Drum Drying Potato Flakes – A predictive Model

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We present a mathematical model which accurately correlates drum drying Russet Burbank and Katahdin potatoes, and predicts drum drying of Superior potatoes. The model consists of the general differential equation with boundary condition equations, auxiliary equations, and equation coefficients. The primary process parameters are; drum speed, steam pressure, number of spreader rolls, wet and dry bulb temperatures, mash moisture, and drum dimensions.

Introduction

Food processing uses much equipment and large quantities of energy, making it economically wise to optimize a process. We are developing a food process simulator computer program using mathematical models to calculate mass and energy balances for describing and optimizing many food processes. Unfortunately, mathematical models for predicting mass and energy rates for most food unit operations, such as drum drying, are unavailable and limit the accuracy of the simulator computer program. To further the development of the simulator, we are studying the potato flake process (1) as a prototype. Previous research produced a predictive mathematical model for hot water blanching of potatoes (2–5). Early work in this laboratory on the development of drum dried potato flakes (1, 6) showed drying capacity was a function of drum speed, number of spreader rolls and mash solids, but no model for drum performance was documented. FRITZE (7), working with whey and corn starch, showed drum speed and number of rolls were important process parameters. He showed that drum drying gives the same type drying curve as air drying, but in a far shorter time. His work showed the relations between supplementary air flow, humidity, and moisture content of the drying material on heat transfer. However, results of his work could not predict drum dryer performance for mashed potatoes. According to MOORE (8), drying rate currently cannot be calculated theoretically but only through empirical knowledge. Current work has focused on developing a theoretical, mathematical model to predict drum dryer operation. This paper presents a predictive model for drum drying mashed potatoes.

Experimental

Three potato varieties were used in the study: Maine Russet Burbank* (26% solids) Maine Katahdin (21% solids), and Long Island Superior (20% solids). The potatoes were stored at 3.3°C until removed for processing. Processing was carried out on a pilot plant scale.

Potatoes were peeled in a pilot model (DSA 45) Kunz 45 L steam peeler at a rate of 200 kg/h. The potatoes were subjected to steam at a pressure of 1.3×10^6 Pa for 18 sec, and passed through a series of high pressure (1×10^6 Pa) water sprays to remove the peels. Peeling losses were 10% or less. The potatoes were rinsed for 2 sec in a 0.25% $NaHSO_3$ solution to prevent enzymatic browning. They required very little hand trimming. They were cut into nominal 1-cm cubes with an Urschel slicer (Model G-A). The free starch liberated during slicing was removed by washing the cubes on a Robins Vibro-Flo shaker.

The potatoes were given the "Philadelphia Cook," that is, they were precooked at 80°C in a Rietz water blancher (Model TL-36K2210) for 16 min and then cooled in an Abbott screw conveyor at a water temperature of 22°C at a residence time of 8 min (9–11). Cubes were then cooked in a continuous atmospheric steam blancher (Robins Model No. 20283) until soft enough to rice (residence time ca. 20 min). The cooked cubes were forced through a continuous ricer (12) and collected in 45 kg batches of mash. The following additives were incorporated into 45 kg of mash by mixing with the flat beater at the slowest speed in a Hobart mixer (Model 6-800): 1) an emulsion containing 30 g glycerol monopalmitate, 1 g milk solids, 3.2 g Teneox VII, and 1000 to 5000 ml water and 2) 0.25 g $NaHSO_3$ to retard nonenzymatic browning during dehydration.

Potato mash was dried on a cast iron, clean, smooth single-drum dryer (Overton Machine Company) with a drum 0.61 m diameter by 0.91 m long. Mash feed rate to the dryer was calculated from the flake rate collected at the doctor blades. Values of the process variables are listed in **Tab. 1.**

Tab. 1 Drum dryer process variables

	Range of variable values				
Mash feed rate, Kg/hr	50	≦	rate	≦	159
Drum speed, rpm	4		6		8
Steam pressure, Pa gage	2.4×10^5		3.8×10^5		5.5×10^5
# Spreader rolls	2		3		4
Roll clearance, cm	0.32		0.64		0.95

* Reference to brand or firm name does not constitute endorsement by the U.S. Department of Agriculture over others of a similar nature not mentioned.

