A Review of Puffing Processes for Expansion of Biological Products

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ABSTRACT

A research objective to develop a puffing process which would improve the rehydration characteristics of air-dried fruits and vegetables led to a review of puffing processes described in the US patent and published literature. The puffing processes found were classified into four categories based on the method responsible for gas evolution: phase change, absorption, adsorption, and chemical reaction. An explosive expansion rate E was calculated for different puffing processes in each category. It appears that E must be in the range 0·05–12 m^3/s kg to puff biological products.

INTRODUCTION

A puffing process is being sought to improve the rehydration characteristics of air-dried fruits and vegetables for use in convenience products. The goal of the research is to produce improved air-dried products which would compete with the more expensive and higher-quality freeze-dried products. The search for this process led to a review of puffing processes which are used to puff cellular or fabricated biological products.

A puffing process involves the release or expansion of a gas within a product either to create an internal structure or to expand or rupture an existing structure. Puffing has been used since ancient times to alter the structural characteristics of foods. Puffed or expanded rice has been a popular snack in India for centuries (Murugesan & Bhattacharya, 1986), where moistened grains are puffed by a high-temperature, short-time heat treatment (usually produced using sand heated to about 200°C).

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Popcorn, another puffed product, is thought to have been introduced to early American settlers by the Indians (Eldredge & Thomas, 1959). Probably the oldest example of a puffing process is the raising of bread.

During the early 1900s puffing techniques became an integral part of the ready-to-eat cereal industry in the United States when batch steam systems were developed for puffing wheat and rice. Fabricated starch-based products in a variety of shapes, colors, and textures followed. Continuous steam puffing systems have been developed to replace batch systems for cereals. These provide better control over processing conditions and produce more uniform products (Clark, 1986). In recent years, the extrusion process has become a popular process for producing puffed or expanded cereals, snacks, pet foods, and meat analogs from starch- or protein-based raw materials (Stanley, 1986).

A system for explosion puffing was reported by Sullivan *et al.* (1965). This process has been investigated and applied commercially to the processing of fruits and vegetables (Sullivan & Craig, 1984). The improvement in functional characteristics of the dehydrated product, particularly its rehydration rate, is the main objective of this process, although other benefits such as increased drying rate, appearance, etc., may arise from the process. This explosion puffing system heats a product with super-heated steam, holds it under pressure for a given time, and then releases the pressure suddenly to puff the product. The original batch process has been developed into a continuous process and used to puff celery (Sullivan & Cording, 1969), carrots (Sullivan *et al.*, 1981), apples (Sullivan *et al.*, 1980), blueberries (Sullivan *et al.*, 1982), and potatoes (Sullivan *et al.*, 1977).

During the energy crisis of the 1970s, puffing processes were investigated as a pretreatment process for separating the cellulose fibers of wood and increasing the hydrolysis of cellulose to glucose. Schultz *et al.* (1983) reported on the steam explosion of mixed hardwood chips. The wood chips were separated into fibers by the rapid expansion of steam upon pressure release. Dale and Moreira (1982) reported on the novel development of an ammonia freeze–explosion process where cellulose fibers were saturated with ammonia and the ammonia discharged rapidly. It appeared that the boiling of ammonia upon rapid decompression disrupted and expanded the fiber structure.

The tobacco industry has developed a number of sophisticated processes since the mid-1960s for expanding (puffing) tobacco, tobacco stems, and tobacco sheets reconstituted from fines. The high market value of tobacco products can easily justify these expensive processes; however, the same may not be true for lower-value food products.

In the case of bread the gas released during the raising of the dough and subsequent baking of bread is responsible for the formation of

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bread's internal porous structure. The carbon dioxide gas is released slowly within the dough and creates the familiar cell structure of bread. The dough expands easily as the restraining product forces are small when compared with those of vegetable cells, etc.

Evaluation of puffing processes described in the literature leads to a logical classification of puffing into four categories based on the methods responsible for gas evolution within the product:

I—phase change,
II—absorption,
III—adsorption,
IV—chemical reaction.

