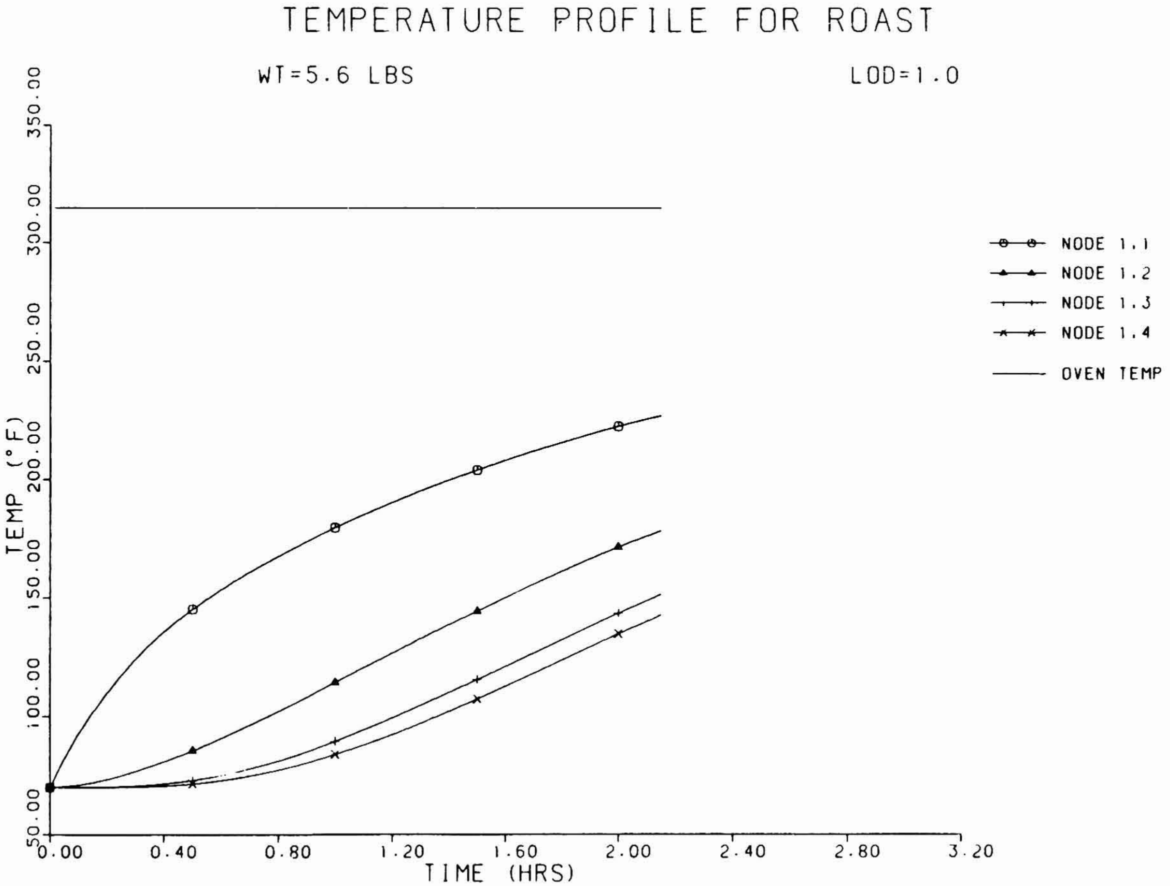
Cooking from 10 °F with aftercook gave very low values of U for all roast weights and shapes (Table 4). Indeed, the results are generally equivalent to the results for multiple cooking stages, considered below. In this case, oven temperatures tended to increase with decreasing LOD but are relatively independent of weight. The proportionate roast always shows the lowest value of U*. For flat and proportionate roasts, the optimal oven temperatures required are very high for all roast sizes. Hence the next best objective function values with optimal oven temperatures within feasible range (less than 550 °F) are also shown. With these values, the three roast shapes again show fairly similar behavior for all three roast sizes. While the values of U* are slightly higher, the same general trends are seen: the proportionate roast still shows the lowest U*.

Aftercooking improves the quality of roast appreciably over simple cooking without aftercook (cf. Table 2). For flat and proportionate roasts, the objective function decreases by more than 50%. Even the slender roast, for which aftercooking did not prove very useful in cooking from room temperature, show a 30% decrease in U* when cooking from 10 °F. However, the roast surface is at the boiling temperature longer (Fig. 3b), so the roast may be drier than the others evaluated thus far.

Optimal Complex Cooking

Since most of the optimization results for different shapes and weights followed similar trends, experiments for multiple oven cooking stages were carried out with a 5.6 lb roast having an LOD of 1.0. Table 5 gives the results for optimal cooking from room temperature using one or two cooking stages with and without aftercook (including previous results).

With two cooking stages (4 variables: two temperatures and two times) the optimizations gave some strange results. See, for example, line 3 of Table 5: a roast doneness of U* = 74 with a second stage at a 20 °F "oven" temperature -obviously too low to be feasible. The next best solution is line 4 with U* = 76. In this case the higher temperature of 545 °F is about the limit of most domestic ovens. Hence, the best roast doneness with feasible temperatures is cooking for


TEMPERATURE PROFILE FOR ROAST
WT=5.6 LBS
LOD=1.0
TEMP (°F)
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.40
0.80
1.20
1.60
2.00
2.40
2.80
3.20
TIME (HRS)
NODE 1.1
NODE 1.2
NODE 1.3
NODE 1.4
OVEN TEMP

(a)