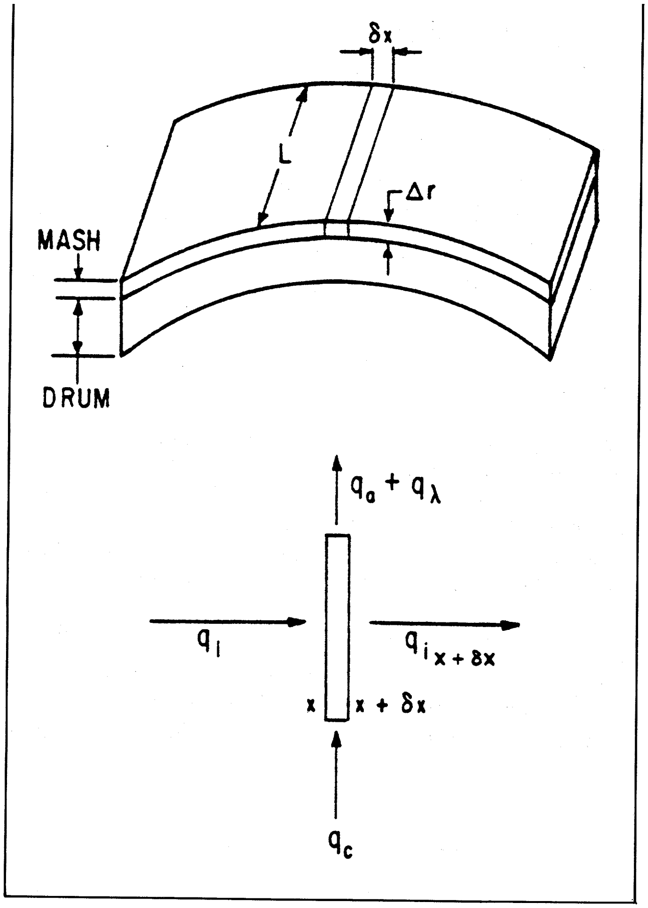

Fig. 1 Diagram of drum and mash sheet for modeling

Potato sheet temperatures were measured with a Wahl Heat Spy infrared thermometer (model HSA-1G) using an emissivity setting of 0.92. The emissivity setting was determined by measuring the temperature of bulk mashed potatoes with a mercury thermometer and setting the emissivity on the infrared thermometer to obtain the same reading. The temperature was measured in the potato mash that accumulates in the nip between the drum and a spreader roll.

Samples for moisture content were taken at various positions on the drum with a small portable stainless steel doctor blade. The doctor blade was 6.7 cm wide. An 8.6 cm spring loaded Teflon wiper blade preceded the doctor blade to remove occasional wet lumps which would contaminate the sample. Moisture content of the drum samples were measured by AOAC Method 7.003 (13).

Theory

Fig. 1 gives a schematic diagram of the drum and mash surface and a cross section of the mash. To develop the model required writing an energy balance over a small volume of mash of cross section L by Δr and travel δx. For a thin sheet of potatoes, we considered the drum surface as an infinite slab so that δx is constant over the thickness, Δr, of the mashed potato sheet. The energy balance is

in − out = Accumulation

$$q_c + q_i\big|_x - (q_a + q_i\big|_{(x+\delta x)}) = q_\lambda \qquad \text{Eqn. [1]}$$

The heat transfer from the drum into and through the mash sheet by conduction is

$$q_c = \frac{KA\,(T_s - T)}{\Delta r\; dx/d\theta} \qquad \text{Eqn. [2]}$$

where T_s is the temperature of the drum surface and T the temperature of the mash. Although Δr obviously varies with location on the drum, we assumed it constant.

Eqn. [2] is divided by dx/dθ, drum speed, to keep units consistent as energy/length. We assumed T_s, the drum surface temperature, was the saturated steam temperature.