These four methods will be discussed in detail and an effort made to compare the methods quantitatively. A better understanding of the methods responsible for puffing and appropriate for puffing fruits and vegetables should result. It will be observed in the examples discussed later that, in reality, more than one method may be responsible for the puffing action. The following quantities will be evaluated for each method by observing the change occurring from the beginning to the end of the process:

ΔV, the change in volume of the system per unit mass;
$E = \Delta V/\Delta t$, the explosive expansion rate, i.e. change in volume of the system per unit time per unit mass.

Free expansion, i.e. no material resistance, and chemical and thermal equilibrium are assumed, to simplify the calculation of ΔV. In the following discussion, a unit mass of product is defined as a unit of mass before expansion.

I—PHASE CHANGE

A phase change is the most commonly used and effective method for expanding products because of the large change in volume associated with a change in phase. A water-based system is used to puff many products, such as breakfast cereals (Clark, 1986), snacks (Gutcho, 1973), fruits and vegetables (Sullivan & Craig, 1984), and textured vegetable proteins (Harper, 1981). Steam puffing is a result of flash volatilization of water to steam upon the sudden release of pressure. It should be noted that such water-based processes also impart a thermal treatment to the product, which in most cases is an essential element for cooking or plasticizing the product before expansion. The thermal treatment can be avoided by use of a vacuum. Moy (1971) describes a vacuum-puffing process for dehydrating thermally-sensitive tropical fruit juices.

An expanding gas can be produced from materials other than water. The literature contains references to ammonia freeze–explosion (Dale & Moreira, 1982) which was used to disrupt the internal structure of cellulose to improve enzymic hydrolysis, and carbon dioxide (Sykes et al., 1985) and Freon (Fredrickson, 1981) which were used to expand tobacco.

Extrusion-cooking

An energy balance on an extruded product before and after puffing can determine the mass of steam released and thus the volume expansion. The mass of steam evaporated is calculated by the following equation (rearranged from Harper (1981)):

$$\Delta M = \frac{c_p(T_1 - T_2)}{h_{fg}} \tag{1}$$

where ΔM is the mass of steam evaporated upon puffing per unit mass of extrudate prior to puffing (kg steam/kg product), c_p is the specific heat of extrudate ($= 1.83$ kJ/kg K), h_{fg} is the latent heat of evaporation of water at 100°C ($= 2257$ kJ/kg), T_1 is the product temperature before puffing (°C), and T_2 is the product temperature after puffing (100°C).

The volume change per unit mass is thus

$$\Delta V = \frac{\Delta M}{\rho_s} \tag{2}$$

where ρ_s is the density of steam at 1 atm pressure and 100°C ($= 0.60$ kg/m³). Substituting eqn (1) into (2) gives

$$\Delta V = \frac{c_p(T_1 - T_2)}{\rho_s h_{fg}} \tag{3}$$

The value of ΔV for an extruded product at 190°C and using the above values for enthalpy, specific heat, and steam temperature was calculated to be 0.12 m³/kg.

The explosiveness of the process is measured by the rate of this volumetric expansion. In an extruder the product passes from a high-pressure region to nearly atmospheric pressure as it flows through a die. Making a simplifying assumption that all the steam expansion occurs during this passage simplifies the calculation of E. Residence time in the

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die of a cooker-extruder was calculated from data presented by Harper (1981) to be in the region of 10 ms. Howkins *et al.* (1986) studied extrusion die swelling of starch doughs with die residence times of up to 0·42 s. Assuming a range of Δt from 10 ms to 0·4 s gives a range of E from 12 to 0·3 m³/s kg.

Steam explosion puffing

Typical moisture contents for the explosion puffing of fruits and vegetable products range between 14 and 35% wb (Sullivan & Craig, 1984). Product moisture is not constant in this type of system as condensation may occur on the product while the product temperature is raised to the saturation temperature of the steam. Some control over the amount of condensation is achieved by superheating the steam (Sullivan *et al.*, 1965). Apples were puffed using steam temperatures of 154–185°C and pressures of 62–124 kPa (Sullivan *et al.*, 1980).

