CONTROL OF CONTINUOUS MICROWAVE DRYING PROCESS OF PEANUTS USING REMOTE TEMPERATURE MEASUREMENT

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ABSTRACT

Process control methods are widely used in food industry for quality assurance purposes. The characteristics and requirements for various food processing operations are described by Mittal (1996) and McFarlane (1995). For peanut processing, a complex fuzzy control system for the roasting process, based in part on theoretical modeling (Landman *et al.*, 1994) was developed by Davidson *et al.* (1999).

The study reported here focuses on the process control for continuous microwave drying of peanuts, where the microwave energy delivered to the dryer can be changed as needed. The utilization of microwave energy in heating and drying applications has been addressed in many books (Decareau, 1985; Metaxa and Meredith, 1983). New designs, such as focusing structures and traveling wave (or planar) applicators, are currently used for heating of fluids (Coronel *et al.*, 2003) and drying of agricultural commodities (Boldor *et al.* 2004). In the drying process, the most important processing parameter is product temperature. Traditional temperature sensors, such as thermocouples, cannot be used for measurements due to the inherent nature of microwaves. In addition, continuous monitoring of internal temperatures of seeds is impossible in continuous drying processes, even when using microwave-immune fiber optic temperature probes (Boldor *et al.*, 2004). However, the correlation between the internal temperatures of peanuts and the surface temperature of the peanut bed (Table 1, Boldor *et al.*, 2004) makes remote temperature measurement of peanut bed surfaces a feasible method for process control purposes. Remote surface temperature measurements are performed using either infrared thermocouples inserted at certain locations along the microwave waveguide, or a properly calibrated infrared imaging system (Goedeken *et al.*, 1991).

Materials and Methods

Field dried peanuts (Runner and Virginia type) at moisture contents ranging from 22 to 52% (dry basis) were used in this study. Samples were shipped from USDA-ARS Peanut National Laboratory in Dawson, Georgia to the Department of Food Science at North Carolina State University during the months of September - November of 2002. The microwave system included a curing chamber (a traveling wave planar applicator, IMS, Morrisville, NC) and a 5 kW microwave generator (IMS, Morrisville, NC). Air flow through the chamber was maintained at 25°C through an electrical fan and heater.

The system was treated as a first order system with dead time, whose transient behavior can be represented in Laplace domain using the following transfer functions (Eqn.1) (Marlin, 2000):

$$G_p(s) = \frac{Y(s)}{X(s)} = \frac{K_p e^{-\theta s}}{\tau_p s + 1} \qquad [1]$$

In this study, process reaction curves as described in literature (Marlin, 2000) were used to determine the process parameters K_p, θ, and τ_p. The major advantage of this method is that the transfer functions of the sensor and the final control element are included in the model. The disadvantage is that the method is limited to first and second order systems with dead time. One of the most widely used process control method is feedback control using a PID (proportional, integral, derivative) algorithm, where response of the controller is proportional with the difference between the desired value (set point SP) and the measured value of the controlled variable (CV). The transfer function of the PID controller is:

$$G_c(s) = K_c\left(1 + \frac{1}{\tau_i s + 1} + \tau_d s\right) \qquad [2]$$

For determination of the initial control parameters K_c, τ_i, and τ_d, the authors used the Ciancone open-loop method (Ciancone and Marlin, 1990) for the two peanut varieties and the three initial moisture contents used in this study (Table 3). The lack of dead time for the sensors placed closer to entrance in the microwave applicator (Table 2) combined with the low signal-to-noise ratio permitted the use of a PI controller, with no derivative component.

Table 1. Example of infrared thermocouples locations, grouping and relationship between internal and surface temperature for Runner type peanuts (Boldor *et al.*, 2004).

Gr.	Sensor	Location (m)	Equation	r^2
A	1	0.476	y = 1.77x - 12.38	0.99
	2	0.552	y = 1.81x - 13.52	0.99
E	12	2.508	y = 1.77x - 12.60	0.94
	13	2.584	y = 1.87x - 14.31	0.94
	14	2.660	y = 1.90x - 15.32	0.94

Table 2. Example of process parameters for Virginia and Runner type peanuts.

