Carrot Dehydration—Optimization Process Studies on the Explosion-Puffing Process

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ABSTRACT

A carrot dehydration process that includes the unique continuous explosion-puffing system (CEPS) is described. A drying study included moisture distribution throughout a two-stage pilot scale dryer as well as bed temperature during first stage drying. Shrinkage losses of carrots by two dehydration methods were investigated, and volume differences were obtained. Measurements of dried carrot properties such as bulk density, color, nonenzymatic browning, rehydration, and disintegration were used to determine optimum operating pressure, temperature, and feed moisture for CEPS. Response surfaces developed from these properties were used simultaneously to establish a constrained optimum.

INTRODUCTION

CARROTS are one of the ten most prevalent vegetables grown in the United States and rank first in available Vitamin A activity (Salunkhe et al., 1973) Fresh carrot quality depends upon a fast harvest and rapid transportation to markets. Although carrots can be preserved at low temperature and high humidity in conditioned atmospheric chambers for a limited time, this is costly, and with time the Vitamin A activity decreases as well as the turgor.

Carrots are chiefly grown for Vitamin A activity, color, and flavor. Processing methods such as canning, freezing, and dehydration have been used to preserve these attributes. Dehydration offers many advantages, such as low transportation costs and unrefrigerated storage (Duckworth, 1966). The effectiveness of drying, especially when the explosion-puffing step is used, is shown by the ease with which water activity of carrots is reduced to its B.E.T. monolayer value [a_w = 0.26; % moisture 4.1% (dry basis)]. At this level oxidation and nonenzymatic browning (NEB) are at a relative minimum, while mold and bacteria growth are prevented (Labuza, 1980; Labuza et al., 1970).

A few years ago freeze-drying was looked upon as the most promising method of drying foods because is eliminated harmful effects on food quality attributed to air drying. However, because of its lower cost hot air drying is still preferred for most fruit and vegetable dehydrations (Van Arsdel et al., 1973). The cost and efficiency of hot air dehydration is limited by piece size because drying time usually increases in proportion to the square of the thickness of the piece because internal diffusion controls (Labuza, 1972). The explosion-puffing process overcomes some of this drawback (Sullivan et al., 1963). The porosity imparted to the food pieces (Sullivan et al., 1977a, 1980) by explosion-puffing facilitates final drying. In fact, the process becomes relatively more desirable as the piece size is increased (Sullivan, 1981). The time of drying carrots with one dimension of 0.16 cm by conventional or by the explosion-puffing process is about the same, but as the piece size is increased, for example, to 1.0 cm cubes, the explosion-puffed carrots dry three times faster to 4% moisture.

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The purpose of this study is to investigate an air drying (explosion-puffing) process for carrots which will reduce drying time, produce high quality low moisture carrot pieces with little loss of Vitamin A (β-carotene) and color. The study includes a continuous explosion-puffing system (CPES) and its operating feasibility.

EXPERIMENTAL

JUMBO IMPERATOR 58 variety carrots, from California's Imperial Valley, obtained from a local wholesaler were used in all experiments.

The unit operations on the process are shown in Figure 1. The process conditions follow. The carrots were lye peeled at low temperature (65.6°C) and high concentration (20% lye) for 3 min, trimmed, which included topping and tailing, and diced to a nominal 1 cm cube. The carrots were sized over a 0.5 cm slotted screen. The overs continued in the processing line, the unders (ca. 15–20%) were sulfited and conveyed to a holding tank. The overs, 1 cm dice, were blanched 4 min in atmospheric steam to inactivate peroxidase and were partially cooked; dipped into a 0.5% solution of sodium bisulfite for 30 sec, which brought the residual SO_2 to about 4,000 ppm [moisture-free basis (MFB)]; and then dried in a continuous belt dryer to predetermined moistures as the experiments required.

Drying studies

Moisture distribution, bed temperature, and piece shrinkage were studied in a two-stage multizone pilot-scale continuous belt dryer (Anon., 1963). The dryer is a Sargent pilot plant research dryer similar to larger commercial dryers. Dryer modifications were made by adding doctor blades to the first and second zones of the first stage to improve drying (Sullivan et al., 1977b). Only one set of doctor blades (in the second zone) was needed to break up and thoroughly mix the the carrot dice.