The value of ΔV for the steam puffing system is calculated with eqn (3), and would be of the same order of magnitude as for the extrusion process. The value for E, however, can only be estimated because the decompression time was not reported. Assuming that this time would be in the range 10 ms–0·5 s then the value of E would range between 12 and 0·24 m³/s kg.

Volatile organic liquid puffing

Fredrickson (1981) described the use of several volatile organic liquids for puffing cured and cut tobacco. Freon-12 was one of several presented as examples. Tobacco was saturated with Freon-12 under pressure slightly above saturation pressure. Upon release of pressure to atmospheric, the tobacco was cooled to −30°C. Then steam at 100°C was passed through the tobacco for 2 min to vaporize the Freon and puff the tobacco rapidly. The bulk density of the tobacco was reportedly decreased by about 46·8%.

Steam heating provides a powerful thermal driving force to evaporate the residual Freon. The volumetric change, ΔV, of Freon-12 can be estimated if it is assumed that no moisture is removed in the process and the Freon vapor leaves the product at −30°C. The volume of Freon gas released is a function of the amount present in the tobacco, thus

$$\Delta V = \frac{C_v}{\rho_y} \qquad (4)$$

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where C_v is the concentration of volatile organic liquid (kg per kg moist tobacco), and ρ_v is the density of volatile organic gas at atmospheric pressure and saturation temperature ($= 2\cdot9$ kg/m^3 at -30°C for Freon).

Assuming that cut tobacco is saturated with 1 kg of Freon per kg of moist tobacco, results in a ΔV of $0\cdot34$ m^3/kg. The rate of heat transfer to the tobacco particle determines the rate of Freon release. Assuming the tobacco lamina has a thickness of $0\cdot635$ mm, a thermal diffusivity of $4\cdot3 \times 10^{-8}$ m^2/s (Duncan *et al.*, 1968) and a Biot number of $0\cdot0$, then the time required for the pure conduction heating to heat the center of the lamina to 90% of the temperature difference is $2\cdot4$ s. Using this time as an estimate of Δt gives an E of $0\cdot14$ m^3/s kg. As this process is transient, the initial expansion rate could be an order of magnitude greater. The rate of gas generation depends on the rate at which external heat is transferred into the tobacco particle. $\dot{E}$ would probably follow an exponential curve with time resulting from heat penetration into the tobacco particle and be highly dependent on particle size of the tobacco.

Carbon dioxide puffing

Carbon dioxide has received considerable attention as a puffing agent for tobacco, and is currently being used to expand or puff tobacco to 'improve' the fill in cigarettes (Sykes *et al.*, 1985). In this patent, the tobacco is saturated with 1–10 parts liquid carbon dioxide per part tobacco under pressure for a period of $0\cdot1$–30 min, the excess liquid carbon dioxide drained, and the pressure released, thus converting a fraction of the residual carbon dioxide in the cells to dry ice. The tobacco preferably contains 10–20% by weight of solid carbon dioxide. The tobacco was then exposed to a hot gas in the temperature range 150–315°C, such as steam-heated air, for a period of about $0\cdot1$–10 s and puffed by the rapid expansion of the subliming carbon dioxide. The volumetric release of gas in the above process ranged between $0\cdot045$ and $0\cdot09$ m^3/kg for this range of dry ice concentration. The expansion rate for a heating contact time of $0\cdot1$–10 s would range between $0\cdot045$ and $0\cdot9$ m^3/s kg.

A related process was patented for puffing fruits. Popper *et al.* (1977) patented a process for producing puffed fruit in which partially dehydrated cubes of fruit (approximately 1 cm side) were submerged in liquid carbon dioxide at 900–1000 psig for $0\cdot5$–6 h. The fruit was puffed 'about three times' upon the gradual (10–20 min) release of pressure. Generally, $0\cdot1$–10 parts of liquid carbon dioxide was used per part of fruit.