The heat transfer into the thin element of mash, δx, at x by mass transfer is q_i;

$$q_i = \frac{dP}{dx}\,c_p\,T \qquad \text{Eqn. [3]}$$

Heat transfer to the atmosphere by convective cooling, q_a, and evaporative cooling, q_λ are;

$$q_a = \frac{hA\,(T - T_a)}{dx/d\theta} \qquad \text{Eqn. [4]}$$

$$q_\lambda = \frac{d\left(\frac{\lambda dW}{dx}\right)}{dx}\,\delta x \qquad \text{Eqn. [5]}$$

Substituting Eqns. [2–5], into Eqn. [1], rearranging terms, and dividing by δx gives

$$\frac{K}{\Delta r}\,\frac{L\delta x}{dx/d\theta}\,(T_s - T) + \frac{dp}{dx}\,c_p\,T\Big|_x - \frac{hL\delta x}{dx/d\theta}\,(T - T_a) - \frac{dP}{dx}\,c_p\,T\Big|_{(x+\delta x)} = \frac{d\left(\frac{\lambda\, dW}{dx}\right)}{dx}\,\delta x \qquad \text{Eqn. [6]}$$

$$\frac{K}{\Delta r}\,\frac{L\delta x}{dx/d\theta}\,(T_s - T) - \frac{hL\delta x}{dx/d\theta}\,T - T_a) - \left[\frac{dP}{dx}\,c_p\,T\Big|_{(x+\delta x)} - \frac{dP}{dx}\,c_p\,T\Big|_x\right] = \frac{d\left(\frac{\lambda\, dW}{dx}\right)}{dx}\,\delta x \qquad \text{Eqn. [7]}$$

$$\frac{KL}{dx/d\theta}\,\frac{(T_s - T)}{\Delta r} - \frac{hL}{dx/d\theta}\,(T - T_a) - \left[\frac{\frac{dP}{dx}\,c_p\,T\Big|_{(x-\delta x)} - \frac{dP}{dx}\,c_p\,T\Big|_x}{\delta x}\right] = \frac{d\left(\frac{\lambda\, dW}{dx}\right)}{dx} \qquad \text{Eqn. [8]}$$

The third term in Eqn. [8] can be written as

$$\frac{d\left(c_p\,T\frac{dP}{dx}\right)}{dx}$$

so Eqn. [8] becomes,

$$\frac{K}{\Delta r}\,\frac{L}{dx/d\theta}\,(T_s - T) - \frac{hL}{dx/d\theta}\,(T - T_a) - \frac{d\left(c_p\,T\frac{dP}{dx}\right)}{dx} = \frac{d\left(\frac{\lambda\, dW}{dx}\right)}{dx} = \frac{\lambda\, d^2W}{dx^2} \qquad \text{Eqn. [9]}$$

The water loss rate, d^2W/dx^2, is numerically equal to the rate change in the mash feed rate, $-d^2P/dx^2$. The term c_pT is not a function of distance, x, so

$$\frac{d(c_p\,T)}{dx} = 0.$$

and Eqn. [9] becomes Eqn. [10]

$$\frac{K}{\Delta r}\frac{L}{dx/d\theta}(T_s - T) - \frac{hL}{dx/d\theta}(T - T_a) = -(\lambda + c_p T)\frac{d^2P}{dx^2} \qquad \text{Eqn. [10]}$$

Eqn. [10] gives the rate of change of the mash feed rate with time expressed as a linear distance on the drum surface, d^2P/dx^2. We want it expressed with respect to time, $d^2P/d\theta^2$. Drum speed in linear dimensions is $dx/d\theta$ which equals $2\Pi R\omega$ where ω is rotation rate and $2\Pi R$ is the length equivalent to one rotation.

$$\text{Hence, } dx = 2\Pi R\omega d\theta \qquad \text{Eqn. [11]}$$

Substituting for dP/dx, feed rate, gives Eqn. [12] and Eqn. [13]

$$\frac{dP}{dx} = \frac{dP}{2\Pi R\omega d\theta} \qquad \text{Eqn. [12]}$$

$$\frac{d^2P}{dx^2} = \frac{d^2P}{(2\Pi R\omega)^2\, d\theta^2} \qquad \text{Eq. [13]}$$