	Virginia				Runners		
	mc%	Gr. A	Gr. C		mc%	Gr. A	Gr. C
K_p	44	6.292	4.287		52	4.771	3.222
	22	6.277	4.288		33	4.824	4.096
τ_p	44	0.288	1.4		52	0.45	1.6
	22	0.288	1.4		33	0.513	3.988
θ	44	-0.038	-0.083		52	0.075	1.117
	22	-0.038	-0.083		33	0.038	1.354

Surface temperature sensors were based on infrared technology (Mullin and Bows, 1993, Goedeken *et al.*, 1991). Infrared thermocouples (model OS36-T, OMEGA Engineering, Inc., Stamford, CN) were placed at various distances along the waveguide as shown in Figure 1 (Boldor *et al.*, 2004). The surface temperatures were monitored and recorded through a data acquisition and control unit (HP34970A, Agilent, Palo Alto, CA) and a master software routine written in LabView (National Instruments Corp., Austin, TX), that also controlled the microwave generator, and monitored and recorded the power levels in the microwave curing chamber through power diodes (JWF 50D-030+, JFW Industries, Inc., Indianapolis, IN).

The feedback control routine was developed in Labview, using a simulation of the first order process with dead-time. Once the optimum control parameters were determined, the control routine was added to the master Labview program.

Results and Discussions

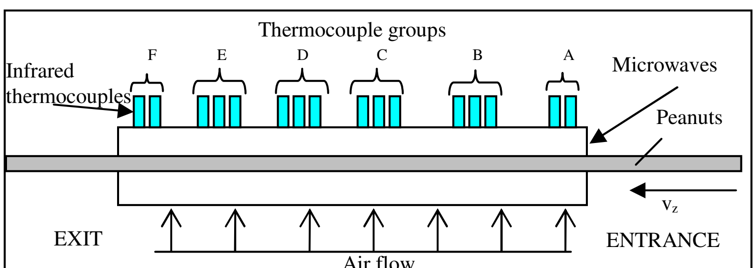

Figure 1. Schematic of the microwave drying system.

Due to infrared thermocouple positioning in groups of 2 or 3 (Figure 1), the process reaction curves were averaged to reduce the number of controlled variables from 16 to 6 (A, B, C, D, E, and F respectively), and furthermore, the last two groups were dropped due to very long dead-times and low process gains (Figure 2). The values for the open loop process parameters are shown in Table 2.

The gain of the process, K_p, for Virginia type peanuts at all moisture contents decreased as sensors were placed further away from the microwave entrance, a decrease that is consistent with the lower temperatures caused by the evaporative, convective and radiating cooling experienced by peanuts undergoing drying (Boldor *et al.*, 2004). In the case of Runner type peanuts, the process gain followed a similar dependence on sensor position, with the exception of peanuts at 33% moisture content (Figure 2, left). At 33% mc, the process gain increased initially from group A to group B, decreasing afterward. At this moisture content, the maximum temperature during drying is located in the same region of the microwave tunnel as the second group of sensors (group B), giving a higher process gain when this group of sensors was used.

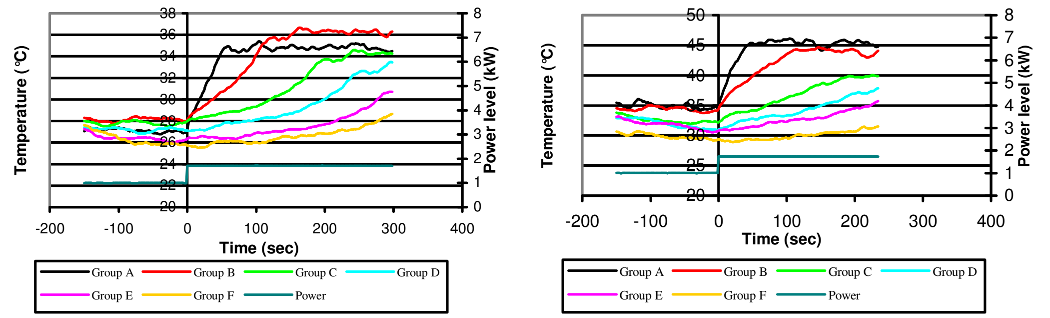

Figure 2. Step response of the six groups of infrared thermocouples for Runner type peanuts at 33% initial mc (left) and for Virginia type peanuts at 26% initial mc (right).