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II—ABSORPTION

Puffing can be achieved by the reduction of the total pressure on a saturated system, causing a release of absorbed gas. A commonly experienced example of this mechanism is the release of carbon dioxide from carbonated beverages upon opening of the container. The effectiveness of this method depends on the solubility of the particular gas in the liquid, which for food puffing is almost exclusively water. The data necessary to define the solubility of a gas in a liquid must generally include the temperature, the concentration of the solute gas in the liquid phase, the pressure of the solute gas in the gas phase, and the total pressure of the system. Equilibrium solubility data can be expressed as solubility in weight or mole percent, or as the Henry's law constant. The solubility of carbon dioxide and ammonia in water are given in Tables 1 and 2 in terms of percent weight. The solubility of nitrogen and methane are given in Table 3 in terms of Henry's law constants.

TABLE 1
Solubility of Carbon Dioxide in Water (Perry & Chilton, 1973)

Total pressure (atm)	Weight of CO_2 per 100 weight of H_2O		
	12°C	25°C	50°C
25	—	—	1·92
50	7·03	5·38	3·41
75	7·18	6·17	4·45
100	7·27	6·28	5·07
200	—	—	5·76
300	7·86	—	6·20
400	8·12	7·54	6·58

TABLE 2
Solubility of Ammonia in Water at 20°C (Perry & Chilton, 1973)

Partial pressure of NH_3 (mmHg)	Weights of NH_3 per 100 weight of H_2O
12	2·0
166	20
470	40
945	60
1450	80

TABLE 3
Solubility of Methane and Nitrogen in Water (Perry & Chilton, 1973)

Temperature (°C)	Henry's law constant $(atm_A/(mol_A/mol) \times 10^{-4}$	
	N_2	CH_4
0	5·29	2·24
10	6·68	2·97
20	8·20	3·76
25	8·65	4·13
30	9·24	4·49
40	10·4	5·20
50	11·3	5·77
100	12·6	7·01

The solubility of gases in the water fraction of a food can be used in part to predict its usefulness for generating a gas upon decompression. The solubilities of nitrogen in water at 1 and 100 atm total pressure and at 25°C are calculated from Henry's law to be

$$Y_{N_2} = \frac{P_{N_2}}{H_{N_2}} = \frac{100 \text{ atm}}{8\cdot65 \times 10^4 \text{ atm}/(\text{mol N}_2/\text{mol})} \quad (5)$$

for $P_{N_2} = 100$ atm, $Y_{N_2} = 0\cdot0012$ mol N_2/mol water, and for $P_{N_2} = 1$ atm, $Y_{N_2} = 0\cdot000\,012$ mol N_2/mol water, where Y is the mole fraction dissolved, P is the pressure (atm), and H is Henry's law constant.
    Converting to a weight basis:

$$C_{N_2} = \frac{Y_{N_2}}{1 - Y_{N_2}} \times \frac{MW_{N_2}}{MW_{H_2O}} = 0\cdot0019 \text{ g N}_2/\text{g H}_2\text{O} \quad (6)$$

where MW is molecular weight.
    Thus, the change in volume of the system upon pressure reduction from 1·00 to 1 atm at 25°C is

$$\Delta V = \frac{C_{100} - C_1}{\rho_{N_2}} = \frac{(0\cdot0019 - 0\cdot000\,019) \text{ g N}_2/\text{g H}_2\text{O}}{1200 \text{ g N}_2/\text{m}^3} = 0\cdot0016 \text{ m}^3/\text{kg H}_2\text{O} \quad (7)$$

The difference between the solubilities of different gases is exemplified by comparing the above with solubilities for carbon dioxide and ammonia. Carbon dioxide has a solubility of 0·0628 g CO_2/g H_2O at

Chilton, 1973)