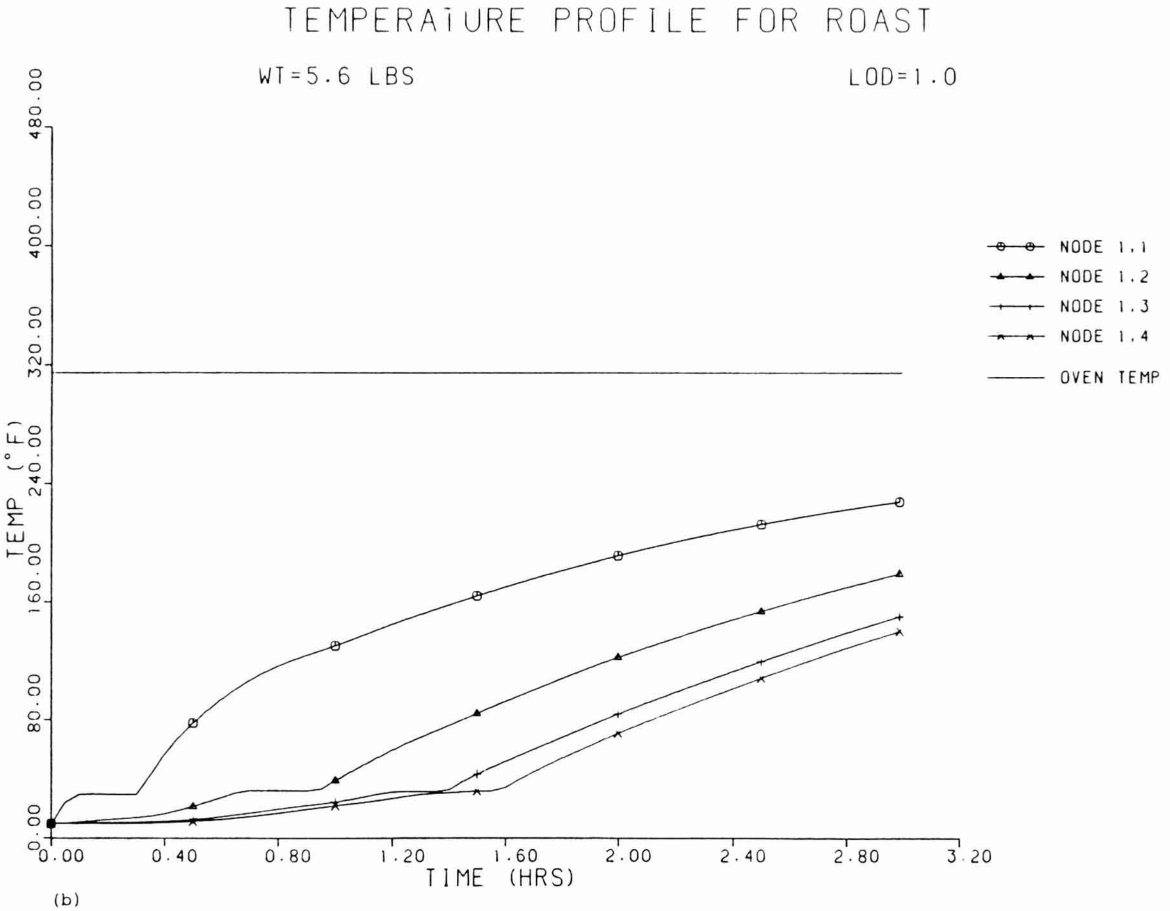


FIG. 2. OPTIMAL SIMPLE COOKING OF ROAST OF 5.6 LB, LOD = 1.0
(a) Roast initially at 70°F throughout. $U^* = 163$
(b) Roast initially at 10°F throughout. $U^* = 184$

TABLE 3.
RESULTS OF OPTIMAL SIMPLE COOKING WITH AFTERCOOK ROAST INITIALLY AT 70°F THROUGHOUT A/C = AFTERCCOK

Weight (lb)	LOD = 0.5	LOD = 1.0	LOD = 2.0
4.4	0.94 hrs at 450°F; 0.33 hrs A/C $U^* = 102$	1.20 hrs at 387°F; 0.44 hrs A/C 1.14 hrs at 409°F; 0.45 hrs A/C $U^* = 75$	0.57 hrs at 654°F; 0.68 hrs A/C $U = 141$ 0.75 hrs at 420°F; 1.00 hrs A/C $U^* = 211$
5.6	1.30 hrs at 376°F; 0.36 hrs A/C $U^* = 93$	1.36 hrs at 394°F; 0.53 hrs A/C 1.28 hrs at 439°F; 0.52 hrs A/C $U^* = 75$	0.87 hrs at 575°F; 0.52 hrs A/C $U^* = 137$
7.8	1.67 hrs at 360°F; 0.37 hrs A/C 1.60 hrs at 366°F; 0.4 hrs A/C $U^* = 93$	1.60 hrs at 427°F; 0.63 hrs A/C 1.8 hrs at 360°F; 0.61 hrs A/C $U^* = 75$	1.06 hrs at 559°F; 0.64 hrs A/C 1.2 hrs at 550°F; 0.43 hrs A/C $U^* = 137$

1.13 lb h at 460 °F and 0.68 h at 136 °F giving U* = 79 (line 5). This roast doneness is appreciably better than single stage cooking (U* = 163), but simple cooking with aftercook gives as good results. The unconstrained optimization (line 3) gives slightly better results but it of little use when the desired temperatures are beyond feasible limits.

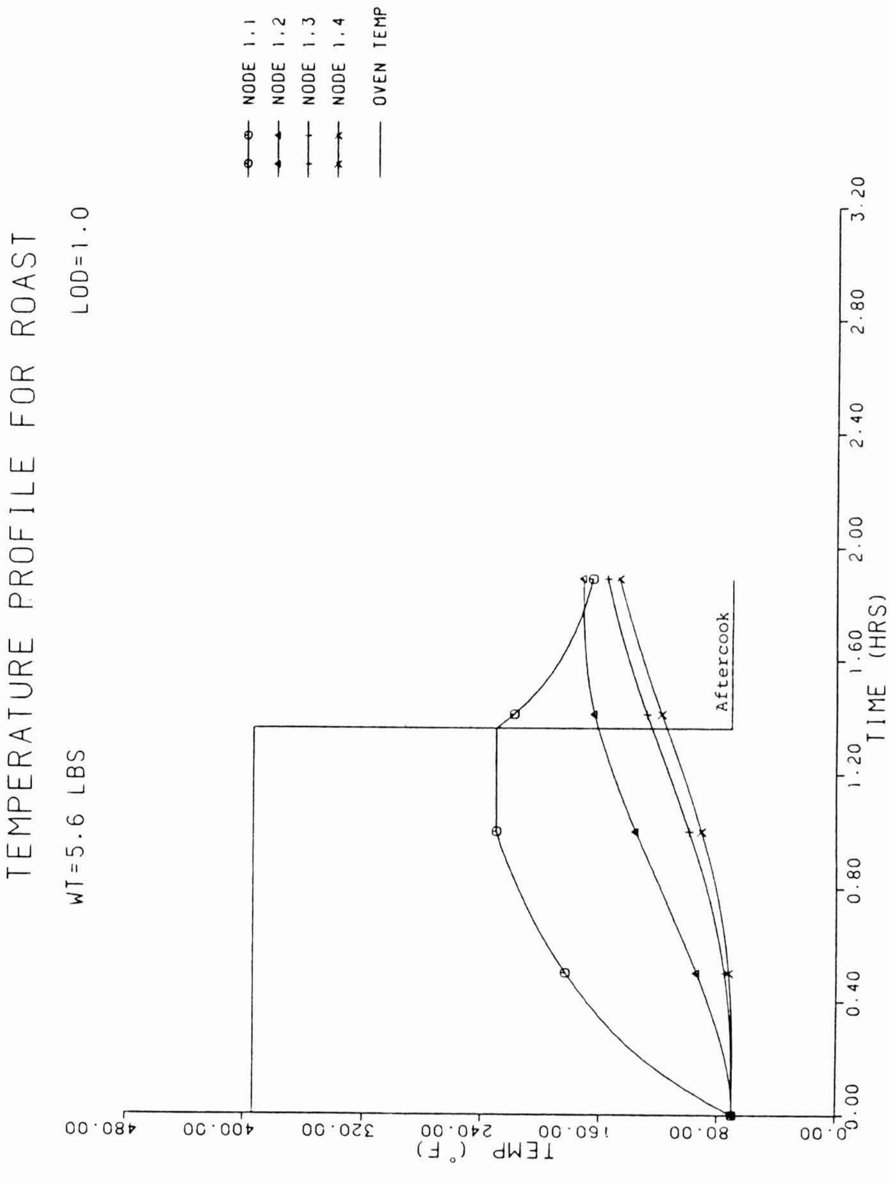
Two stage cooking from 70 °f with aftercooking gives a roast doneness of U* = 70 (line 6) which is better than those for other cooking processes (except for simple cooking from freezing with aftercook), but again the temperatures are not feasible. The best roast doneness with feasible temperatures gives U* = 75 (line 7): both stages have essentially the same temperature (394 °F and 395 °F), so the process is basically a single cooking stage with 0.51 h of aftercook. The roast doneness is comparable to that of a single cooking stage with aftercook (line 2).

More cooking stages are not presented. Even though increasing the number of cooking stages should improve the roast quality within the feasible temperature limits, practically, the roast doneness does not improve appreciably from the value obtained using simple cooking with aftercook.