Dryer. The moisture distribution study of the continuous belt dryer was made over ten runs. Samples were taken before and after drying, at the centerpoint of each drying zone, and at transfer. Carrots (1 cm dice) were dried from about 89% (wet basis) to about 40% moisture. Although other drying conditions were also suitable, the following conditions were used: Stage 1–air velocity 3 m/s downward through the bed, temperature 82°C, belt speed 10.7 cm/min and a feed or bed depth of 5 cm entering the dryer; Stage 2–air velocity 2 m/s downward through the bed, temperature 49°C and belt speed 2.0 cm/min.

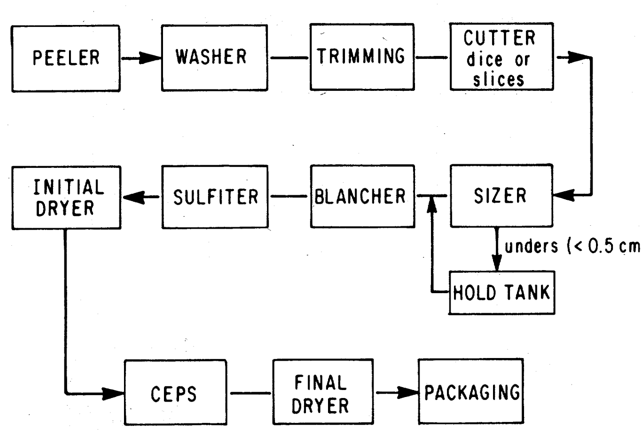

Fig. 1—Explosion-puffed process for carrots.

The carrot bed temperature in Stage 1 was measured by a point thermocouple inserted into a carrot die, recording the temperature as the die was conveyed through this stage. This study was not extended to Stage 2 because carrots leaving Stage 1 were close to the dry bulb temperature and this temperature would be maintained until the carrot pieces left the dryer. The temperature study was made in seven of the ten experimental runs.

Shrinkage. The shrinkage study was undertaken to determine if explosion-puffed carrots when rehydrated would return more nearly to the size of fresh carrots than would conventionally hot air dried carrots. Carrot dice were separated into four fractions: raw, dice dried by the explosion-puffing process (at two pressures 207 and 310 kPa), and dried by conventional hot air drying. Carrots for the shrinkage tests were all dried in a tray dryer at 82.2°C. Carrots were dried to the desired moistures, ca 4% for conventional and ca 25% for explosion-puffed. After explosion-puffing, these carrots were dried in the tray dryer at 66°C to ca 4% moisture.

Twenty-five dice were randomly chosen from each of the four lots. The dice were rehydrated by boiling for 45 min for the conventional dice, and for 5 min for the explosion-puffed. These times correspond to the constant plateau of the coefficient of rehydration.

The sides of the dice were measured with a micrometer at approximately the center of opposing edges. All six sides were measured. As it could not be assumed that the carrot dice were isotropic, the dimensions of the carrot along rhree axes were recorded separately, and the two measurements for similar sides were averaged. The dimensions were then grouped as longest, intermediate, and shortest.

All lots were tested three times. Volume loss was determined by comparison of the calculated volumes of raw and rehydrated dice.

Table 1—Experimental conditions for optimization tests

Moisture % Lot #1	Moisture % Lot #2	Pressure kPa	Temperature (°C)
22.0	21.6	140	150
24.4	24.0	170	165
27.9	26.2	210	190
31.0	31.3	240	
32.9	34.3		

Testing the continuous explosion-puffing system (CEPS)

Capacity. The volumetric rate of 1 cm carrot dice that CEPS will accept without malfunction was not determined. However, the maximum volumetric rate for 1 cm potato dice (454 kg/hr) has been determined (Sullivan et al. 1977a). Since the bulk densities of 1 cm carrot and 1 cm potato dice at 25% moisture (wet basis) are the same, their capacities should be the same.