To get the change in mash rate with time or drying rate, substitute Eqn. [13] into Eqn. [10], and obtain the drum dryer model, Eqn. [14]

$$-\frac{d^2P}{d\theta^2} = \frac{\frac{KL}{\Delta r}(T_s - T) - hL(T - T_a)}{\frac{\lambda + c_p T}{2\Pi R\omega}} \qquad \text{Eqn. [14]}$$

To use the drum dryer model we need boundary conditions and auxiliary equations to solve it. One boundary condition exists at equilibrium when the mash is fully dry and drying rate equals zero, Eqn. [15].

$$-\frac{d^2P}{d\theta^2} = 0 = \frac{\frac{K}{\Delta r}L(T_s - T_F) - hL(T_F - T_a)}{\frac{\lambda + c_p T}{2\pi R\omega}} \qquad \text{Eqn. [15]}$$

(This is not a condition archieved in normal processing; but is an equilibrium boundary condition applied simply to solve the equation). T_F is the mash temperature at equilibrium. Rearranging Eqn. [15] gives h, convective heat transfer coefficient, as a function of the thermal conductivity and equilibrium mash temperature, T_F.

$$h = \frac{K}{\Delta r}\left(\frac{T_s - T_F}{T_F - T_a}\right) \qquad \text{Eqn. [16]}$$

Thermal conductivity obviously varies with moisture content of the mash as it dries. If we assume a linear relationship then;

$$\frac{K}{\Delta r} = \frac{K_0}{\Delta r}M \qquad \text{Eqn. [17]}$$

where K_0 is the thermal conductivity at the hypothetical initial boundary condition where the moisture, M, is 1.0. (Again, this is not an actual drum dryer condition). Denoting $K/\Delta r$ as h_c, the conductive heat transfer coefficient, since we assumed Δr is constant and $K_0/\Delta r$ as h_c^0, Eqn. [17] becomes

$$h_c = h_c^0 M = \frac{K}{\Delta r} \qquad \text{Eqn. [18]}$$

at the hypothetical initial boundary condition. When M = 1.0, h_c equals h_c^0. At this point, we have the model, Eqn. [14], and boundary conditions for h_c, Eqn. [18], and h, Eqn. [16]. Substituting Eqn. [18] for $K/\Delta r$ in Eqn. [16] and Eqn. [14], the model equation becomes;

$$-\frac{d^2P}{d\theta^2} = \frac{h_c^0 ML(T_s - T) - h_c^0 M\left(\frac{T_s - T_F}{T_F - T_a}\right)L(T - T_a)}{\frac{\lambda + C_p T}{2\Pi R\omega}} \qquad \text{Eqn. [19]}$$

To evaluate Eqn. [19], the model, we still need an auxiliary equation for T, the mash temperature, and T_F, the equilibrium mash temperature. We used Eqn. [20] to calculate C_p.

$$C_p = 3347 + 418(1 - M) \quad \text{J/Kg}\cdot\text{K} \qquad \text{Eqn. [20]}$$

Results and Discussion

Semi-log plots (not shown) of mash temperature, T, *vs.* moisture, M, gave approximate straight lines at constant steam pressure suggesting an exponential equation would fit the data. Reasoning that, at constant drying rate, T was equal to the wet bulb temperature, T_W, and was equal to T_F at equilibrium, we correlated the data using Eqn. [21].

$$T = T_W + (T_F - T_W)\,\text{EXP}(-CM) \qquad \text{Eqn. [21]}$$

where C is a constant. **Fig. 2** is a plot of $(T-T_W)$ vs. M at 5.52 x 10^5 Pa gage. This and plots at 3.79×10^5 and 2.41×10^5 Pa gage (not shown) give approximate straight lines of slope C.