Results for optimal complex cooking of frozen meat are shown in Table 6. Simple cooking results with or without aftercook are repeated on the first two lines. Addition of the thawing stage (lines 3,8,9) does not show any improvement, though aftercooking definitely helps. With two cooking stages the problem of infeasible optimal temperatures recurs (lines 4,6,8). The best roast doneness with feasible temperatures without aftercook is U* = 184), but simple cooking with aftercook produces better results. Two stage cooking with aftercooking produces as good roast doneness as for single stage with aftercook. Figure 5 shows a multi-stage cooking experiment of line 9, Table 6, after 16.3 h thawing. As above, more cooking stages are not indicated.

Summary

These results show that multiple oven temperature stages do not produce appreciably better results within the limits of feasible temperatures. In addition, thawing frozen meat before cooking does not seem to improve roast quality. However, dryness might be a problem due to the generally high oven temperature and the relatively longer time the surface is at the boiling temperature. Simple cooking with aftercook appears to give the best done roast in most of the cases and is a very practical approach. The various results are compared in Table 7 for a range of weights and shapes. These are discussed further in the **Conclusions.**


TEMPERATURE PROFILE FOR ROAST
WT=5.6 LBS
LOD=1.0
NODE 1.1
NODE 1.2
NODE 1.3
NODE 1.4
OVEN TEMP
Aftercook
TEMP (°F)
0.00
80.00
160.00
240.00
320.00
400.00
480.00
TIME (HRS)
0.00
0.40
0.80
1.20
1.60
2.00
2.40
2.80
3.20

(a)

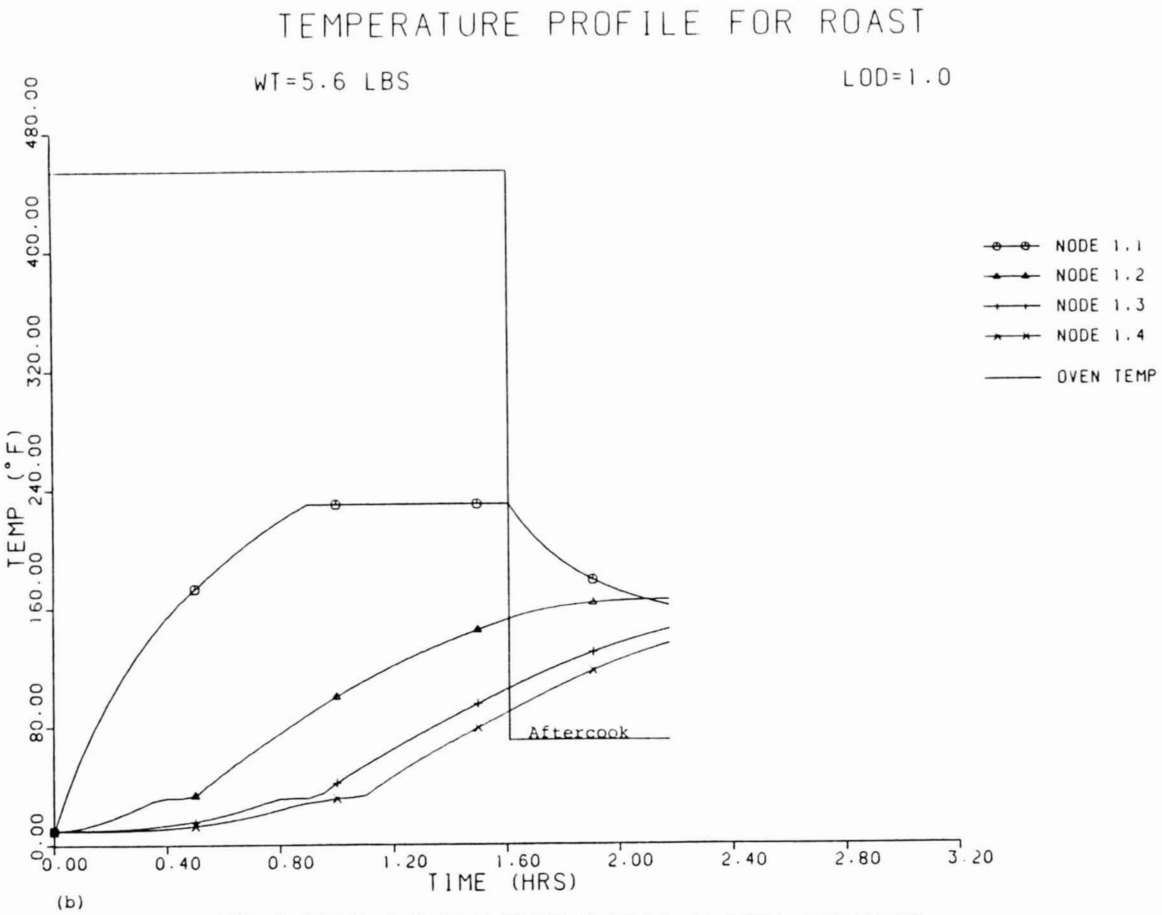


FIG. 3. OPTIMAL SIMPLE COOKING OF ROAST WITH AFTERCOOK:
OF 5.6 LB, LOD = 1.0

(a) Roast initially at 70 °F throughout. $U^* = 78$
(b) Roast initially at 10 °F throughout. $U^* = 66$