Optimization. Optimization of CEPS was on a quality basis and was achieved by determining the effect of initial moisture, internal pressure, and temperature on partially dried carrot dice as reflected in the final product. Two different lots (1,270 kg each), purchased 3 mo apart, were dired to five moistures (Table 1). Forty-five kg were made for each moisture condition. The experimental design of 60 conditions included five moisture levels (22–34%), four levels of pressure (138–242 kPa) and three levels of temperature (150–190°C) (Table 1). The design was duplicated.

Carrot dice explosion-puffed in CEPS were fed at a rate of 130 kg/hr for each test. Because of the small lots used in each experiment, it was more practical to use a tray dryer for finishing drying. All samples were dried to 4–5.5% moisture (SO_2 content 250–400 ppm) in a hot air tray dryer, then evaluated. The chemical and physical attributes evaluated were: bulk density, rehydration, percent disintegration, color difference, and nonenzymatic browning. These properties were chosen because they most clearly reflected the quality of the explosion-puffed product. Fast rehydration or water pickup is a desired characteristic of explosion-puffed material. The greater the puff, the more porous the product, and the more readily the water is picked up, as reflected by rehydration values. Bulk density decreases during explosion-puffing, and for carrots it should be between 255 and 290 kg/m^3. A value higher than the latter is indicative of an inadequate puff; lower, the product is overpuffed, causing excessive rupture. Minimal disintegration is desired. NEB and color difference values relate to eye appeal and flavor. Generally, as these products brown they become less desirable.

Storage evaluation

No formal storage test was made on the explosion-puffed dried carrots. After each experiment the carrots were dried to 4.0–5.5% moisture, packed in unsealed plastic bags, put into 30 x 18 in. fiber drums, and stored at 3.3°C. We had observed that explosion-puffed carrots used as demonstration samples in apothecary jars which were exposed to light retained their color, while conventional dried carrots darkened and freeze dried samples bleached out. For this reason, samples were taken from carrots stored in the fiber

