

# Factors That Influence the Microwave Expansion of Glassy Amylopectin Extrudates

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## ABSTRACT

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The microwave expansion of glassy, unexpanded amylopectin pellets was studied. Amylopectin was extruded at three levels of specific mechanical energy (483, 809, and 846 kJ/kg), and 35–40% moisture content, without expansion at the die. Glassy pellets were obtained by drying and equilibrating the extrudates at five water activities ( $a_w$  0, 0.11, 0.33, 0.67, and 0.75). The pellets were characterized by measuring volume, porosity, and moisture content. The pellets were then expanded in a constant power microwave oven to determine the degree of expansion. When subjected to microwave heating, regardless of extrusion condition and initial  $a_w$ , the pellets expanded from the center where the highest temperature was

recorded and then expansion advanced in the whole volume. Maximum expansion was reached after 30 sec of heating, after which samples started to burn from the center. Samples simultaneously expanded and lost moisture, both processes being faster and more intense for pellets of higher initial  $a_w$ . No expansion was observed for the pellets stored at  $a_w$  0, while collapse was observed for pellets stored at  $a_w$  0.73. A linear correlation between pellet expansion temperature and glass transition temperature was obtained. A hypothesis for the microwave expansion of glassy extrudates was formulated and represented on a state diagram.

Snack foods are readily consumed all over the world. The global market for snacks was evaluated at \$44.36 billion in 1997, out of which about \$15 billion was represented just by the United States market (Shukla 2000). According to a report of the Snack Food Association, sales of savory snack food in the United States increased by 6.2% between 1999 and 2000 and by 5.1% between 2000 and 2001, and the growth trend seems to continue for 2002. In terms of sales, this represents \$19.38 billion for 2000 and \$21.8 billion for 2001 (IFT Newsletter, July 31, 2002. <http://www.ift.org/extra/newsletter/>). Due to their functional properties, the usual raw materials used for production of expanded snacks are starches and flours which contribute to the unique structure and texture of the expanded products.

Third-generation snacks gained increasing attention and market place in the recent years (Van Hulle et al 1981, 1983; Spratt et al 1988; Van Lengerich et al 1989; Shachat and Raphael 1990; Suknark et al 1999; Ernoult et al 2002). Nonexpanded pellets can be formed by extruding cereal flours at high moisture contents (30–35%), moderate shear and temperature, and die temperatures <100°C (Suknark et al 1999; Ernoult et al 2002). After cooling and drying to 5–10% moisture, the extruded pellets become glassy and very stable (Spratt et al 1988; Osman et al 2000) and can be expanded by baking (Chen and Yeh 2000), deep fat frying (Osman et al 2000), or microwave heating (Van Hulle et al 1981, 1983; Spratt et al 1988; Ernoult et al 2002). Ernoult et al (2002) and Lee et al (2000) have studied the microwave expansion of unexpanded corn starch pellets, Chen and Yeh (2000) investigated the expansion of rice pellets, Suknark et al (1999) obtained and characterized tapioca starch with catfish and tapioca starch with partially peanut flour half-products.

Microwave energy is increasingly used for expansion of foods, the typical application being the microwave expansion of popcorn (Lin and Anatheswaran 1988; Pordesimo et al 1990, 1991; Mohamed et al 1993). Third-generation snacks expanded by microwave heating bring tremendous extension to popcorn expansion as it becomes possible to use food polymers to form various biological origin snacks in any desirable shape.

In microwave heating, the heat is generated by the molecular friction of electrical dipoles and charged molecules under an oscillating field of specific frequency and by the heat transferred by conduction, convection, and evaporation within the food itself (Mud-

gett 1982, 1989; Tong et al 1992; Bernussi 1998). The biggest challenge encountered in microwave heating is the uneven distribution of temperature within the product, which depends on the type of oven, location of the sample in the oven, sample size and geometry (Tong et al 1992; Chen et al 1993; Schiffmann 1993; Tong and Lund 1993; Van Remmen et al 1996; Gropper et al 1997). Focusing of microwave energy can produce overheating at edges, corners, in the center, or in so-called hot spots, depending on the composition and geometry of the food (Van Remmen et al 1996; Gropper et al 1997). Interestingly, it is possible to harness this explosive energy to manufacture expanded food textures.

The mechanism that governs cereal expansion, particularly by extrusion, was extensively studied in the literature and several authors demonstrated the role of bubble growth dynamics in this process (Kokini et al 1992; Fan et al 1994; Schwartzberg et al 1995; Della Valle et al 1997). The mechanisms involved in expansion processes other than extrusion seem to follow a similar pattern. Extending the theories of previous authors regarding the mechanism of expansion, Aguilera and Stanley (1999) suggested that the formation of the final structure of indirect snacks is based on the transition of the amorphous matrix to the rubbery and flow states that occurs during heating. Moisture content plays a critical role in cereal expansion due to its ability to generate the driving force during the flash off process and also through its impact on the extensional viscosity and phase transitions of the food polymer matrix. Lee et al (2000), Chen and Yeh (2000), and Ernoult et al (2002), using different extrusion processes and microwave heating regimes, reported that maximum expansion took place at 10% moisture content of cereal pellets. When used for the manufacturing of indirect snacks, starch is usually pregelatinized, as the limited amount of moisture and heat available in the expansion stage do not allow the starch to gelatinize and form a network that can be expanded by the super-