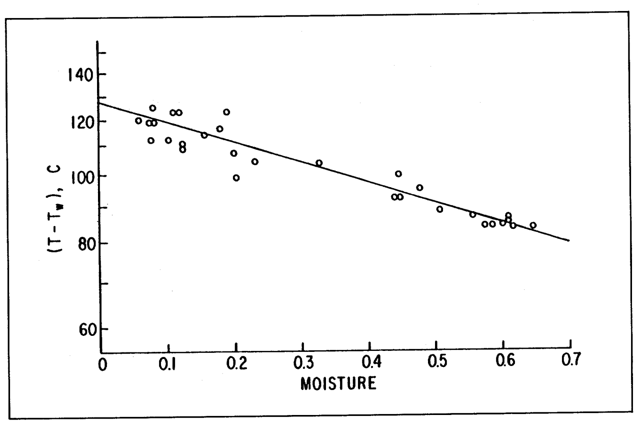

Fig. 2 Data and correlation of $(T-T_w)$ with mash sheet moisture (wet basis), Eqn. [21], for Russet Burbank potatoes at 5.52×10^5 Pa gage steam
The slope is coefficient c and intercept is (T_f-T_w).

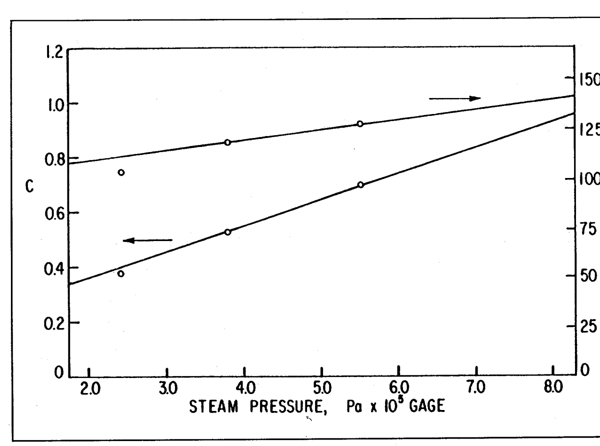

Fig. 3 Plot of slopes (coefficient c) and intercepts (T_f-T_w) vs. steam pressure for Russet Burbank potatoes for Eqn. [21] Correlation lines correspond to Eqns. [22] and [23]

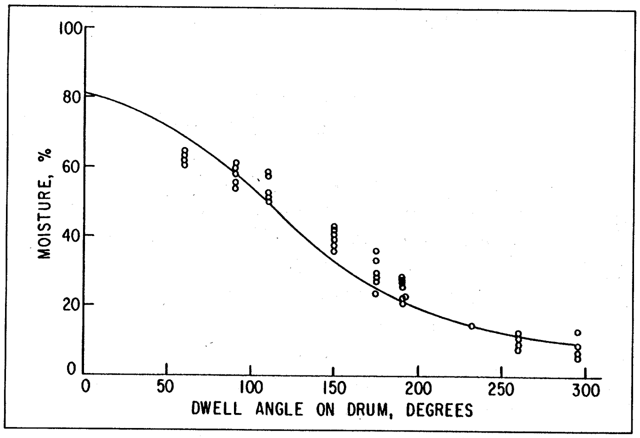

Fig. 4 Typical plot of drum dryer experimental data points and correlation curve moisture % vs. dwell angle degrees, for five experiments with Russet Burbank potatoes, four RPM drum speed, four spreader rolls, and 3.79 × 10^5 Pa gage steam pressure