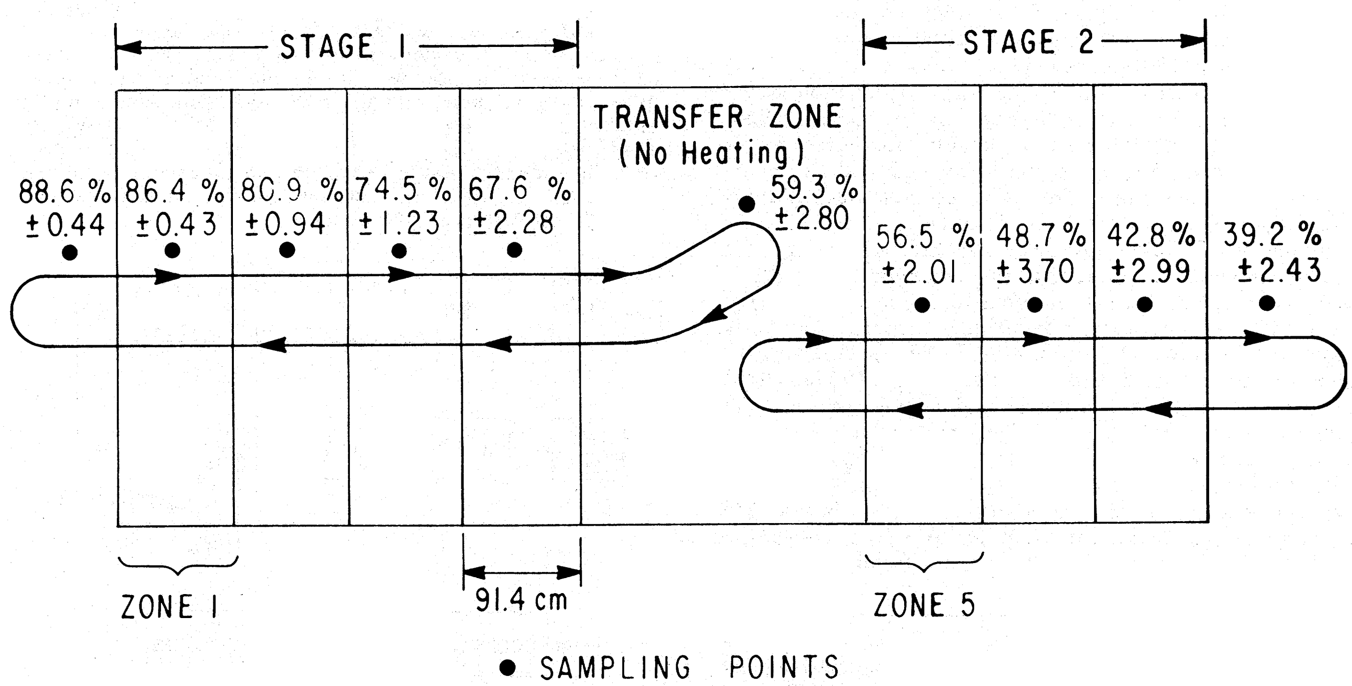

Fig. 2—Moisture distirbution of carrot dice before, during, and after drying in continuous belt dryer.

be used by a processor during drying to estimate moistures in the dryer.

Shrinkage study

During dehydration carrots, like all vegetables, undergo a plastic deformation, and as drying progresses the deformation becomes in part irreversible (Potter, 1968). Table 2 shows average values of micrometer measurements of carrot dice in the raw and rehydrated state. It also shows an overall mean dimension of the sides "$\overline{X}$," an average dimension for each side, and the calculated volume of the rehydrated dice which is represented as a percentage of the raw dice volume.

Highly significant differences ($p < 0.01$) were found between the raw and the explosion-puffed dice and between the explosion-puffed and the conventionally dried dice. Raw dice dimensions were compared separately against those of seven explosion-puffed samples and evaluated by t-test. However, when explosion-puffed dice were compared directly to conventionally dried dice, the "t" test showed a highly significant different ($t = 10.15$).

The volume of the conventional dice when rehydrated was 47.4% of the original dice calculated volume, and the explosion-puffed, 63.5 to 67%. Explosion-puffed dice do not return to their fresh volume but recover about 15% more than conventionally dried dice. This has an economic significance to the processor.

Optimization study

The results of these experiments (responses) were related to the controlled variables by simple quadratic equations. The controlled or independent variables were pressure, temperature, and moisture. The responses chosen as dependent variables were bulk density, rehydration, percent disintegration, and color difference measurements.

A second-order regression equation in terms of the independent variables was fitted to the data of each response. These empirical equations were used as models of the puffing process. Figures 4, 5, and 6 show typical response surfaces.

The optimization of a dependent variable can be restricted, or constrained, by the requirement that the other dependent variables fall between specified levels. Therefore, constant-value lines shown on these response surface plots represent limits which could delineate the permissible region. In practice, more than one constraint (Table 3) is considered in the optimization. The variable being extremized, of course, is not fixed.

A program solving constraint nonlinear optimization problems (Evans, 1975) was applied to optimization models. Table 3 lists the model and the limits imposed on the optimal solution. A line of optima was generated as a functionof the model's radius ($\sqrt{P^2 + M^2 + T^2}$).

Figure 7 displays an optimal ridge for % disintegration. It is evident that slight improvements in % D can be realized without other predictable harm by extrapolating to higher feed moistures. An important external consideration is that puffing at higher moistures allows more drying to be done in the faster, puffed, state. Therefore, Table 4 lists the opti-

Table 4—CEPS optimum point for 1 cm carrot dice

Independent variables		Dependent variables	
Pressure	131 kPa	ρ (Bulk density)	278.9 kg/m^3
Temp	190°C	NEB (nonenzymatic browning)	33.4
Moisture	34.8%	% Disintegration	1.42%
		Rehydration	2.44g H_2O/g dry solid
		Test of optimal conditions	
Pressure	131 kPa	ρ (Bulk density)	292 kg/m^3
Temp	188.6°C	NEB	14.5
Moisture	31.4%	% Disintegration	0.50%
		Rehydration	3.17g H_2O/g dry solid

Table 5—Correlation coefficients for batches #1 and #2

	Batch #1	Batch #2
Bulk density ρ g/m^3	0.85	0.92
Rehydration g H_2O/g bone dry solid	0.92	0.93
% disintegration	0.74	0.85
NEB	0.85	0.74