TABLE I  
Extrusion Parameters of Unexpanded Amylopectin Pellets

Parameter	Condition 1	Condition 2	Condition 3
Moisture content of feed (%)	40	35	35
Temperature profile [t <sub>1</sub> -t <sub>2</sub> -t <sub>3</sub> -t <sub>4</sub> ] (°C)	34-74-125-83	35-70-129-86	33-70-129-93
Die temperature [t <sub>5</sub> ] (°C)	88	96	96
Torque (%)	29	30	24
Screw speed (rpm)	400	440	400
Mass flow rate (g/min)	80	95	95
SME (kJ/kg)	846	809	483

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heated steam (Schiffmann 1993; Wang 1997). Lee et al (2000) reported a nonlinear correlation between the degree of gelatinization and the expansion bulk volume of extruded cornstarch pellets, and an optimum level of starch gelatinization for maximum expansion of  $\approx 50\%$ . The addition of solid fat to amylopectin pellets had a beneficial effect on expansion, while liquid fat decreased it (Ernoul et al 2002).

Despite a few studies that focus on microwave expansion of cereal pellets, very limited data is available so far in this domain. Therefore, the objective of this study was to investigate some of the most important factors responsible for the microwave expansion of cereal pellets, as well as the mechanism of expansion.

## MATERIALS AND METHODS

### Raw Material

In this work, Amioca starch (98% amylopectin) donated by National Starch and Chemical (Bridgewater, NJ) with 12.3% moisture content was used. Amylopectin, a highly branched, large biopolymer ( $M_w = 10^7$ – $10^8$  Da), is a major component of cereal flours. It is also a good carbohydrate food model because during extrusion it forms a polymeric network that is the base for a highly porous matrix. At the same time, using a single food component as opposed to a complex mixture simplifies the data analysis by eliminating the effect of other components and their interactions (Cisneros and Kokini 2002a,b).

### Extrusion

Amylopectin was extruded using a laboratory corotating twin-screw extruder (model ZSK-30, Werner&Pfleiderer, Ramsey, NJ), with five heating zones. The screw configuration is presented in Fig. 1. The extruder allowed the control and reading of the torque, screw speed, barrel, and die temperature, and die pressure. A slit die with the channel dimensions of  $150 \times 20 \times 1.5$  mm was used.

The dry amylopectin was fed into the extruder from a feeder with corotating twin screws (K-Tron, Pittman, NJ), which allowed a precise control of the feeding rate. The moisture content during extrusion was adjusted using a metering pump (U.S. Motors, St. Louis, MO) equipped with a frequency controller (Reliance Co., Greenville, SC). The water was fed from a tank filled with tap water and introduced in the extruder barrel through a water inlet positioned next to the solids feed inlet. The extrusion conditions that led to unexpanded extrudates are shown in Table I. Specific mechanical energy input (SME) was calculated according to Godavarti and Karwe (1997).

### Sample Handling

As the extrudates exited the slit die as ribbons they were cut into rectangles of  $15 \times 20$  mm (1.5 mm thick), which were cooled and dried in open air overnight. The dry pellets were then equilibrated at different  $a_w$  levels in dessicators over supersaturated solutions of LiCl ( $a_w$  0.11),  $MgCl_2$  ( $a_w$  0.33), KI ( $a_w$  0.68), and NaCl ( $a_w$  0.75). The pellets reached equilibrium in about three weeks and had final moisture contents 4–15% (db). Totally dehydrated samples were obtained by equilibrating over  $P_2O_5$  ( $a_w$  0) for three weeks, followed by freeze-drying for two days. The  $a_w$  of the samples was checked throughout storage and it was considered that equilibrium was reached after the measured  $a_w$  did not change.

### Pellet Characterization

The  $a_w$  of the equilibrated pellets was measured by inserting one pellet into the measuring cell of a hygrometer (Rotronic Hygroscop DT, Huntington, NY). The readings were made after the value displayed by the hygrometer stabilized. The hygrometer was calibrated using salt solutions with known  $a_w$  values. The measured  $a_w$  values were used further in the study.

The moisture content of the native amylopectin and extruded samples was measured by air-drying for 2 hr at  $135^\circ C$  (Thermolyne Oven Series 9000, Approved Method 44-19, AACC 2000).

The porosity of the pellets was calculated as

$$\text{Porosity} = 1 - (\text{bulk density/solid density}) \quad (1)$$

The bulk density was determined as the ratio between sample mass and volume. The volume was determined using the displacement method with glass beads of 0.5 mm diameter (Biospec Products). The volume measurements were made on 10 samples at a time for accurate results. The solid density of the extruded amylopectin ( $1,514 \text{ kg/m}^3$ ) was taken from Cisneros (1999), who measured it with a He stereopycnometer (Quantachrome SPY-2, Syosset, NY).

The degree of expansion (DE) was expressed as the relative volume change

$$DE = dV/V_i \quad (2)$$

where,  $dV = (V_f - V_i)$ ,  $V_f$  – final volume,  $V_i$  – initial volume.