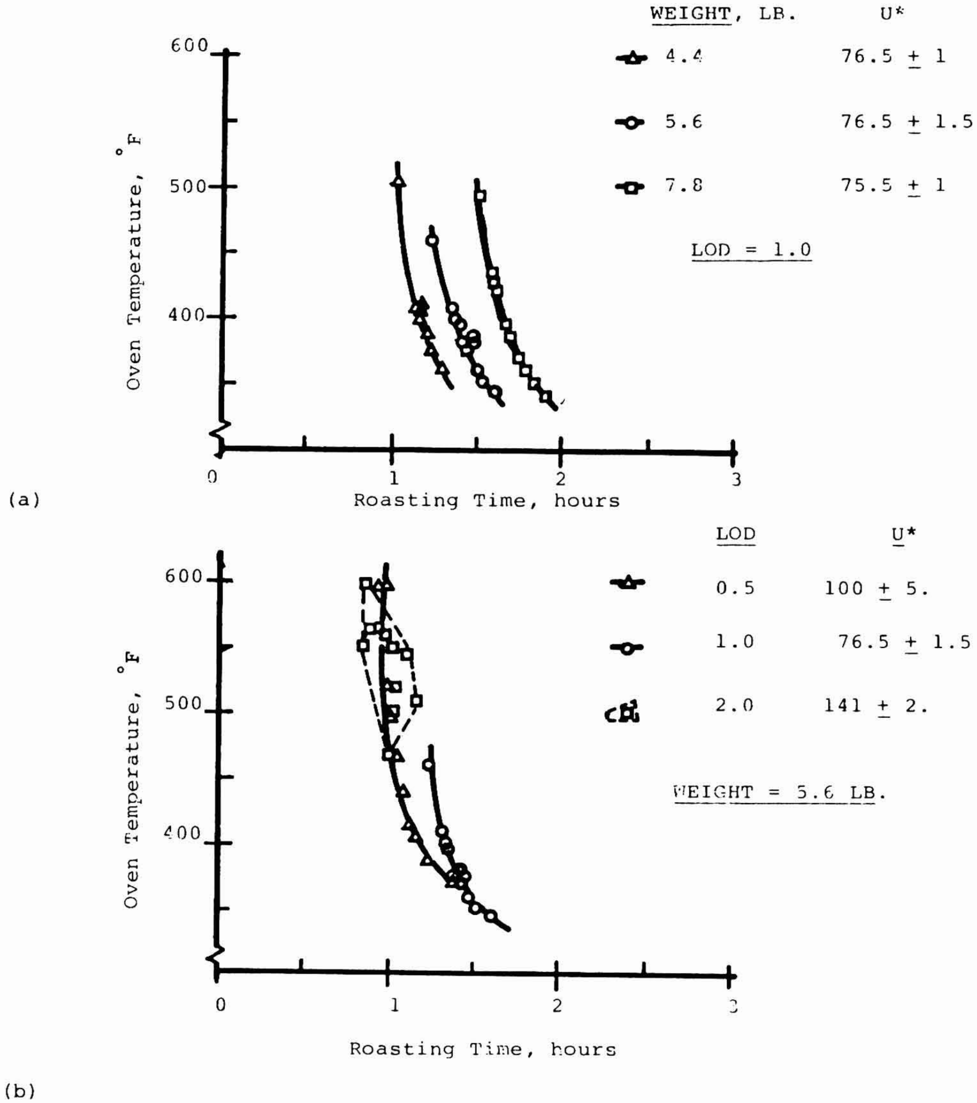


FIG. 4. REGIONS OF OPTIMA WITH ESSENTIALLY THE SAME VALUE OF U
Simple Cooking With Aftercook.
(a) As a function of roast weight, LOD = 1
(b) As a function of LOD, weight = 5.6 lb

TABLE 4.
RESULTS OF OPTIMAL SIMPLE COOKING WITH AFTERCOOK ROAST INITIALLY AT 10°F THROUGHOUT

Weight (lb)	LOD = 0.5	LOD = 1.0	LOD = 2.0
4.4	1.22 hrs at 582°F; 0.32 hrs A/C U*= 77 1.43 hrs at 428°F; 0.33 hrs A/C U* = 94	1.28 hrs at 552°F; 0.63 hrs A/C U*= 61 1.46 hrs at 496°F; 0.5 hrs A/C U*= 66	1.43 hrs at 374° F; 0.59 hrs A/C U*= 96
5.6	1.47 hrs at 557°F; 0.39 hrs A/C U*= 81 1.8 hrs at 398°F; 0.36 hrs A/C U*= 91	1.61 hrs at 512°F; 0.53 hrs A/C U*= 64 1.8 hrs at 454°F; 0.58 hrs A/C U*= 66	2.06 hrs at 332° F; 0.72 hrs A/C U*= 92
7.8	1.73 hrs at 554°F; 0.55 hrs A/C U*= 77 2.54 hrs at 360°F; 0.38 hrs A/C U*= 88	1.76 hrs at 550°F; 1.01 hrs A/C U*= 53 2.04 hrs at 498° F; 0.88 hrs A/C U*= 60	2.49 hrs at 325°F; 0.78 hrs A/C U*= 94

TABLE 5.
RESULTS OF OPTIMAL COOKING OF 5.6 LB ROAST,
LOD = 1.0 ROAST INITIALLY AT 70°F THROUGHOUT

Line	Cycle*	Objective	Cooking process.
1	0/1/0	$U^* = 163$	0 / 2.15 hrs at 315°F / 0
2	0/1/1	$U^* = 75$	0 / 1.36 hrs at 394°F / 0.53 hrs
3	0/2/0	$U^* = 74$	0 / 1.31 hrs at 447°F; 0.47 hrs at 20°F / 0
4		$U^* = 76$	0 / 1.1 hrs at 545°F; 0.62 hrs at 104°F / 0
5		$U^* = 79$	0 / 1.13 hrs at 460°F; 0.68 hrs at 136°F / 0
6	0/2/1	$U^* = 70$	0 / 1.03 hrs at 592°F; 0.42 hrs at 56°F / 0.19 hrs
7		$U^* = 75$	0 / 0.76 hrs at 394°F; 0.62 hrs at 395°F / 0.51 hrs

*Thawing/Number of oven cooking stages/Aftercook.

TABLE 6.
RESULTS OF OPTIMAL COOKING OF 5.6 LB ROAST, LOD = 1.0 ROAST INITIALLY AT 70°F THROUGHOUT

Line	Cycle*	Objective	Cooking process
1	0/1/0	$U^* = 184$	0 / 3.00 hrs at 315°F / 0
2	0/1/1	$U^* = 66$	0 / 1.80 hrs at 454*F / 0.58 hrs
3	1/1/1	$U^* = 68$	14.5 hrs / 1.51 hrs at 465° F / 0.56 hrs
4	0/2/0	$U^* = 65$	0 / 1.25 hrs at 575°F; 1.05 hrs at 147.5° F / 0
5		$U^* = 78$	0 / 1.33 hrs at 477.5° F; 1.08 hrs at 205.11° F / 0
6	0/2/1	$U^* = 60$	0 / 1.27 hrs at 580°F; 0.66 hrs at 138°F / 0.29 hrs
7		$U^* = 66$	0 / 1.04 hrs at 444°F; 0.85 hrs at 362°F / 0.58 hrs
8	1/2/1	$U^* = 66$	12.71 hrs / 1.21 hrs at 560° F; 0.55 hrs at 150°F / 0.3 hrs
9		$U^* = 71$	16.34 hrs / 1.27 hrs at 463°F; 0.47 hrs at 185°F / 0.3 hrs

*Thawing/Number of oven cooking stages/Aftercook.

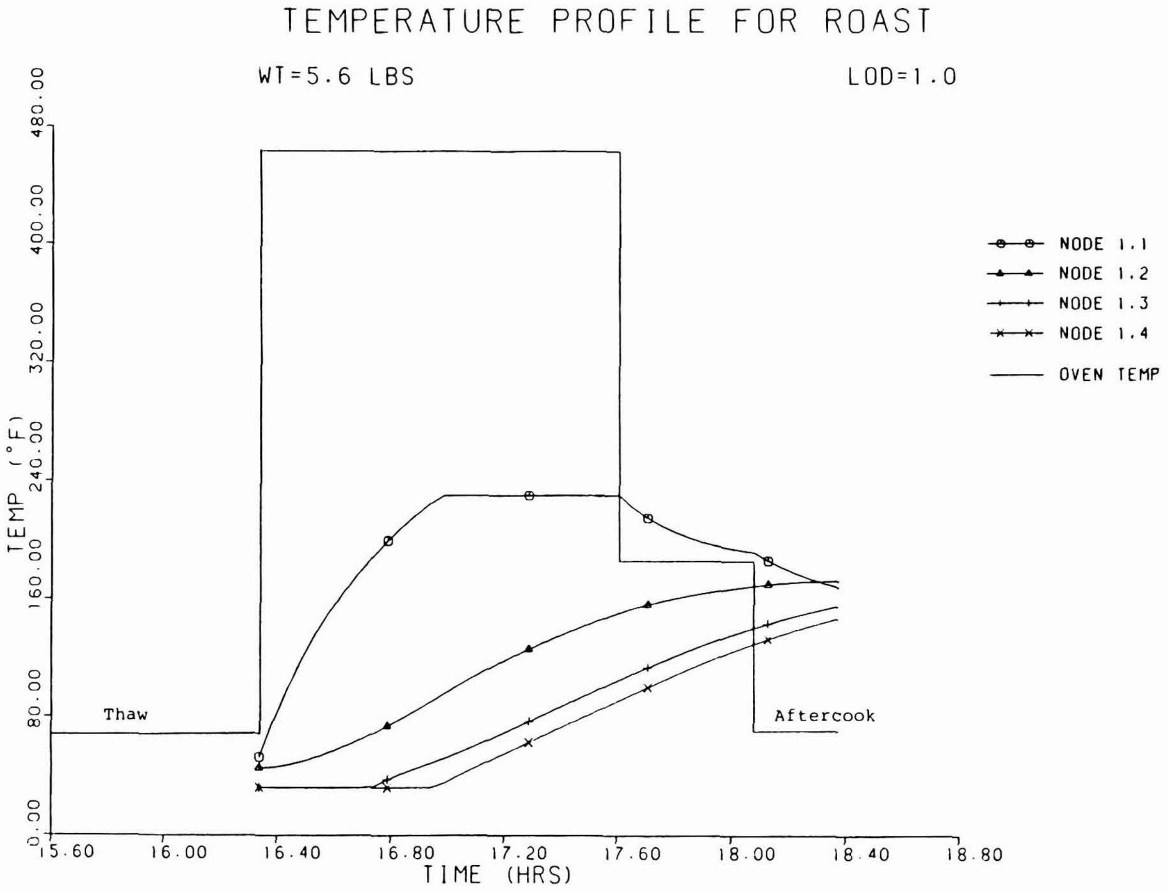


FIG. 5. OPTIMAL COMPLEX COOKING OF A 5.6 LB, LOD = 1 ROAST
Roast initially at 10°F