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100 atm and 25°C, and water will absorb about 0·50 g NH$_3$/g H$_2$O at atmospheric pressure and 20°C. The last two examples are special cases where the gas absorbed reacts chemically with the solvent. Carbon dioxide in water forms carbonic acid with the following equilibrium relationship:

$$CO_2 \text{ (dissolved)} + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-}$$
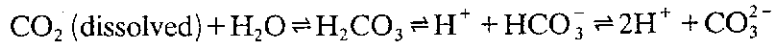
A puffing system which employs nitrogen gas decompression to puff or expand a product has an explosive expansion rate much smaller than that with carbon dioxide. A current design for a cell disruption bomb (Parr Instrument Company, Moline, IL) achieves complete disruption of cells at a pressure of 68 atm using nitrogen gas. A liquid–cell mixture is placed in a 920-ml bomb to about two-thirds of its volume and pressurized with nitrogen gas. After equilibrium, the pressure in the bomb is used to force nitrogen-saturated liquid–cell mixture through a discharge valve. The shear forces combined with the explosive decompression of nitrogen disrupt the cells. Assuming that the liquid–cell mixture passes through the valve in 10 ms, then the explosive expansion rate per unit weight of mixture is

$$E = \frac{\Delta C_{N_2}}{\Delta t \rho_{N_2}} = \frac{0\cdot0013 \text{ g N}_2/\text{g H}_2\text{O}}{(10 \text{ ms})(1200 \text{ g N}_2/\text{m}^3)} \qquad (8)$$

$$E = 0\cdot11 \text{ m}^3/\text{s kg}$$

This is small compared with the explosive expansion rates for phase change expansions but has been effective for homogenization of mammalian tissues (Hunter & Commerford, 1961), bacteria (Fraser, 1951), and plant cells (Loewus & Loewus, 1971). The combined effect of shear and gas release should be considered as responsible for the cell disruption.

Haas and Prescott (1972) saturated food products with several different gases under pressure and then froze the products (under pressure), released the pressure, and finally air-dried the product. Several of the products treated in this manner had increased volume, faster drying rates, and faster rehydration rates as compared with air-dried or freeze-dried products. These authors postulated that gas bubbles were formed in tissue cells when the product water was removed by ice crystallization during freezing. The gas then remained in the tissue during the drying step and prevented cell collapse. High diffusivity gases such as carbon dioxide, nitrous oxide and helium were found to be ineffective, whereas best results were achieved with methane, nitrogen, carbon monoxide, air, Freon-13 (CClF$_3$), and ethane.

The high solubility of gases which react with water should be considered when analyzing the expansion potential of gas. Additionally, these gases may have a delayed release of gas. The rate of desaturation is logarithmic and proportional to the concentration of gas in solution (Quinn & Jones, 1936).

The concentration of solutes in the water fraction of a food product will reduce the saturation potential of a gas, and the ionic and covalent bonds by which water is bound to the surfaces of a product will also reduce the potential for saturation of a gas.

III—ADSORPTION

Gas adsorption may occur on the external or internal surface of a product and particularly at sites which have force fields. Two types of adsorption may occur: (1) physical adsorption and (2) chemisorption (Smith, 1970).

Physical adsorption

Physical adsorption is similar to the process of condensation in that the forces of attraction are relatively weak and the molecules are concentrated in multiple layers at the surface. The amount of physical adsorption decreases rapidly with increasing temperature. Physical adsorption is dependent on surface irregularities and is usually proportional to surface area. At temperatures below the critical temperature, higher vapor pressures result in multilayer adsorption. Capillary condensation and surface physical adsorption are generally very small above the critical temperature of the adsorbed gas (Smith, 1970). The principles of physical adsorption are used to measure surface area and pore size distribution of materials.

Chemisorption

Chemisorption of a gas on to a solid surface involves much stronger forces between atoms and molecules and results in liberation of large heats of adsorption. A unique characteristic of chemisorption is its limitation to a monomolecular layer. Examples of the use of adsorption, either physical adsorption or chemisorption, as a puffing mechanism are few. A patent to Hawkins (1931) described the use of a gas which may be air, carbon dioxide or steam at 1·36 atm to pressurize tobacco followed by pressure release. The tobacco expanded by about 5–15% upon release of pressure.