### Thermal Analysis

The glass transition temperature ( $T_g$ ) and the heat capacity ( $C_p$ ) of the unexpanded pellets were measured by differential scanning calorimetry (DSC) using a TA 4000 thermal analysis system with a DSC 30-S cell and a TC11 TA processor (Mettler Instrument, Highstown, NJ). The calorimeter was calibrated using the specific fusion heat of indium as a reference at a heating rate of  $5^\circ C/min$ . To avoid moisture evaporation during heating, the samples were inserted in stainless steel medium-pressure crucibles (Mettler). Samples of  $\approx 40$  mg were introduced in the crucibles, which were then hermetically sealed and inserted in the furnace of the calorimeter. The heating rate used for the measurements was  $10^\circ C/min$ . The  $T_g$  was determined as the midpoint of the step change in heat capacity, using GraphWare TA 72 software (Mettler). Because the  $T_g$  partially interfered with a sub- $T_g$  relaxation, all the samples were rescanned immediately after the first scan to erase the thermal history and to confirm the location of the  $T_g$ . For each sample, two replicates were made and the average of the  $T_g$  values obtained in the first scan was used in the study.

### Microwave Expansion

The pellets were expanded in a constant power microwave oven at 600W and 2,450 MHz (AVCTM-80 moisture-solids analyzer, CEM Corporation). The dimensions of the microwave oven cavity were  $38.1 \times 31.7 \times 19.1$  cm. The oven was equipped with a microbalance with a sensitivity of  $10^{-4}$  g. An incorporated microcomputer processed the weight loss data acquired from the electronic balance during the microwave heating of the samples. At the end of heating, the percentage weight loss was displayed on the digital screen of the oven. The pellets were placed individually in the microwave oven and expanded by heating them for 0, 5, 10, 15, 20, 30, 40, 50, and 60 sec, respectively.

### Temperature Measurements

To obtain information about the thermal history of the pellets during microwave heating, surface temperature measurements were made with an IR camera (Probeye thermal video system, model 7300). The infrared imager was attached to an image processor and a color video monitor (Sony, PVM-1344Q). The surface temperature was represented on the screen by a high-contrast eight-

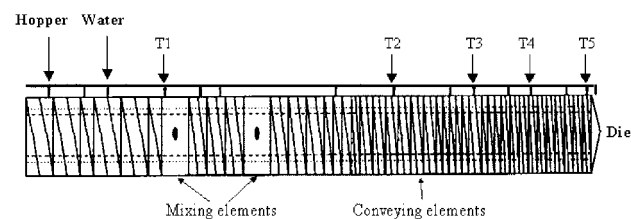


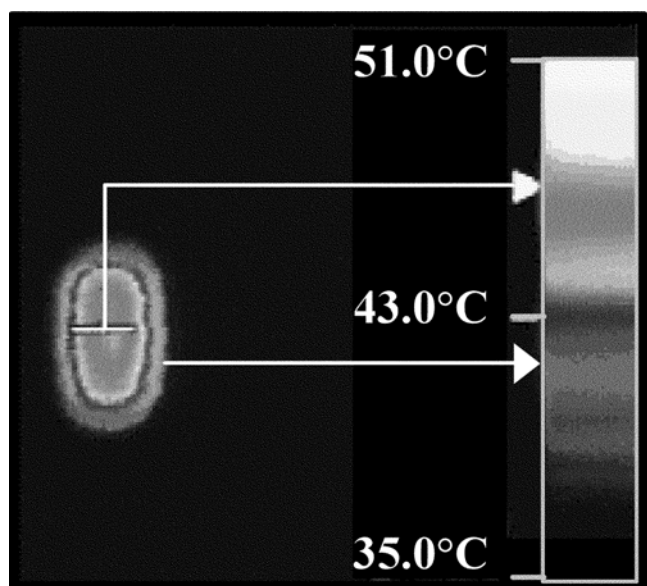
Fig. 1. Screw configuration for extrusion of pellets.

color scale. Triplicate measurements demonstrated the reproducibility of the results. Because it was not possible to take pictures through the opaque door of the microwave oven, the sample temperature was measured within  $\approx 5$  sec after opening the door.

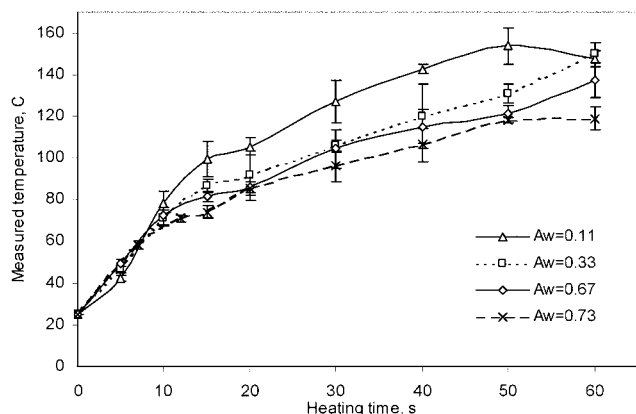
## RESULTS AND DISCUSSION

### Temperature Distribution Inside Pellets

Obtaining accurate temperature measurements during microwave heating of glassy products is a challenging task because fiber optics cannot be used. Tong et al (1992) performed temperature measurements during microwave heating of bread through the screen of a microwave oven door using an IR camera. By calibration performed with a Luxtron fluoroptic temperature sensing unit, they showed that the measured temperatures were higher than the real ones due to the effect of screen heating. In the present work, the IR measurements were performed after opening the microwave oven door, so it is expected that the temperature measurements were not very accurate, especially at higher temperatures, due to evaporative and convective cooling. Measurement of product temperature after cessation of microwave heating was reported previously by Yoshida and Kajimoto (1989) for microwave heating of soybean in a system that also did not allow direct measurements during the process. Another concern regarding the accuracy of the IR temperature measurements is the difference between the measured surface



**Fig. 2.** Surface temperature measurement using the IR camera ( $a_w$  0.67, extrusion condition 3, heating time 5 sec). Temperature decreases from center to periphery.