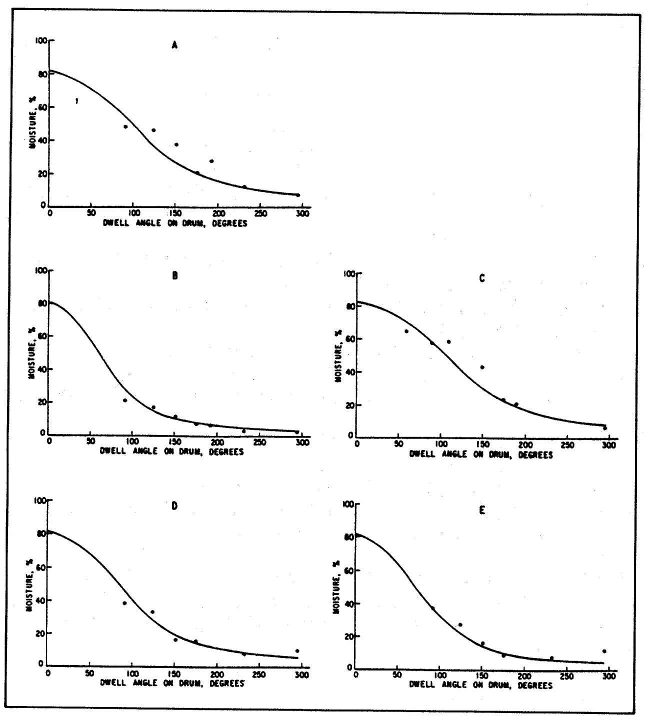

Fig. 5 Predicted drum drying curves and experimental data points for long Island Superior potatoes
A - 5 RPM, 4 spreader rolls, 5.17 × 10^5 Pa gage steam pressure
B - 5 RPM, 2 spreader rolls, 5.17 × 10^5 Pa gage steam pressure
C - 4 RPM, 4 spreader rolls, 3.79 × 10^5 Pa gage steam pressure
D - 5 RPM, 3 spreader rolls, 5.17 × 10^5 Pa gage steam pressure
E - 4 RPM, 3 spreader rolls, 5.17 × 10^5 Pa gage steam pressure

The intercept at M = O gives the value of $(T-T_W)$ at (T_F-T_W). **Fig.3** plots the slopes, C, vs. steam pressure and the intercepts (T_F-T_W), vs. steam pressure.
The points at 2.4 × 10^5 Pa gage are not on the lines. We chose to ignore them for establishing the lines because the experimental determinations of mash temperatures at 2.4 × 10^5 Pa gage appeared to be somewhat erratic and less reliable than at higher steam pressures. Therefore, the auxiliary equations for T and T_F for the model, Eqn. [19], are empirical Eqn. [22], empirical Eqn. [23], and correlation Eqn. [21].

$$C = 9.27 \times 10^{-7} \text{ (Pressure, Pa)} + 0.178 \qquad \text{Eqn. [22]}$$
$$T_F = T_W + 99.11 + 5.12 \times 10^{-5} \text{ (Pressure, Pa)} \qquad \text{Eqn. [23]}$$

However, a model is a hypotheis-only a hypothesis-until verified. And the best verification is correlation of experimental data followed by test of prediction. We made 24 experimental runs on the drum dryer with Russet Burbank potatoes to determine the best values for h^o_c (heat transfer coefficient at M = 1.0-hypothetical value). Plots of sheet moisture vs. position on the drum exhibited typical drying curves. (Dwell of 0° is the feed position and 295° is the doctor blade). **Fig.4** is a plot of typical experimental data (and the correlation curve) for five duplicate runs. To correlate the data from all 24 experimental runs with different experimental conditions, we first drew a smooth curve through the raw data for each of the 24 runs. (Fig.4 shows the co-relation curve and raw data; not the smooth curve). Then we picked off moisture values at 20° increments to use as "smoothed experimental data." Next, using a Hooke-Jeeves Pattern Search, the computer calculated the best value of h^o_c for all 24 runs simultaneously. With the trial value of h^o_c known, and the initial mash feed rate experimentally known, the computer determined the $d^2P/d\theta^2$ curve for each run. Integrating each of these curves gave $dP/d\theta$ vs. drum position and a straightforward calculation gave M vs. drum position. Comparing the trial calculated moisture values and smoothed experimental data, we adjusted h^o_c via the programmed pattern search to minimize the error.
However, all this depended on experimental knowledge of initial feed rate, $dP/d\theta$. But $dP/d\theta$ is a dependent variable subject to processing parameters. *A priori,* it would be unknown. It would be better to be able to calculate initial feed rate. A multiple linear correlation of the feed rates for these runs produced the correlation of Eqn. [24] with a multiple correlation coefficient of 0.96.

$$\frac{dP}{d\theta} = -103.0 + 29.995 \text{ (X1)} + 6.59 \times 10^{-5} \text{ (X2)} + 43.073 \text{ (X3)} \qquad \text{Eqn. [24]}$$

X1 = drum speed, rpm
X2 = steam pressure, Pa gage
X3 = number rolls.