TABLE 7.
COMPARISON OF OPTIMAL AND CONVENTIONAL ROASTING CYCLES

		Value of U Cooking from 70°F at 350°F		Optimal value of U		
					Cycle*	
Weight (lb)	LOD	Cookbook Recommendations (20 mins/lb)	Remove at Rare Core (140 °F)	U*	Oven	Aftercook
4.4	0.5	205.0	215.0	77	1.22 @ 582	0.32
	1.0	824.0	201.0	61	1.28 @ 552	0.63
	2.0	160.0	316.0	96	1.43 @ 374	0.59
5.6	0.5	599.0	196.0	81	1.47 @ 557	0.39
	1.0	227.0	203.0	64	1.61 @ 513	0.66
	2.0	819.0	336.0	92	2.06 @ 332	0.72
7.8	0.5	2182.0	223.0	77	1.73 @ 554	0.55
	1.0	575.0	211.0	53	1.76 @ 550	1.00
	2.0	2636.0	342.0	94	2.49 @ 325	0.78

*Optimal: Roast initially frozen, T = 10°F One roast cycle with aftercook

MODIFIED OBJECTIVE FUNCTIONS

As noted earlier, other objective functions could be considered, although we would expect to always have some doneness profile criterion. Some modifications to be appended to the temperature profile could be:

- (i) Minimize cooking time (including aftercook time, if used).
- (ii) Minimize energy consumption. Energy consumption is proportional to oven temperature times cooking time. Obviously, there is no penalty for thawing and aftercooking times.
- (iii) Minimize the time for which the elements are at the boiling point. This is to avoid a dry roast due to boiling of all the moisture. Normally this only affects the surface elements.

These were tested for a 5.6 lb roast, LOD = 1.0, initially at 70 °F for one cooking stage plus aftercooking, as follows.

First, cooking time (i) and energy consumption (ii) were appended to Eq. (2) with a multiplier of 100 on cooking time (to make the three terms roughly equal in magnitude). Starting from several initial guesses, the optimal results were (nominally) 1.26 h at 405 °F with 0.56 h aftercook. The temperature deviation criterion (U*) was 86.0 and energy value was 401. This can be compared with the comparable optima in Tables 3 and 4, viz.:

Table 3: 1.36 h at 394 °F; U* = 75; energy = 536;

Table 4: 1.61 h at 513 °F; U* = 64; energy = 842.

The improvements were slight in cooking time: energy expenditure increased the better the roast profile.

Minimizing the boiling time of the outer surface, (iii) above, times 100 to minimize dryness similarly did not make much difference. This gave a doneness measure of U* = 79.07 cooking at 348 °F for 1.57 h with 0.45 h aftercook. The boiling time was 0.2 h as compared with 0.35 h without this penalty.

Thus, in both cases the modified objectives accomplished their purposes, but the gains are relatively small.

ABOUT THE OPTIMIZATION PROCESS

The numerous optimization runs reveal the varied nature of the objective functions.

Sometimes all initial guess led to nearly the same optimum. For example, the results of optimal simple cooking of a 4.4 lb roast (LOD=0.5) from room temperature showed a distinct optimal value around 1.45 h at oven temperature of 355 °F. All but one optimization run converged near this value. Some of the cases showed local minima. Optimal simple cooking of 7.8 lb roast with LOD = 0.5 from room temperature returned the following optima: around 2.09 h at 339 °F (the best); 1.8 h at 380 °F; and 1.7 h at 420 °F.

Other cases suggested flat regions containing various combinations of optimal cooking times and oven temperatures. For example, simple cooking with aftercook from room temperature of a 7.8 lb roast, LOD = 1.0 shows such a result where all optimizations converge to an objective function value near 75, but the optimal cooking times, oven temperatures and aftercook times are quite different for each of the runs. This was also seen in Fig. 4.

Flat nonoptimal regions, sometimes near the optimal value, also plaqued the optimizations. Sometimes the search algorithm would be unable to get out of the flat region and converged to some point within it. (Incidentally, the gradient-based search algorithm also had this problem). Optimal simple cooking of the 4.4 lb roast (LOD=2.0) from 10 °F exhibits this: most optimizations were unable to reach the optimum of 1.69 h at 403 °F with objective function U* = 124; often they got stuck in a flat region characterized by U = 130. The roast cooked from 70 °F showed the same characteristic. Only one run managed to reach the best result of U* = 141, whereas most of the others got stuck in a flat region around U = 211.

Simple cooking of 4.4 lb roast (LOD=1.0) from 10 °F shows an extreme case cluttered with local minima and flat regions; only one run reached the assumed optimal value of 2.49 h at 326.8 °F with U* = 193.5, whereas other runs converge at local minima like 2.42 h at 332 °F with U = 208 and 2.13 h at 384 °F, or stop in the flat region around 1.8–2.0 h at 460–420 °F with U=246.

Due to such topologies of the objective function, it is possible that the absolute minimum values have still been missed, and these results only indicate the better values rather than the best ones. However, it should be noted that small differences in the objective function values (say within +/− 2 units of the optimal value) are negligible and describe essentially the same quality of roast. At worst, such small variations would imply a deviation of a degree or two at one of the node temperatures, which is small compared to the desired temperatures, i.e., 10 °F to 20 °F differences describing different donenesses. Also the oven controls are crude and cannot practically be controlled as finely as the results here would indicate.

The specific results depend upon the objective function, at least to some extent. For example, in the basic equations (1,2), differential weighting could be imposed on the deviations, thereby penalizing deviations from the desired move at certain points. As long as the desired temperatures ($T_S(i,j)$ are not some highly distorted or physically difficult to achieve profile, we expect that the results will be fairly robust irrespective of the weighting. Such differential weightings can be very useful, but the exact specification is generally contentious.

The objective function is an approximate quantification of the roast quality. A comparison of its values indicates which processes yield better roast doneness. Hence, spending time and money to find a unique minimum which is a few tenths better than a feasible value already obtained or a set of optimal weighting factors is of questionable practical value.

Constraints on maximum and minimum temperatures could easily have been incorporated. In all but a few cases, these would have been inactive, although they would have added some computation. Computationally, constraints can really bog down a solution. Since equally good feasible results were found, explicit implementation of constraints was not required in these cases.

CONCLUSIONS

The study has demonstrated how a mathematical model can be used to answer (or suggest reasonable answers to) a relatively complex heat transfer problem.

The model was used to ''optimize'' an objective function, which otherwise would have required an extensive experimental program. For a reliable model and a meaningful objective function, the amount of confirming experimentation, cost and time, can be significantly reduced.