**Fig. 3.** Measured temperature vs. heating time at different  $a_w$  levels (extrusion condition 1).

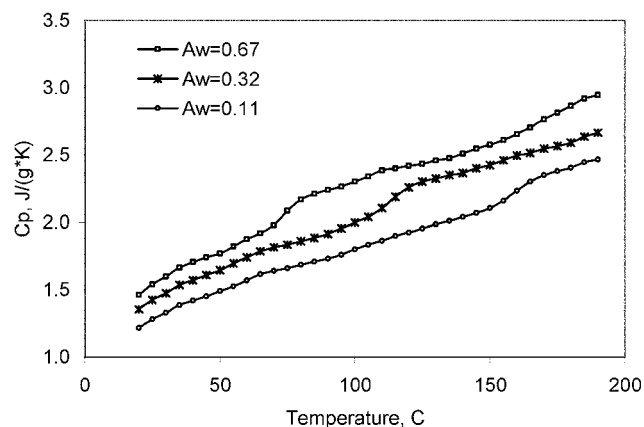
temperature and the temperature in the center of the samples. Tong and Lund (1993) have shown that the surface temperatures during microwave heating of bread samples were significantly lower than the center temperatures because of evaporative and convective cooling. Due to the above-mentioned limitations, the temperature data obtained in this study will be interpreted mostly qualitatively.

The temperature distribution in the microwave heated pellets showed that the temperature was the highest in the center and the lowest at the periphery (Fig. 2). Similar temperature distributions were reported for the microwave heating of cylindrical samples of agar (Van Remmen et al 1996) and potato tissue (Chen et al 1993). According to Buffler (1993), when microwave rays with penetration depths bigger than the dimensions of the heated sample enter the product through all surfaces, they concentrate in the central region, leading to a local increase in temperature. On the other hand, Goedeken (1994) and Tong et al (1992) stated that although according to Lambert's Law during the microwave heating of slabs the center should be the coldest spot, the effects of conduction and surface cooling tend to even out the temperature difference. For a thin slab, microwaves incident on one face are reflected from the other face of the slab, leading to power absorption patterns that cannot be described by Lambert's Law (Datta 2001) and can explain why the hottest temperature was recorded in the center of the pellet.

The pellet temperature increased abruptly with heating time for the first 10 sec, after which the rate of increase slowed down, approaching a plateau toward the end of the heating period (Fig. 3). Initially, all samples heated similarly, but after the first 10 sec, the pellets with lower  $a_w$  heated up faster than those with higher  $a_w$ . A similar behavior was reported by Yoshida and Kajimoto (1989) for the microwave heating of soybean. It is well known that the presence of water plays a major role in the microwave heating of food matrices. However, when the viscosity of the system is high (i.e., at low moisture contents), water mobility is low and the conductive heat transfer plays a significant role in the heating process (Cowburn 1994). Because the heat capacity of the amylopectin pellets was smaller at lower  $a_w$  (Fig. 4), conductive heating was higher in the low  $a_w$  samples as compared with the high  $a_w$  samples, which explains the high temperature of the low  $a_w$  pellets. On the other hand, it is likely that the high  $a_w$  samples have undergone more intense evaporative cooling than the low  $a_w$  samples, which further decreased their temperature.

### Microwave Expansion and Factors of Influence

When subjected to microwave heating, the pellets started to expand from the center (Fig. 5) regardless of extrusion conditions and initial  $a_w$ . Their volume increased for the first 30 sec of heating, after which samples started to burn, also from the center. This can be observed a darker region in Fig. 5 where the center of the samples heated  $>30$  sec. Simultaneously with expansion, the



**Fig. 4.** Heat capacity (determined by differential scanning calorimetry) as a function of temperature for amylopectin samples at different  $a_w$  levels.

samples lost weight (Fig. 6); it was considered that for the first 30 sec, before burning in the center was observed, the weight loss was solely due to moisture loss. The samples with higher  $a_w$  showed a faster and quantitatively higher moisture and weight loss, which is similar to the behavior reported by Yoshida and Kajimoto (1989) for the microwave heating of soybean.

The dynamics of expansion showed an initial sharp increase, followed by a plateau after 30 sec of heating (Fig. 7). Higher degree of expansion was observed for the samples with higher initial  $a_w$  and moisture content. The effect of moisture on expansion can be related to the mechanical properties of the matrix: a pellet expands easier if its mechanical resistance is low, which is the case at high moisture content. This is consistent with the findings of Chen and Yeh (2000), who showed that expansion ratio was inversely related to the intrinsic viscosity of rice pellets. For the samples with  $a_w$  0.73, a decrease in volume occurred after maximum expansion took place. At this  $a_w$ , the maximum expanded matrix collapsed because it did not have enough mechanical resistance to withstand the superheated steam pressure.

As shown in Fig. 8, a good correlation between expansion and moisture loss was obtained for all  $a_w$  and extrusion conditions. Expansion increased with moisture loss following a second-order polynomial relationship ( $R^2 = 0.86$ ). This curve showed that maximum expansion without collapse corresponds to moisture losses of 10–12% (db). This is consistent with the findings of Lee et al (2000), Chen and Yeh (2000), and Ermoût et al (2002), who reported that maximum microwave expansion of cereal pellets occurred at  $\approx 10\%$  mc.