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De la Burde *et al.* (1981) patented a process for the carbon dioxide puffing of tobacco. In that process, tobacco was in contact with carbon dioxide gas at a pressure of 17–72 atm for 0·25–30 min. The tobacco moisture content was preferably 8–22% wet basis. The pressure was released over 1–800 s and the residual amount of carbon dioxide remaining in the tobacco was 1–3% or more. Pre-cooling of the tobacco before or during pressurization increased the retention of gaseous carbon dioxide in the tobacco. These authors stated that 'adsorption/absorption characteristics of gaseous CO_2' are enhanced by maintaining pressurized conditions close to the saturation point. Puffing resulted when the tobacco containing carbon dioxide was rapidly heated, for instance, in a stream of heated gas at 100–370°C. Puffed volume using this process increased by some 100–150% over untreated control, i.e. from 3·6 cm^3/g for the control to 7·6 cm^3/g for de la Burde *et al.*'s (1981) Example 1.
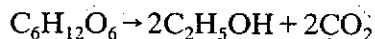
The volumetric release of gas for a tobacco product containing 1 or 3% of carbon dioxide was calculated using eqn (4) to be 0·45 or 1·35 m^3/kg respectively. As stated in the patent, the tobacco was heated at 100–370°C for 1–600 s. Assuming a Δt of 1–10 s (typically used by de la Burde *et al.*), the explosive expansion rate E should have a range of 0·000 75–1·35 m^3/s kg. The comments on transient heating apply here as well, and the transient explosive expansion rate could be an order of magnitude higher. The puffing mechanism of de la Burde *et al.*'s (1981) process may be a combination of absorption, adsorption and phase change. The primary mechanism is considered to be adsorption.

IV—CHEMICAL REACTION

Puffing a product using a chemical reaction to liberate a gas is a common mechanism employed in the baking industry, and the tobacco industry has developed several chemical reaction technologies for puffing tobacco. Carbon dioxide is the principal but not the sole gas for providing the 'raising' effect in bakery foods (Matz, 1972). Yeast fermentation and added chemical reagents are the principal sources of carbon dioxide for the baking industry.

Yeast fermentation

Yeast cells are mixed with dough and fermented under controlled environmental conditions. The most obvious chemical reaction is the conversion of sugars to ethyl alcohol and carbon dioxide, i.e.

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De la Burde *et al.* (1981) patented a process for the carbon dioxide puffing of tobacco. In that process, tobacco was in contact with carbon dioxide gas at a pressure of 17–72 atm for 0·25–30 min. The tobacco moisture content was preferably 8–22% wet basis. The pressure was released over 1–800 s and the residual amount of carbon dioxide remaining in the tobacco was 1–3% or more. Pre-cooling of the tobacco before or during pressurization increased the retention of gaseous carbon dioxide in the tobacco. These authors stated that 'adsorption/absorption characteristics of gaseous CO_2' are enhanced by maintaining pressurized conditions close to the saturation point. Puffing resulted when the tobacco containing carbon dioxide was rapidly heated, for instance, in a stream of heated gas at 100–370°C. Puffed volume using this process increased by some 100–150% over untreated control, i.e. from 3·6 cm³/g for the control to 7·6 cm³/g for de la Burde *et al.*'s (1981) Example 1.

The volumetric release of gas for a tobacco product containing 1 or 3% of carbon dioxide was calculated using eqn (4) to be 0·45 or 1·35 m³/kg, respectively. As stated in the patent, the tobacco was heated at 100–370°C for 1–600 s. Assuming a Δt of 1–10 s (typically used by de la Burde *et al.*), the explosive expansion rate E should have a range of 0·000 75–1·35 m³/s kg. The comments on transient heating apply here as well, and the transient explosive expansion rate could be an order of magnitude higher. The puffing mechanism of de la Burde *et al.*'s (1981) process may be a combination of absorption, adsorption and phase change. The primary mechanism is considered to be adsorption.

IV—CHEMICAL REACTION

Puffing a product using a chemical reaction to liberate a gas is a common mechanism employed in the baking industry, and the tobacco industry has developed several chemical reaction technologies for puffing tobacco. Carbon dioxide is the principal but not the sole gas for providing the 'raising' effect in bakery foods (Matz, 1972). Yeast fermentation and added chemical reagents are the principal sources of carbon dioxide gas for the baking industry.