Specifically for this study, Table 7 compares various cooking algorithms: cooking according to cookbook recommendations (column 1); removal at specified core temperature - assuming a thermometer or probe (column 2); and the optimal (cooked from 10 °F) plus aftercook (column 3). The cookbook recommendations (column 1 results) for a rare case are 20 min/lb. at 350 °F. The doneness profiles can be seen in (Townsend *et al.* 1989, Table 5). These are presented as baseline values, only for comparison purposes. This strategy tends to overdoneness in the larger roasts. In the smaller roasts the differences between column 1 and 2 (nonoptimal roasting) would be different to present; indeed, two of the cookbook recommendations are ''better'' in the 4.4 lb size. In all the cases the optima are significantly better. In several cases, the improvement is by a factor of 10 or more. Moreover, the improvements are not easily predictable, so that simple corrections and results are not apparent. About the only rule that we would have confidence in would be the one developed in (Townsend *et al.* 1989) for simple cooking: for a homothetic family of roasts and a given desired doneness, cooking time is proportional to $(\text{weight})^{0.5}$, approximately. However, as shown here even this is not the best one can do with a relatively little added effort. We can propose some new approximate rules are not too complex. For example, for this universal profile with a rare center an approximate set of rules could be:

for LOD $= <$ 1.0,

cook frozen at 550° or higher plus aftercook. All times are proportional to $(\text{weight})^k$ for equal LODs.

for LOD $>$ 1.0

All times are proportional to $(\text{weight})^k$ for equals LODs. In the above, k is about 0.50 (as seen in (Townsend *et al.* 1989). These are not quite optimal, but they would seem to give improved results. This study indicates that superior heat treat results can be effected using the techniques of modeling and optimal design.

NOMENCLATURE

i,I	radial index
j,J	axial index
LOD	length over diameter ratio of the cylindrical roast
T, T(i,j)	actual maximum temperature achieved at a point(i,j)
T_S, $T_S(i,j)$	maximum desired temperature at a point (i,j), corresponding to doneness
U	objective function
U*	optimal value of U
Wt	weight of the roast

APPENDIX

Model Equations and Parameter Values

Model equations for a cylindrical roast divided into elements are shown in Fig. 1. Details of the model geometry are given in (Townsend *et al.* 1989).

Given: Roast initial temperature, T(i,j) throughout and oven temperature, T_∞. Heat flow into/out of an element ((i,j) understood) during a time interval $d\theta$ is

$$d\theta \ \Sigma \ q(n) = Q_m + Q_\ell \tag{A.1}$$

q(n) is the heat transferred by conduction, convection or radiation. In (A.1)

$Q_m = mC_p\triangle T$, the heat capacity, and is used to calculate the element temperature rise, $\triangle T$, when not at a phase change temperature (see below)

Q_ℓ = latent heat (function) defined at specified temperature, a cumulative value. At this temperature, $\triangle T = 0$ until all the material has changed phase.

m, C_p and $\triangle T$ are the mass, specific heat, and temperature change of element (i,j).

The left side of (A.1) is known from element boundary conditions. The right side computes the element temperature rise/fall during $d\theta$. Heat conduction between interior elements is

$$q_k = kA_x \frac{\partial T}{\partial x} \tag{A.2}$$

A_x is the surface area across which heat is conducted due to the temperature gradient $\partial T/\partial x$; k is the thermal conductivity.

Heat transfer to the surface roast elements from the oven temperature (T_∞) occurs by convection and radiation.

For convection:

$$q_c = hA_x\,(T - T(i,j)) \tag{A.3}$$

$$\text{where} \quad h = \frac{\text{Nu}\ k_a}{D} \tag{A.4}$$

The Nusselt number Nu is a function of the Grashof and Prandtl numbers:

$$\text{Nu} = .40\,(\text{GrPr})^{1/4}, \text{ vertical cylinder} \tag{A.5}$$

$$\text{Nu} = .525\,(\text{GrPr})^{1/4}, \text{ horizontal cylinder} \tag{A.6}$$

$$\text{Gr Pr} = \left(\frac{D^3\ \rho_a\ g}{\mu_a}\ \left|\frac{T_\infty - T(i,j)}{T_a}\right|\right)\left(\frac{c_{Pa}}{k_a}\right) \tag{A.7}$$

cf. (Rohsenow and Choi 1961; Kreith 1973; Bird *et al.* 1960).

In the above, k_a, ϱ_a, μ_a and c_{pa} are the thermal conductivity, density, viscosity and specific heat respectively of the fluid (air) at the film temperature adjacent to the surface element (i,j), and

$$T_a = \frac{T_\infty + T(i,j)}{2} \tag{A.8}$$

For Radiation:

$$q_r = (\alpha \text{ or } \epsilon)\,J_x A_x\,(T_\infty{}^4 - T(i,j)^4) \tag{A.9}$$

α and ϵ are the absorbtivity and emissivity and J_x is the view factor (assumed 1).

The solution is by a marching procedure, described in [1].

Nominal values of the parameters for beef are based on (Rohsenow and Choi 1961; Kreith 1973; Bird *et al.* 1960)

density, ϱ	80 lb/ft^3
specific heat, c_p	1.0 BTU/lb °F
thermal conductivity, k	.4 BTU/hr ft °F
view factor, J_x	1.0
absorptivity, α	.9
emissivity, ϵ	.9

The coefficients of radiation absorptivity and emissivity are assumed to be essentially equal; the above value is based on black paint.

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HEAT TRANSFER DURING FLUIDIZED BED PUFFING OF RICE GRAINS

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ABSTRACT

A pneumatic rice puffing machine was developed for increasing the production capacity of puffed rice for which a knowledge of the heat transfer process during puffing was required. The physical properties of the rice grains and other fluidization parameters, necessary for this study was experimentally determined. The surface heat transfer coefficient in case of hot air fluidized bed puffing was found to be 155.39 W/m²K. The calculated grain surface temperature for puffing was about 170°C and this did not vary significantly for experimental puffing air temperatures ranging from 200°C to 270°C. The air temperature ranging from 240°C to 270°C with corresponding exposure time of 9.7 s to 7s was found to be optimum for higher expansion ratio (8.5 to 10) and better color of the product. The temperature differentials between surface and center temperatures and between surface and average temperatures of the grains at the time of puffing were found to vary linearly with various puffing air temperatures and their ratios remained almost constant at 2.056.

INTRODUCTION

Puffed rice is a favorite breakfast cereal in India. It is also a popular food product in many other countries made in different forms like puffed rice balls or bars, confections or candies. It is produced by the heat expansion of parboiled milled rice. The method traditionally followed in India is sand roasting in which parboiled rice is heated with hot sand for puffing. Gun puffing process is common in China, Phillippines and Korea (Juliano and Sukurai 1985; Patterson and Bray 1985) and in this case raw milled rice is used directly for puffing. Automated rotary machines are employed in United States for the production of puffed rice (Brockington 1967). Apart from these processes, puffing can also be achieved by heating the rice in hot air or oil (Roberts *et al.* 1951).

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In order to enhance the production of puffed rice, pneumatic puffing was considered as a potential alternative in India and other developing countries and accordingly, a puffing machine working on the principle of hot air fluidized bed puffing was designed and fabricated. An understanding of the heat transfer process taking place at the time of puffing was required for the design and development of this puffing machine. The physical properties of rice grains like, true density, bulk density, thermal conductivity and thermal diffusivity and the fluidization parameters like bed height and expanded bed height required for this study were experimentally determined.

In this investigation, the heat transfer coefficient on the surface of the grains was evaluated first and the surface temperature, center temperature and average temperature of the grains at the time of puffing were subsequently estimated for different air temperatures for further insight into the actual process taking place during air puffing.