Using this correlation with the above pattern search program, we correlated all 24 runs and found an h^o_c of 3123 $W/m^2 \cdot {}^\circ K$ (550 $BTU/ft^2 \cdot h \cdot {}^\circ F$).
This is the correlation curve shown in **Fig.4** with the raw experimental data. Essentially the same curve was found whether we used the correlated or experimental value for the initial $dP/d\theta$.
The correlation is excellent, well within experimental accuracy. What about prediction? We made five runs with Long Island Superior potatoes. Using Russet Burbank correlation results

$$h^o_c = 3123 \frac{W}{m^2 \cdot {}^\circ K} \text{ and Eqn. [24]}$$

and the model as above, we predicted the drum drying curves for the five runs.
The results – experimental data points and predictive curves – are plotted in **Fig.5.**
The agreement is excellent, well within experimental accuracy, considering the difficulty collecting good moisture data.
To determine the effect of potato variety, we made eight runs with Katahdin potatoes – a potato not normally used for

processing. The h^o_c value was slightly higher 3336 $W/m^2 \cdot {}^\circ K$ (587.5 $BTU/ft^2 \cdot h \cdot {}^\circ F$).

The processing capacity, $dP/d\theta$, was less for Katahdin potatoes. The feed rate correlation equation for Katahdin potatoes is Eqn. [25] with a multiple correlation coefficient of 0.995.

$$\frac{dP}{d\theta} - 112.7 + 21.38\,(X1) + 9.33 \times 10^{-5}\,(X2) + 47.97\,(X3) \qquad \text{Eqn. [25]}$$

where X1 = drum speed, rpm
X2 = steam pressure, Pa gage
X3 = number rolls.

Conclusions

The mathematical model is accurate for potato flakes. It adequately correlates drum drying of Russet Burbank and Katahdin potatoes and predicts drum drying of Superior potatoes. The model will enable processores to simulate and optimize potato flake processing when the model is incorporated into the ERRC Food Process Simulator computer simulation program.

Nomenclature

- A – cross sectional area for heat transfer, length^2
- C – coefficient in mash temperature relation, wt mash/wt H_2O
- C_p – mash heat capacity, energy/wt temp
- $dP/d\theta$ – mash flow rate, wt/time
- $dW/d\theta$ – moisture loss rate to air by evaporation, wt/time
- dx – differential drum distance, length
- $dx/d\theta$ – drum rotation speed, length/time
- h – convective heat transfer to air, energy/time length^2 · temp
- h_c – conductive heat transfer coefficient through mash, energy · wt mash/time · length^2 · temp · wt H_2O
- h^o_c – $vK_o/\Delta r$, energy/time · length^2 · temp
- K – thermal conductivity of mash, energy/time · length · temp
- K_o – thermal conductivity of mash at hypothetical moisture value of 1.0, energy · wt mash/time · length · temp · wt H_2O
- L – drum width, length
- M – moisture, wt H_2O/wt mash
- P – total quantity of potatoes fed, weight
- q_a – heat transfer from mash to air, energy/time
- q_c – heat transfer through mash by conduction, energy/time
- q_i – heat transfer by mash, energy/time
- q_λ – heat transfer from mash to air by evaporating water, energy/time
- Δr – mash thickness, length
- R – drum radius, length
- T – mash temperature
- T_a – air or dry bulb temperature
- T_F – equilibrium mash temperature
- T_s – saturated steam temperature
- T_W – wet bulb temperature
- W – total quantity of water evaporated from potatoes, also unit of power, watt
- ω – drum speed, revolutions/time
- δx – small distance of travel on drum surface, length
- θ – time
- λ – latent heat of vaporization, energy/wt

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Composition and Functional Characteristics of Barley Distillers Dried Grain in Sausage

Distillers dried grain is a high fiber, high protein byproduct with the potential of a nutritious food additive. Barley distillers grain (BDG), both whole and milled fractions, were analyzed for chemical composition and tested in Polish sausage for functional characteristics. Protein content (dmb) ranged from 18.9% in the shorts fraction to 38.3% in the fine fraction. Neutral detergent fiber ranged from 34.1% in the fine fraction to 65.5% in the shorts. Acid detergent fiber values were similar in all fractions and the whole BDG, averaging 28.4%. Water solubility and emulsifying capacity were poor in the sausage product, although acceptability by a taste panel was not different from controls containing soy isolate. It was concluded that although BDG contributes little in functional characteristics to meat products, it could be utilized as an extender.