Although this study did not focus on the effect of microwave power on expansion, preliminary data obtained at different power levels indicated that expansion and burning increased with the

delivered power. This is probably due to higher temperatures achieved inside the pellets at higher microwave power, which is consistent with the findings of Tong et al (1992), Tong and Lund (1993), and Khraisheh et al (1997), who reported a linear increase of absorbed power and temperature in the heated matrix with microwave power.

For the experimental conditions used in this study, expansion was not influenced by the extrusion SME (483–846 kJ/kg). This can be due to the relatively limited range of extrusion SME used, which did not change dramatically the properties of the pellets in terms of starch conversion and fragmentation. Although the degree of starch conversion was not determined, it was assumed that under the extrusion condition used, starch was fully gelatinized (based on the studies of Cisneros [1999], and Cisneros and Kokini [2002a,b]). Regarding starch fragmentation, DSC measurements showed that for the limited SME range and relatively high extrusion moisture content (35–40%) used, there was no influence of the extrusion conditions on the  $T_g$  of the amylopectin pellets. Figure 9 shows an example of DSC thermogram and  $T_g$  analysis. A linear dependency between the  $T_g$  of extruded amylopectin and  $a_w$  was found (Fig. 10), which is common to many amorphous foods in the  $a_w$  range of 0.1–0.8 (Roos 1995). The “insensitivity” of  $T_g$  to extrusion conditions is consistent with the findings of Gropper et al (2002), who reached a similar conclusion when extruding a mixture with 33% starch and 31% water and SME in the range of 344–2,108 kJ/kg. Because the  $T_g$  was the same for all extrusion conditions, this means that all extrudates had similar degrees of starch fragmentation and therefore similar melt viscosities at the same  $a_w$ . As melt viscosity controls the bubble growth during

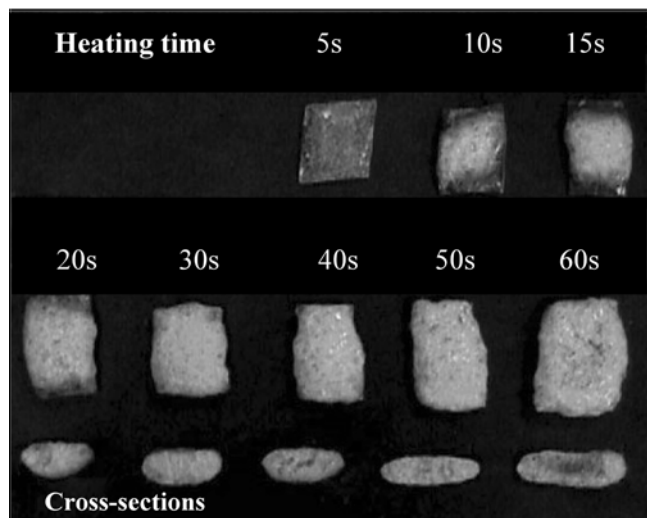


Fig. 5. Amylopectin pellets as a function of microwave heating time.

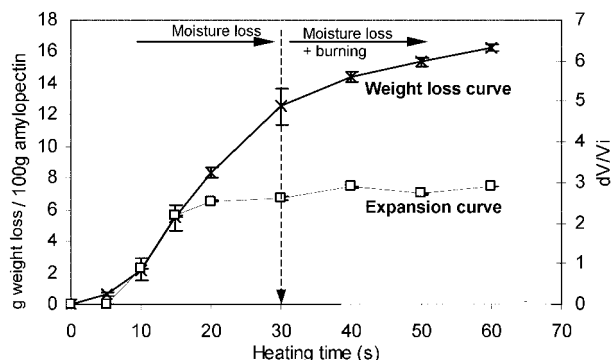


Fig. 6. Transformations during microwave heating of amylopectin pellets (extrusion condition 1,  $a_w$  0.67).

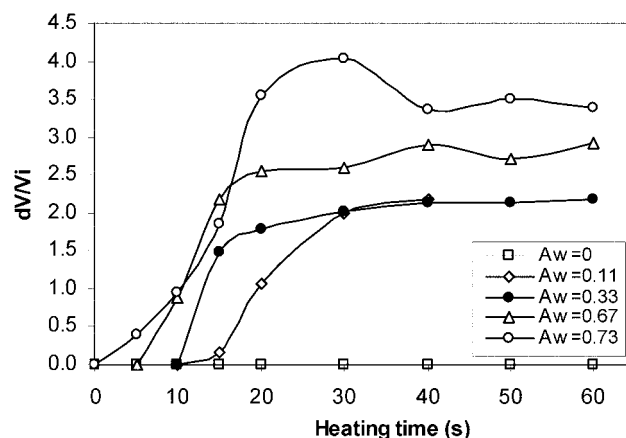


Fig. 7. Expansion vs. heating time at different  $a_w$  levels (extrusion condition 3).

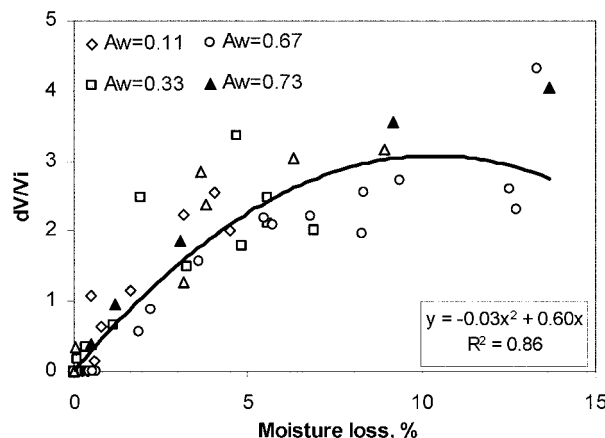


Fig. 8. Expansion vs. moisture loss for all extrusion conditions and initial pellets  $a_w$  level (data collected for the first 30 sec of heating). Trendline pertains to the cumulative data.

expansion, it is then expected that all extrudates will expand similarly.