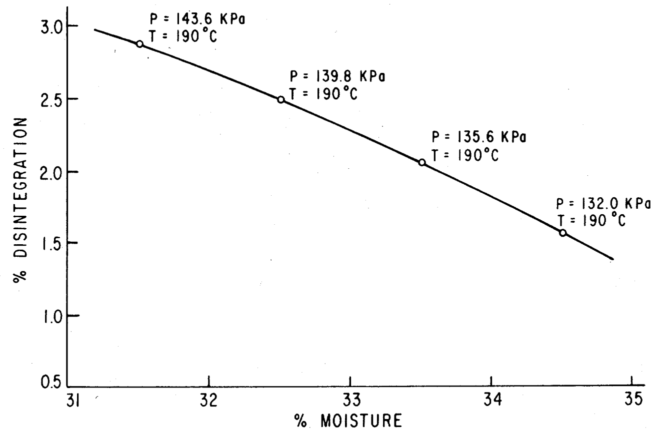

Fig. 7—Optimal ridge generated from model's radius, % disintegration vs % moisture.

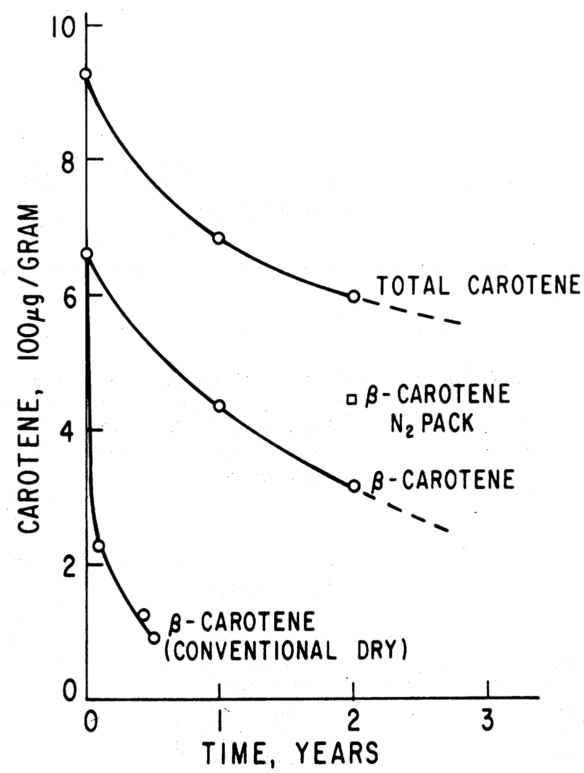

Fig. 8—Total and β-carotene retention in air and nitrogen pack at 3.3°C.

two-step procedure for rehydration and extraction was combined into a single extraction. The sample was extracted in a Waring Blendor for 15 min, after which the slurry was washed into a centrifuge bottle and centrifuged at 2,500 RPM for 15 min. The supernatant was decanted into a 200 ml volumetric flask containing 10 ml of 10% $PbAc_2$. The precipitate was washed two times with extracting solution, and centrifuged, and the supernatant was added to the volumetric flask. This was made to volume with HOAc-HCHO solution and filtered through non-absorbent glass-wool.

A 10 ml aliquot of the filtrate was mixed with an equal volume of absolute alcohol. The mixture was stirred thoroughly, allowed to stand 15 min, then centrifuged for 10 min at 3,000 rpm. Absorbance of the supernatant was read at 420 and 600 nM on a Beckman model B spectrophotometer. Results are reported as $\Delta A(X10^3)$, where $\Delta A = A_{420}-A_{600}$.

Total and β-carotene

Carotenoid pigments were extracted by blending explosion-puffed carrot dice with 95% ethyl alcohol and Skellysolve B. Absorbances were measured at 450 nM with a Hitachi-Perkin Elmer UV-Visible spectrophotometer. Total pigment was determined as total carotene by use of $E^{1\%}_{1\ cm}$ 2500.

β-Carotene was determined by the method of DellaMonica and McDowell (1965).

RESULTS & DISCUSSION

Drying studies

The initial drying of carrots was from about 89% (wet basis) to about 40% moisture. The moisture distribution (Fig. 2) is depicted for the two-stage multizone dryer. Sample points are indicated, and moistures and their confidence limits (95%) are shown. Approximately 3 hr and 10 min were required to dry 143 kg to about 40% (wet basis). The measurable SO_2 content after initial drying had dropped to 1,000 ppm.