MATERIALS AND METHODS

Paddy

The experiments were conducted with local variety of paddy known as 'Panloi' of West Bengal. It was procured from the farmers in bulk, cleaned, sun dried to 12 to 13% moisture content, wet basis (w.b.) and stored in metal containers in the laboratory at room temperature.

Preconditioning

The parboiling and milling of paddy, and the preconditioning of rice was done by the method followed by Chinnaswamy and Bhattacharya (1983, 1985). Rice at the moisture content of 10.5% (w.b.) was used for all further studies.

Physical Properties

The length (L), width (W) and thickness (T) of the rice grain were measured as average of 20 randomly selected grains using travelling microscope. True density of rice (ϱ_p) was determined using air comparison pycnometer (Beckman - Model 930) and bulk density (ϱ_b) by the standard apparatus. Porosity (ϵ) and equivalent diameter of rice grain were calculated using the formula,

$$\text{porosity, } \epsilon = \frac{\rho_p - \rho_b}{\rho_p} \qquad (1)$$

$$\text{Equivalent diameter, } D_p = \left[4\,L \left(\frac{W + T}{4} \right)^2 \right]^{\frac{1}{3}}$$

(considering prolate spheroidal shape for rice grain). (2)

The thermal conductivity (K) and thermal diffusivity (a) of rice were measured at an average temperature of ambient and product temperatures following the method and instrumentation of Sreenarayanan and Chattopadhyay 1986. For this, approximate temperature was measured with the help of a digital thermometer at an air temperature of 250 °C used for puffing.

Puffing Time Measurement

The time taken by the rice grains to puff was measured at different air temperatures ranging from 200 °C to 270 °C using a stop watch having least count of 0.1 s. The time was noted from the time the grain was put into the hot air stream until it puffed. Average of five recorded readings was computed for each air temperature.

Bed Height and Expanded Bed Height

A separate set up was fabricated for measuring the bed height with a vertical transparent tube of same diameter (5 cm) as that of the puffing column of the puffing machine. Similar flow of air as in the case of the puffing machine (at 6 m/s) was maintained through this tube using a blower and control valve. A micromanometer (E. Vernon Hill and Co., Calif., Type C) was used for the measurement of air velocity. A quantity of 90 g rice (this being the quantity of rice that would remain in the puffing column at any time during puffing operation in order to obtain 20 kg/h puffing capacity) was put into this pipe and the expanded bed height was determined using a measuring scale. The bed height without flow of air also was noted.

Surface Heat Transfer Coefficient

The surface heat transfer coefficient of the grains was determined using the following expression (MacConnachie and Thodos 1963):

$$J_m = J_t = \frac{1.15}{[R_e/(1-\epsilon')]^{0.41} - 1.52} \tag{3}$$

where J_m and J_t are the colburn. J - factors in the famous colburn analogy, (Colburn 1933; Chilton and Colburn 1934)

$$\text{namely, } J_m = J_t = \tfrac{1}{2}F_a \tag{4}$$

R_e = Reynold's number
F_a = Fanning number

The thermal colburn J-factor,

$$J_t = St_t \times P_r^{2/3} \tag{5}$$

Where St_t = thermal stanton number
P_r = Prandtl number

The following expression for heat transfer coefficient (h) can be deduced from the above relationships.

$$\frac{h\ P_r^{2/3}}{\rho\ c\ v} = \frac{1.15}{\left[\dfrac{\rho\ v\ D_p}{\mu\ (1-\epsilon')}\right]^{0.41} - 1.52} \tag{6}$$

Where,
c = specific heat of air, J/kg K
v = velocity of air flow, m/s
ρ = density of air, kg/m³
μ = viscosity of air, kg/m s
ϵ' = bed porosity at v

In the above expression all the air properties are taken at the mean temperature. The porosity of the expanded bed can be found from the expression of pressure drop across the bed ($\triangle$P), which remains constant with change in air velocity (McCabe *et al.* 1985).

$$\begin{aligned} \text{i.e.,}\quad \Delta P &= L\ (\rho_p - \rho)\ (1 - \epsilon)\ g \\ &= L'\ (\rho_p - \rho)\ (1 - \epsilon')\ g \end{aligned} \tag{7}$$

Where,
L = bed height at the onset of fluidization, m
ϵ = bed porosity at the onset of fluidization,
g = acceleration due to gravity
L′ = expanded bed height at v, m

Porosity, ϵ' can be found from Eq. (7) and surface heat transfer coefficient, h from Eq. (6).

Grain Temperature During Puffing

For finding the temperature of the rice grain at the time of puffing, the rice grain is considered as long circular cylinder and the heat transfer is considered to be taking place along the radial direction only. For the case of unsteady state heat transfer through a long cylindrical grain having diameter '2a', the surface temperature (T_S), average temperature ($\overline{T}$) and center temperature (T_C) of the grain after a time 'θ' measured from the time the grain is introduced to the hot air are given by,

$$\frac{T' - T_S}{T' - T_O} = \frac{2\,L_C\,e^{-C_1^2 X_C}}{C_1^2 + L_C^2} \qquad (8)$$

$$\frac{T' - \overline{T}}{T' - T_O} = \frac{4\,L_C\,J_1(C_1)\,e^{-C_1^2 X_C}}{C_1\,(C_1^2 + L_C^2)\,J_O(C_1)} \qquad (9)$$

and

$$\frac{T' - T_C}{T' - T_O} = \frac{2\,L_C\,e^{-C_1^2 X_C}}{(C_1^2 + L_C^2)\,J_O(C_1)} \qquad (10)$$

Subject to the condition that $\alpha\,\theta/a^2 > 0.2$. The equations (8) to (10) are obtained by solving the heat transfer equation,

$$\frac{\partial T}{\partial \theta} = \alpha \left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\,\frac{\partial T}{\partial r} \right]$$ with initial and boundary conditions.

i) when $\theta = 0$, $T = T_O$, $r \leq a$ and
ii) when $\theta > 0$, $h\,(T' - T) = K\left[\frac{\partial T}{\partial r}\right]$, $r = a$

Where,

T' = temperature of air, °C
T_O = initial temperature of grain, °C
a = equivalent radius of the grain, m
i.e., $= (W + T)/4$
L_C = $h\,a/K$
X_C = $\alpha\,\theta/a^2$
C_1 = first root of the transcendental equation,
$C\,J_1(C) - L_C J_O(C) = 0$, in radians
J_O = bessel function of order zero
J_1 = bessel function of order one.

RESULTS AND DISCUSSION

Physical Properties

Table 1 shows the average dimensions of the parboiled rice grain. The length of the grain was thus much greater than its width and thickness as well as the cross section of the grain was such that it could be assumed to be nearby circular with an equivalent radius, a, which justified the assumption of considering rice grain as long cylindrical body. Other physical properties and fluidization parameters measured for this study are listed in Table 2.

It may be noted from Table 2 that the grain bed expanded by approximately 11 times at an air velocity of 6 m/s keeping the total pressure drop across the bed constant, which influenced the design of the height of the puffing column.

Puffing Time

The exposure times (θ) of the grains for puffing determined at different air temperatures ranging from 200 °C to 270 °C are given in Table 3.

Puffing time 'θ' increased with decreasing air temperature and hence the rasidence time of grains inside the puffing column was comparatively more for lower air temperatures. The experiments were conducted for air temperatures of 200 °C to 270 °C and exposure times between 16.5 s to 7 s for puffing of rice grains. However, higher expansion ratios, ER (ratio of volume of the expanded product and volume of rice) of 8.5 to 10, for the puffed rice were obtained between 240 °C to 270 °C and exposure time of 9.7 s to 7 s. At lower temperatures below this the ER obtained was lower and at temperatures higher than 270 °C discoloration of the puffed rice took place although the ER slightly increased.