Although the entrapped air is considered to have an important role in bubble nucleation, and thus in expansion (Cisneros 1999; Cisneros and Kokini 2002a), no relationship was found between the porosity of the unexpanded pellets (0.138–0.321) and the expanded volume. Hosoney et al (1992), who examined nucleation in third-generation wheat starch extrudate rods, indicated that the starch hilum was the main nucleation site, while air bubbles in the extrudates were the nucleation sites for the large cells. Additionally, it is possible that the free volume of the starch polymer acts as a nucleation site. While the entrapped air and porosity may play a role in nucleation and expansion, it is possible that the other nucleation sites mentioned above play the major role, which can explain the apparent lack of correlation between porosity and expansion.

### Mechanism of Microwave Expansion

Cell growth during expansion is governed by the biaxial extension of the cell walls, and the capacity of the amorphous walls to deform is due to its transition to the rubbery and flow states during heating (Kokini et al 1992; Schwartzberg et al 1995; Della Valle et al 1997; Aguilera and Stanley 1999). Based on their experiments on hot oil puffing of nonexpanded pellets, Della Valle et al (1997) defined the temperature at which bubbles appear ( $T_{bo}$ ) as a  $T_g$ . Chen and Yeh (2000), studying the expansion of rice pellets, stated that the expansion temperature would be in the range of  $T_g$  to  $T_g + 100^\circ\text{C}$ . They obtained evidence that the expansion temperature ( $T_e$ ) increased linearly with  $T_g$ .

In this study, it was observed that expansion occurred later for the samples with low  $a_w$  (Fig. 8), despite the fact that they heated

up faster than those with higher  $a_w$ . The expansion temperature ( $T_e$ ) was taken as the surface temperature at full expansion, because that was the moment when the surface layer of the pellets expanded. Although the temperature measurements were subjected to some degree of experimental error, a good correlation between the expansion temperature and the  $T_g$  of the pellets was obtained (Fig. 11). An accurate measurement of  $T_e$  in the glassy matrix would be required to obtain an accurate, quantitative relationship between  $T_e$  and  $T_g$ .

Therefore, one can hypothesize that during microwave expansion of cereal pellets moisture is the factor that initiates heating and generates the superheated steam necessary for expansion, while the glass to rubber transition of the starch matrix is the phenomenon that allows expansion and formation of the final structure. Upon microwave heating, when the temperature exceeds the boiling point of water, the water contained by glassy amylopectin pellets is transformed into superheated steam. The vapors accumulate at nuclei in the glassy matrix, creating a locally high pressure. As the cereal matrix undergoes a phase transition from glassy to rubbery state during heating, it starts to yield under the high superheated steam pressure, and expansion takes place. As moisture is lost from the matrix, or upon cessation of microwave heating, the matrix reverts to the glassy state, where the mechanical resistance is high enough to maintain the shape of the formed cells. If the matrix is too soft, which is the case of the high moisture  $a_w$  samples, collapse occurs. If heating continues after all the moisture is eliminated from the matrix, samples begin to burn. This hypothesis is summarized on the state diagram shown in Fig. 12.

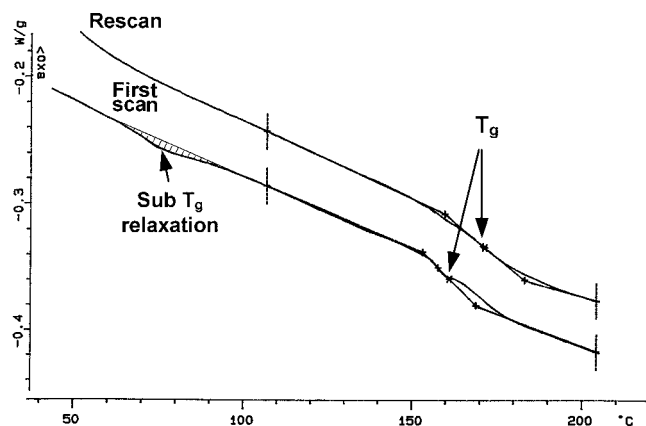


Fig. 9. Differential scanning calorimetry thermograms for extruded amylopectin (extrusion condition 2,  $a_w$  0.11).

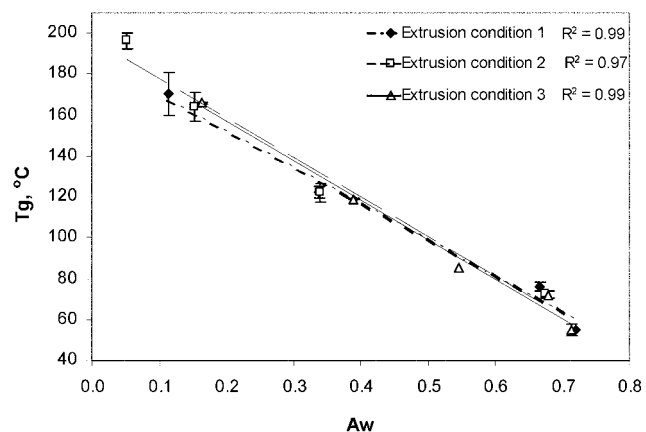


Fig. 10.  $T_g$  vs.  $a_w$  for amylopectin pellets for all extrusion conditions.