The temperature of th dryer bed was recorded for the first drying stage while the carrots were drying. The bed temperatures and the moisture distribution throughout stage one are shown in Figure 3. These temperatures can

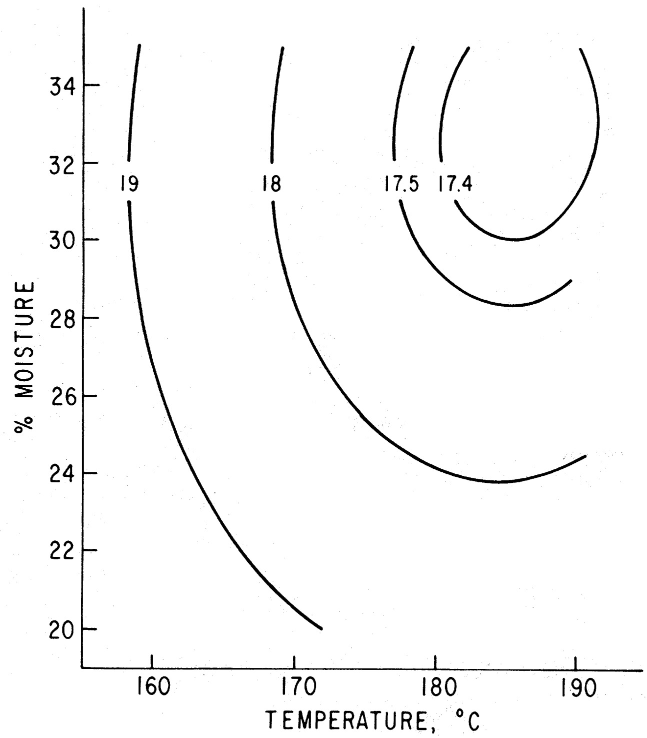

Fig. 5—Response surface of bulk density at 131 kPa, % moisture vs temperature.

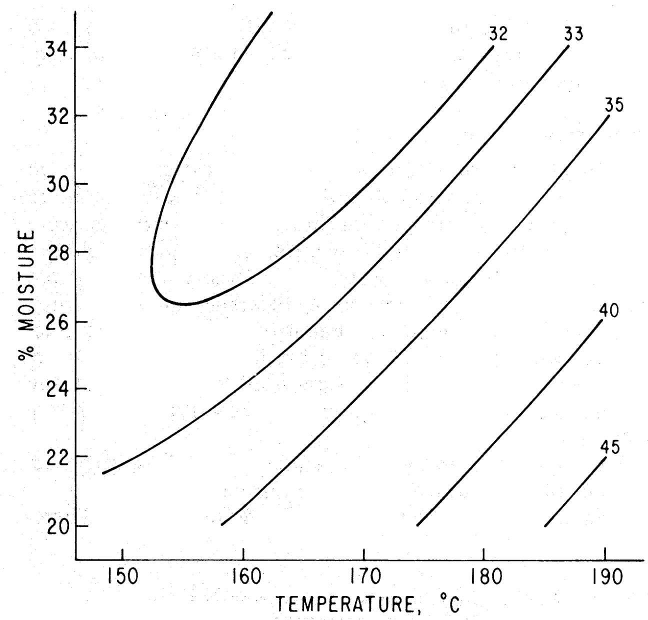

Fig. 6—Response surface of nonenzymatic browning at 131 kPa, % moisture vs temperature.