Introduction

Production of ethanol from grain to meet the biofuel demand has resulted in a high protein by-product, distillers dried grain (DDG). Barley-derived distillers dried grain (BDG) has potential as a nutritious food ingredient, provided its functional properties are suitable.

Nutritional analyses have indicated BDG is a potential fiber and protein source in human foods (1, 2). Although it was successfully incorporated into baked products at levels up to 15% (3, 1, 4), poor functional characteristics limited its use at higher substitutions. Low volume, poor texture, and color and flavor changes discouraged incorporation into food products (5, 6, 2). Several studies have reported the use of DDG in meat systems. FINLEY and HANAMOTO (7) found that brewers grain derived from corn could be dry milled to produce a high protein product applicable to extruded or fabricated foods. A protein concentrate obtained from brewer spent grain press water made an acceptable meat extender when extruded with other cereal protein (6). JUNILLA *et al.* (8) reported that sausage containing 1% brewers grain, brewers yeast, or stillage rated almost equal to the control.

The objective of this study was to determine the chemical composition of BDG and its milled fractions and to assess their functional properties in a sausage product. Solubility, emulsification and water binding were assessed and sausages were evaluated by a taste panel for acceptability.

Materials and Methods

Distillers Dried Grain

Barley distillers dried grain (BDG) was obtained from the Alcotec biofuel plant at Ringling, Montana, USA, which utilizes 100% barley in its fermentation process. The BDG was centrifuged to separate spent grain from the stillage and then dried by a direct heated rotating drum.

Milling of BDG was done at 10% moisture level using a Buhler mill. A high protein flour or fine fraction, a coarse bran fraction and a shorts fraction of finely ground bran and adherent endosperm were obtained. Representative milling data for BDG showed an average yield of 33% flour, 32% bran and 35% shorts (9). These fractions along with whole unmilled BDG were evaluated.

Chemical Analysis

Proximate analysis of the whole BDG and fine, coarse, and shorts milled fractions and sausage product were performed in duplicate. AOAC (10) methods for moisture (14.058), ash (14.006), crude fiber (14.060), fat (7.045), and protein (2.049) were used. A conversion factor of 6.25 was used to calculate protein percentage from nitrogen. Neutral and acid detergent fiber content were analyzed by the GOERING/VAN SOEST method adapted from the U.S.D.A. Handbook (11).

Amino acid analysis was performed on DDG samples by AAA Laboratory, Mercer Island, Washington. The ion-exchange chromatographic methods developed by SPACKMAN *et al.* (12) were utilized, with 24 hour 6N HCl at 110°C. Serine was increased by 10% and threonine by 5% to compensate for destruction by acid. One crystal of phenol was added before acid hydrolysis.

Functional Properties

Functional properties identified for whole BDG and milled fractions included protein solubility, emulsifying capacity and water-holding capacity. Protein solubility of BDG and milled fractions were determined by a procedure outlined by INKLAAR and FORTUIN (13). Soluble protein at pH of 3.9 in the supernatant was measured by the AACC Biuret Method 46–15 for wheat (14). This was expressed as the ratio of water soluble protein to total protein times 100.

The method of YASUMATSU *et al.* (15) was used for determining emulsifying activity, expressed as ratio of emulsified layer to whole layer. A 1.4 g sample was suspended in water (20 ml), and soy oil (20 ml) was added. This mixture was blended at high speed in an Osterizer blender for one min. The emulsion was divided into three 15 ml centrifuge tubes and centrifuged at 3,000 rpm for 5 minutes. The emulsifying activity was calculated as

$$\frac{\text{Height of emulsified layer (mm)}}{\text{Height of whole layer in centrifuge tube (mm)}} \times 100$$

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