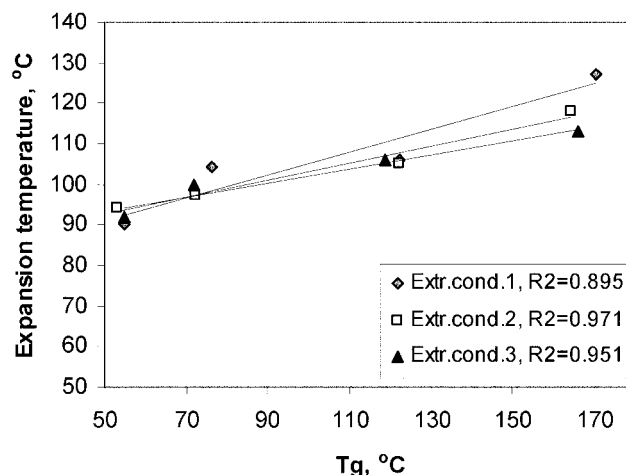


Fig. 11. Correlation between  $T_g$  and surface temperature at full expansion ( $T_e$ ).

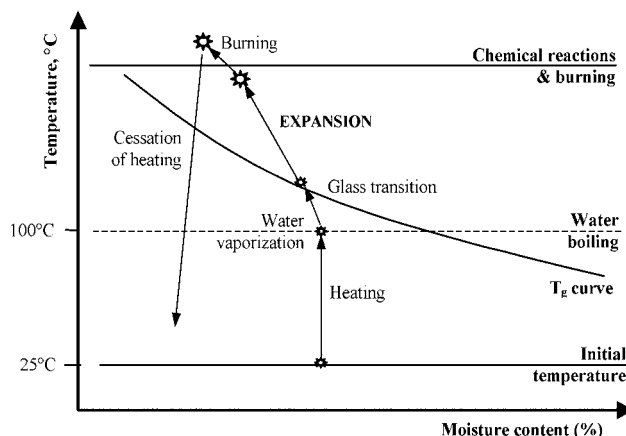


Fig. 12. State diagram for microwave expansion of unexpanded amylopectin extrudates

## CONCLUSIONS

Further understanding of the factors and mechanisms involved in microwave expansion of cereal pellets adds to the knowledge base that currently exists in the domain of expansion. Besides their theoretical value, the findings of this study can be used by the food industry as a base for the development of microwavable snacks of desired texture, shape, and composition.

## ACKNOWLEDGMENTS

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## LITERATURE CITED

American Association of Cereal Chemists. 2000. Approved Methods of the AACC, 10th ed. The Association: St. Paul, MN.

Aguilera, J. M., and Stanley, D. W. 1999. Microstructural principles of food processing and engineering, 2nd Ed. Aspen Publishers: Gaithersburg, MD.

Bernussi, A. L. M. 1998. Effects of production by microwave heating after conventional baking on moisture gradient and product quality of biscuits (cookies). *Cereal Chem.* 75:606-611.

Buffler, Ch. R. 1993. Microwave Cooking and Processing. Van Nostrand Reinhold: New York.

Chen, C. M., and Yeh, A. L. 2000. Expansion of rice pellets: examination of glass transition and expansion temperature. *J. Cereal Sci.* 32:137-145.

Chen, D. S. D., Singh, R. K., Haghighi, K., and Nelson, P. E. 1993. Finite element analysis of temperature distribution in microwaved cylindrical potato tissue. *J. Food Eng.* 18:351-368.

Cisneros, F. H. 1999. Air bubble nucleation during starch extrusion. PhD thesis. Rutgers, The State University of New Jersey: New Brunswick, NJ.

Cisneros, F. H., and Kokini, J. L. 2002a. A generalized theory linking barrel fill length and air bubble entrapment during extrusion of starch. *J. Food Eng.* 51:139-149.

Cisneros, F. H., and Kokini, J. L. 2002b. Effect of extrusion operating parameters on air bubble entrapment. *J. Food Process Eng.* 25:251-283.

Cowburn, P. 1994. The Role and Function of Starches in Microwaveable Food Formulation. National Starch: Bridgewater, NJ.

Datta, A. K. 2001. Fundamentals of heat and moisture transport for microwaveable food product and product development. In: Handbook of Microwave Technology for Food Application. A. K. Datta and R. C. Anantheswaran, eds. Marcel Dekker: New York.

Della Valle, G., Vergnes, B., Colonna, P., and Patria, A. 1997. Relations between rheological properties of molten starches and their expansion behaviour in extrusion. *J. Food Eng.* 31:277-296.

Ernoul V., Moraru C. I., and Kokini J. L. 2002. Influence of fat on the expansion of glassy amylopectin extrudates by microwave heating. *Cereal Chem.* 79:265-273.

Fan, J., Mitchell, J. R., and Blanshard, J. M. V. 1994. A computer simulation of the dynamics of bubble growth and shrinkage during extrudate expansion. *J. Food Eng.* 23:337-356.

Godavarti, S., and Karwe, M. V. 1997. Determination of specific mechanical energy distribution on a twin-screw extruder. *J. Agric. Eng. Res.* 67:277-287.