Yeast fermentation

Yeast cells are mixed with dough and fermented under controlled environmental conditions. The most obvious chemical reaction is the conversion of sugars to ethyl alcohol and carbon dioxide, i.e.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

The rate of gas production based on commonly used percentages of yeast is 350 ml CO_2/h/100 g dough (Reed & Peppler, 1973). The value of E for yeast fermentation based on a unit mass of dough is thus 1.0×10^{-6} m^3/s kg. The rate of gas evolution by yeast is variable and depends on the substrate, yeast concentration and activity, and a host of other biological variables (Reed & Peppler, 1973).

Chemical reagents

Chemical leavening or baking powder will commonly generate a total of 214 ml CO_2/100 g dough (Reed & Peppler, 1973) which translates into an E of 2.4×10^{-3} m^3/s kg if the gas is assumed to be uniformly liberated over a 15-min period at the end of the baking period. Common leavening agents are sodium bicarbonate ($NaHCO_3$) and ammonium bicarbonate (NH_4HCO_3), which are both decomposed by heat to liberate carbon dioxide.

Armstrong *et al.* (1973) describe a process in which tobacco is treated with ammonia, or ammonia and carbon dioxide, or other chemical combinations to form ammonium carbonate or ammonium bicarbonate within the cells of tobacco. Impregnation of tobacco first with 3–6% by weight of ammonia and then with 2–8% by weight of carbon dioxide was found to give the desired expansion. Cooling of the tobacco is required during the impregnation step because of the exothermic heat of solution and reaction of ammonia, carbon dioxide and water. The tobacco was expanded upon heating for about 0.1–0.2 s in a hot gas which had a temperature of 260–315°C. The combined volume of carbon dioxide and ammonia gas (at STP of 1 atm and 0°C) released from the tobacco was calculated to be 0.068 and 0.216 m^3/kg for the low and high impregnation rates listed above, respectively. The range of E using the 0.1–0.2 s residence time in the hot gas for Δt is between 0.34 and 2.16 m^3/s kg. As before, the comments on transient heat transfer apply.

Other chemical expanding systems have been reported for expanding tobacco such as alkaline hydrogen peroxide (Rainer & Hearn, 1983), hydrogen peroxide and catalase (Roser, 1971) and a foaming mixture of calcium carbonate and strong acids (Muyamoto & Yasu, 1974).

CONCLUSIONS

It appears from this review that the rate of gas evolution within a product, with the exception of microbial fermentation processes, is controlled by the rate of change in pressure, rate of heat transfer, or by the

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Method	
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II (absorption)	
III (adsorption)	
IV (chemical reaction)	

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TABLE 4
Comparison of Expansion Rate for Methods of Gas Generation

Method	Process	Explosive expansion rate, E $(m^3/s\ kg)$
I (phase change)	Extrusion	0·3–12
	Steam explosion	0·24–12
	Freon-12	0·14–1·4
	Carbon dioxide	0·045–0·9
II (absorption)	N_2 cell disruption bomb	0·11
	NH_4 freeze-explosion	
III (adsorption)	CO_2 tobacco puffing	0·000 75–1·35
IV (chemical reaction)	Yeast fermentation of dough	$1·0 \times 10^{-6}$
	Chemically leavened dough	$2·4 \times 10^{-3}$
	NH_3–CO_2–H_2O tobacco puffing	0·34–2·16

rate at which absorbed gases which react chemically with water come to chemical equilibrium. The puffing processes were classified into four categories based on the method responsible for gas evolution: phase change, absorption, adsorption and chemical reaction. The magnitude of explosive expansion rate E was estimated for several processes in each category and are summarized in Table 4. It appears that the explosive expansion rate must be in the range of 0·05–12 m³/s kg to puff cellular products or fabricated food products. The baking industry uses much smaller values of E.

Other factors, not covered in this review, must be considered in the selection of a puffing process for a food product. The potential for residual chemicals or volatiles such as Freon, the extraction of organic flavor volatiles with a carbon dioxide process, and the development of off-flavors or colors by the volatile or thermal process necessary to generate the gas release must be considered. Based on this review, there appear to be many options for development of a puffing process for dehydrated fruits and vegetables.

ACKNOWLEDGEMENT

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