Surface Heat Transfer Coefficient and Grain Temperature During Puffing

The surface heat transfer coefficient was calculated using Eq. (6) to be 155.39 W/m² K. All the air properties were taken at the mean temperature of ambient, 30 °C and hot air temperature, 250 °C. Variation of 'h' within the range of air temperatures, 200 °C to 270 °C was found to be insignificant and hence this value of 'h' was taken for all further calculations. The surface temperature, average temperature and center temperature of the grains at the time of puffing were calculated using Eq. 8, 9 and 10 for different air temperatures. C_1, $J_O(C_1)$ and $J_1(C_1)$ were taken from Carslaw and Jaeger 1959 and Loncin and Merson 1979.

The above equations, 8 to 10 were further modified using the experimentally determined values as follows:

$$\frac{T' - T_S}{T' - T_O} = 0.8305\, e^{-0.09383\,\theta} \qquad (11)$$

TABLE 1.
AVERAGE DIMENSIONS OF 20 PARBOILED RICE GRAINS

Length, L m	Width, W m	Thickness, T m	Equivalent dia., D_p m	Equivalent radius, a m
7.19×10^{-3}	2.55×10^{-3}	1.71×10^{-3}	3.195×10^{-3}	1.065×10^{-3}
Standard deviation				
0.2514×10^{-3}	0.0850×10^{-3}	0.0294×10^{-3}	0.0619×10^{-3}	0.2437×10^{-3}

TABLE 2.
PHYSICAL PROPERTIES AND FLUIDIZATION PARAMETERS

True density, ρ_p kg/m^3	Bulk density, ρ_b kg/m^3	Bed porosity, ϵ	Porosity at 6 m/s, ϵ'	Static bed height, L m	Expanded bed height, L' m	Thermal Conductivity, K* W/m K	Thermal diffusivity, α* m^2/s
1465	780	0.4676	0.9522	0.05	0.557	0.2251	8.6533×10^{-8}
Standard deviation							
1.5811	1.4635	1.5×10^{-3}	8.8431×10^{-4}	-	0.0115	8.3424×10^{-3}	0.6240×10^{-8}

*K and α values are at an average temperature, 90 °C

TABLE 3.
PUFFING TIME AND TEMPERATURE VARIATION
INSIDE THE GRAIN DURING PUFFING

T' °C	θ s	T_s °C	$\bar{T}$ °C	T_c °C
200	16.5	169.98	164.16	158.02
220	12.5	171.17	161.71	151.72
230	11.3	172.47	161.32	149.55
240	9.7	169.81	156.21	141.85
250	8.6	168.47	152.65	136.00
260	7.7	167.25	149.29	130.31
270	7.0	166.65	146.63	125.49

$$\frac{T' - \bar{T}}{T' - T_o} = 0.9914\, e^{-0.09383\,\theta} \qquad (12)$$

$$\frac{T' - T_c}{T' - T_o} = 1.1613\, e^{-0.09383\,\theta} \qquad (13)$$

Calculated values of T_S, $\bar{T}$ and T_C are shown in Table 3. As the air temperature increased from 200 °C to 270 °C, and value of T_S did not change appreciably. However $\bar{T}$ and T_C showed slightly decreasing trends with increasing air temperature. From the values shown in the Table 3 it can be seen that $T_S - T_C$ and $T_S - \bar{T}$ varied linearly with air temperatures and the ratios of $T_S - T_C/T_S - \bar{T}$ remained constant ($\cong 2.056$) for different air temperatures.

The variation of grain temperatures and hot air temperature for puffing of rice grains at different exposure time is shown in Fig. 1.

It can be seen from Fig. 1 that puffing of rice grain took place when the surface grain temperature attained a value of around 170 °C. The lower values of $\bar{T}$ and T_C obtained at higher air temperatures were may be due to comparatively lesser exposure time for puffing. After the rice grain was fully puffed and before it came out from the puffing column the extra exposure time at higher air

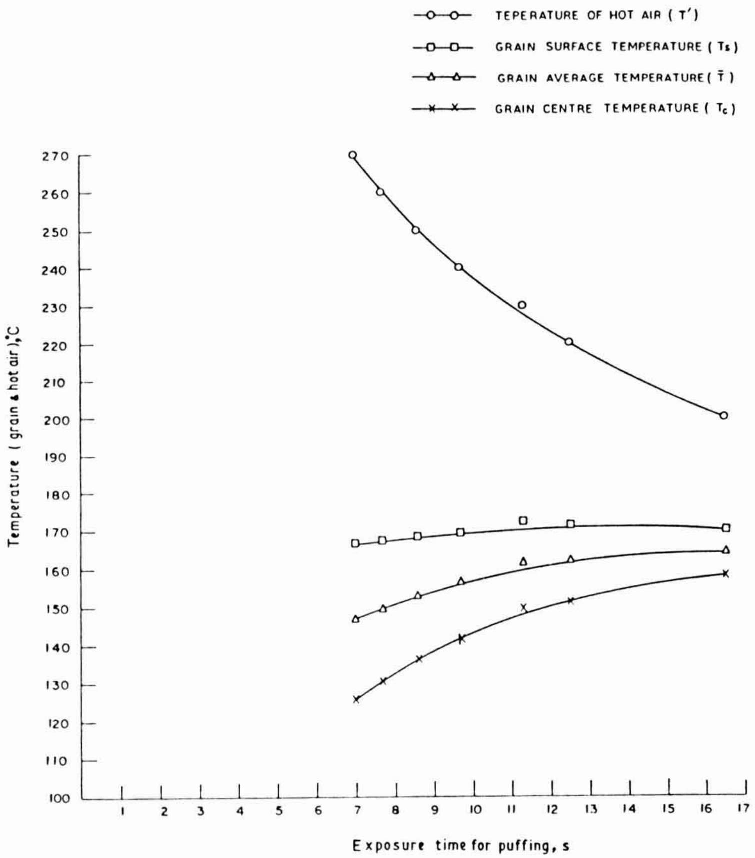

FIG. 1. RELATIONSHIP BETWEEN TEMPERATURE OF HOT AIR AND GRAIN AND EXPOSURE TIME FOR PUFFING OF RICE GRAINS

temperatures above 270 °C caused the discoloration of the puffed rice. Therefore, if the puffed rice can be cooled down immediately after the completion of puffing, it might be possible to utilize higher air temperatures for puffing without causing discoloration.

SUMMARY AND CONCLUSIONS

Heat transfer process during rice puffing was studied for the design and development of a continuous pneumatic rice puffing machine. For this purpose the relevant physical parameters of rice, namely, physical dimensions, true and bulk densities, static and expanded bed heights of the fluidized bed, thermal conductivity, thermal diffusivity and puffing time at different air temperatures were experimentally determined.

The surface heat transfer coefficient in case of pneumatic puffing was calculated to be 155.39 W/m² K at an air temperature of 250 °C. Calculated grain surface temperature was found to be around 170 °C for puffing. The experimental puffing air temperature range of 200 °C to 270 °C showed insignificant variation in the values of both surface heat transfer coefficient and grain surface temperature. The optimum air temperature range for rice puffing was experimentally determined as 240 °C to 270 °C with corresponding exposure time of 9.7 s to 7 s to obtain ER of 8.5 to 10. The temperature differentials between surface and center temperatures and between surface and average temperatures of the grains at the time of puffing were found to vary linearly with various puffing air temperatures and their ratios remained almost constant at 2.056.

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