Goedeken, D. L. 1994. Microwave baking of bread dough with simultaneous heat and mass transfer. PhD thesis. Rutgers, The State University of New Jersey: New Brunswick, NJ.

Gropper M., Ramon, O., Kopelman, I. J., and Mizrahi, S. 1997. Effects of microwave reheating on surimi gel texture. *Food Res. Int.* 30:761-768.

Gropper, M., Moraru, C. I., and Kokini, J. L. 2002. The effect of specific mechanical energy on the properties of extruded protein/starch mixtures. *Cereal Chem.* 79:429-433.

Hoseney, R. C., Mason, W. R., Lai, C. S., and Guetzlaff, J. 1992. Factors affecting the viscosity and structure of extrusion-cooked wheat starch. In: Food Extrusion Science and Technology. J. L. Kokini, C.-H. Ho, and M. Karwe, eds. Marcel Dekker: New York.

Khraisheh, M. A. M., Cooper, T. J. R., and Magee, T. R. A. 1997. Microwave and air drying I. Fundamental considerations and assumptions for the simplified thermal calculations of volumetric power absorption. *J. Food Eng.* 33:207-219.

Kokini, J. L., Chang, C. N., and Lai, L. S. 1992. The role of rheological properties on extrudate expansion. In: Food Extrusion Science and Technology. J. L. Kokini, C.-H. Ho, and M. Karwe, eds. Marcel Dekker: New York.

Lee, E. Y., Lim, K. I., Lim, J. K., and Lim, S. T. 2000. Effects of gelatinization and moisture content of extruded starch pellets on morphology and physical properties of microwave expanded products. *Cereal Chem.* 77:769-773.

Lin, Y. E., and Anantheswaran, R. C. 1988. Studies on popping of popcorn in a microwave oven. *J. Food Sci.* 53:1746-1749.

Mohamed, A. A., Ashman, R. B., and Kirleis, A. W. 1993. Pericarp thickness and other kernel physical characteristics relate to microwave popping quality of popcorn. *J. Food Sci.* 58:342-346.

Mudgett, R. E. 1982. Electrical properties of foods in microwave processing, *Food Technol.* 36:109-115.

Mudgett, R. E. 1989. Microwave food processing. *Food Technol.* 43:117-126.

Osman, M. G., Sahai, D., and Jackson, D. S. 2000. Oil absorption characteristics of a multigrain extrudate during frying: effect of extrusion temperature and screw speed. *Cereal Chem.* 77:101-104.

Pordesimo, L. O., Anantheswaran, R. C., Fleischmann, A. M., Lin, Y. E., and Hanna, M. A. 1990. Physical properties as indicators of popping characteristics of microwave popcorn. *J. Food Sci.* 55:1352-1355.

Pordesimo, L. O., Anantheswaran, R. C., and Mattern, P. J. 1991. Quantification of horny and floury endosperm in popcorn and their effects on popping performance in a microwave oven. *J. Cereal Sci.* 14:189-198.

Roos, Y. H. 1995. Phase Transitions in Foods. Academic Press: New York.

Schiffmann, R. F. 1993. Understanding microwave reactions and interactions. *Food Product Design* April:72-88.

Schwartzberg, H. G., Wu, J. P. C., Nussinovitch, A., and Mugerwa, J. 1995. Modelling deformation and flow during vapor-induced puffing. *J. Food Eng.* 25:329-372.

Shachat, M. A., and Raphael, S. J. 1990. Process for making microwave puffed snack products. US patent, 4,950,492.

Shukla, T. P. 2000. Modern snack foods. *Cereal Foods World* 45:477.

Spratt, W. A., Timbers, G. E., and Paton, D. 1988. Microwave-puffable half-products of starch-containing material and their production process. European patent EP0312363.

Suknark, K., Phillips, R. D., and Huang, Y. W. 1999. Tapioca-fish and tapioca-peanut snacks by twin-screw extrusion and deep-fat frying. *J. Food Sci.* 64:303-308.

Tong, C. H., and Lund, D. B. 1993. Microwave heating of baked dough products with simultaneous heat and moisture transfer. *J. Food Eng.* 18:319-339.

Tong, C. H., Sheen, S. A., Fu, Y. F., Goedeken, D. L., and Lund, D. B. 1992. Microwave heat transfer in food. Pages 149-163 in: Advances in Food Engineering. P. Singh and M. A. Wirakartakusumah, eds. CRC Press: Boca Raton, FL.

Van Hulle, G. J., Anker, C. A., and Franssell, D. E. 1981. Food composition and method for preparing cheese-coated, puffed snacks upon microwave heating. US patent 4,251,551.

Van Hulle, G. J., Anker, C. A., and Franssell, D. E. 1983. Method for preparing sugar-coated, puffed snacks upon microwave heating. US patent 4,409,250.

Van Lengerich, B. H., Ringwood, C. L., and Plains, M. 1989. Filled, microwave expandable snack food product and method and apparatus for its production. US patent 5,124,161.

Van Remmen, H. H. J., Ponne, C. T., Nijhuis, H. H., Bartelis, P. V., and Kerkhof, P. J. A. M. 1996. Microwave heating distributions in slabs, spheres and cylinders with relation to food processing. *J. Food Sci.* 61:1105-1113.

Wang, S. W. 1997. Starch and starch derivatives in expanded snacks, *Cereal Foods World* 42:743-745.

Yoshida, H., and Kajimoto, G. 1989. Effects of microwave energy on the tocopherols of soybean seeds. *J. Food Sci.* 54:1596-1600.

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