The time constants of the processes increased as expected as the sensors were placed further away from the microwave tunnel entrance. However, there was a fairly significant variation between the time constants of the same groups of sensors for different initial moisture contents. This variation was probably caused by difference between the fixed location of the infrared thermocouples and the changing locations of maximum temperatures with moisture content. These peculiarities of the locations of maximum temperatures probably require a more adequate measurement of surface temperature distribution, maybe using an infrared camera. The camera may be useful in determining the location of the maximum temperature (and moisture content), a critical information for the determination of the needed number of passes through similar drying chambers to obtain a desired final moisture content. Although there is a good mathematical model of temperature distribution in continuous microwave drying (Boldor *et al.*, 2004), more data representing the drying kinetics, together with better mathematical models of moisture distribution, are needed to create an advanced control system for the microwave drying process. The limitations of the data acquisition system used for this study and the lack of knowledge described previously, determined the use of a simple feedback control loop to maintain the surface temperature of the peanut bed. The tuning of the PI feedback controller was simulated in Labview using the servo scenario, with the controller acting to track set point changes.

Table 3. Examples of initial tuning parameters for Virginia (26% mc) and Runner (36% mc) type peanuts.

	Virginia			Runners	
	Gr. A	Gr. C		Gr. A	Gr. C
K_c	0.178	0.282		0.233	0.262
τ_i	0.084	1.219		0.127	1.823
τ_d	0.009	0.090		0	0.232

Table 4. Initial and optimum tuning parameters and time to get to the set point for Runner type peanuts at 33% initial mc.

	Initial	Optimum
K_c	0.228	1.75
τ_i	0.127	1.02
Time (sec)	121.5	33

The optimum tuning parameters (Table 4) were determined such that the process variable never overshot the set point. The results of the simulation for Runner-type peanuts at 33% mc are shown in Figure 3. In general, these optimum parameters worked well in the temperature ranges used in real life situation (Figure 4).

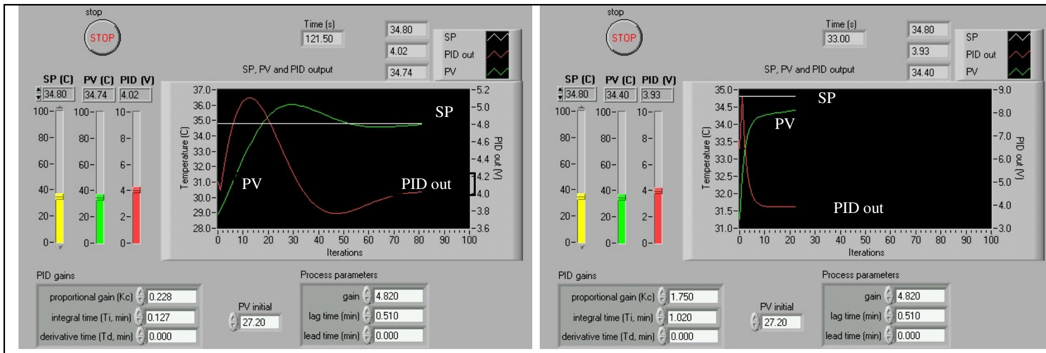

Figure 3. Simulation result for initial (left) and optimum (right) tuning parameters.

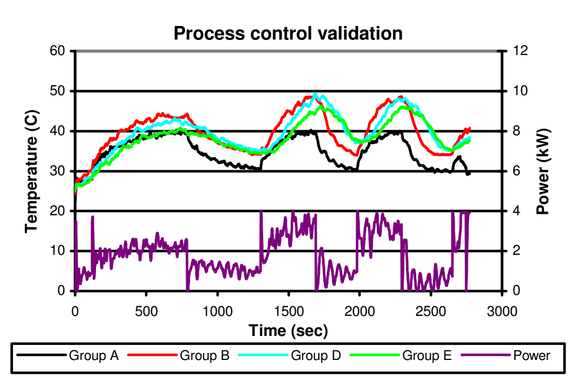

Figure 4. Validation of the process parameters (K_c=1.75, t_i=1.02)

Conclusions

Process reaction curves were determined for peanuts undergoing microwave drying in a continuous applicator. The determined process parameters were used to estimate initial tuning parameters of a PI feedback control loop to maintain a constant surface temperature. Computer simulation was successfully implemented to determine the optimum tuning parameters, which were afterward implemented in the real system. Possibilities of improvement of the process control procedure were discussed, including the use of an infrared thermal imager to determine the locations of maximum temperature, and methods to determine the number of passes required to obtain desired final moisture content.

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