Table 3—Multiple correlations and coefficients of a carrot model for optimum study

Model form: $Y = C_o + c_1P + c_2T + c_3M + c_4PT + c_5TM + c_6PM + c_7P^2 + c_8T^2 + c_9M^2$

Y	Bulk density	NEB	% disintegration	Rehydration
R^2	0.83	0.67	0.63	0.85
Upper limit	18	50	5	5
Lower limit	0	0	2	2.3
c_o[a]	132.33259548	74.75002570	−16.06828581	−6.72438798
c_1	−1.34484085	2.49104633	−6.49498864	0.16449747
c_2	−0.46887792	−0.69597388	1.04697741	0.01517178
c_3	−0.84517204	1.83089079	−6.04211173	0.19407076
c_4	−0.00088967	−0.00635349	0.00143442	−0.00015265
c_5	−0.00041235	−0.01434746	0.00063819	−0.00010918
c_6	0.02410303	0.03427441	0.15211667	0.00011866
c_7	0.01669000	0.01666667	0.04333333	−0.00107000
c_8	0.00068069	0.00192308	−0.00161404	−0.00000804
c_9	0.00817057	0.03468386	0.04189977	−0.00212704

[a] Sufficient significant places are provided so that the reader can recalculate the response surface. No unexpected precision should be inferred.

drums for 1½ and 2 yr and analyzed for color difference and carotene.

Processing of unders

After the overs were processed, the unders were conveyed from the holding tank, blanched, and dried to ca. 4% moisture on the continuous belt dryer. This product was added to the explosion-puffed material before it was packed.

Analytical procedures

Reconstituted carrots at room temperature were used for determining nonenzymatic browning (NEB), color difference, total carotene and β-carotene. Dehydrated carrot dice were used to determine moisture content, bulk density, rehydration, disintegration, and SO_2.

Color measurement

A Gardner Automatic Color Difference Meter was used for all color measurements (Hunter, 1942). The reconstituted carrots were placed in glass cells, and color values for each sample were obtained as Hunter "a," "b," and "R_d" units. R_d measures the reflectance of the sample, "a" signifies redness if positive and greenness if negative, and "b" signifies yellowness if positive and blueness if negative. The instrument was standardized each time with a standard color tile CSR 0020 (R_d = 7.0; a = +59.7; b = +19.3.

Moisture

Moisture content was obtained by the standard vacuum oven method. All samples were dried at 70°C under vacuum for 16 hr. Results are expressed on a wet basis.

Sulfur dioxide (SO_2)

Sulfur dioxide was determined by the method of Nury et al. (1959) with modification.

A 15g sample was extracted with a mixture conttaining 45 ml of a special buffer solution (Ross and Treadway, 1960) plus 240 ml of distilled water.

An aliquot of the blend was weighed into a tared 100 ml volumetric flask, then 4 ml of 0.5N NaOH was added. The solution was swirled 30 sec, permitted to stand on an additional 1½ min, then 4 ml of 0.5N HCl was added. Then 20 ml of sodium tetrachloromercurate solution containing sulfamic acid (0.60g/liter) was added to prevent interference by nitrogen dioxide (West and Ordoveza, 1962). The mixture was diluted to 100 ml with water, then mixed and filtered. Two ml of the filtrate were used for the colorimetric analysis.

Disintegration

Percent disintegration was determined in a 100g sample; disintegrated pieces were manually separated and weighed.

Rehydration

A 25g sample was placed in boiling water for 5 min, then drained and weighed. The amount of water gained per gram of dry solids was determined by subtracting the original sample weight (25g) from the weight of the rehydrated carrots and dividing this weight by that of the solids in the 25g sample.

Table 2—Comparisons of side dimensions and volumes

			Reconstituted dice		
		Raw dice	Conventionally dried	Explosion-puffed at 207 kPa	Explosion-puffed at 310 kPa
$\bar{X}$	cm	0.98	0.76	0.84	0.85
$\bar{x}_1$	cm	1.03	0.90	0.90	0.92
$\bar{x}_2$	cm	0.98	0.75	0.84	0.85
$\bar{x}_3$	cm	0.92	0.62	0.78	0.80
$(\bar{X})^3$	cm^3	0.93	0.44	0.59	0.62
% of raw dice volume		–	47.4	63.5	67.0

Bulk density

Bulk density was determined by filling a tared crystallizing dish of known volume with dried carrot dice then weighing the carrots and determining the weight per volume.

Nonenzymatic browning

NEB was determined by the method of Baloch et al. (1973) with modifications.

Because of the varying moisture contents of the samples being analyzed for NEB, a standardized amount of sample equal to 5.00g carrot solids/100 ml extracting solution (2% acetic acid-1% formaldehyde; HOAc-HCHO) was established. Also, Baloch's

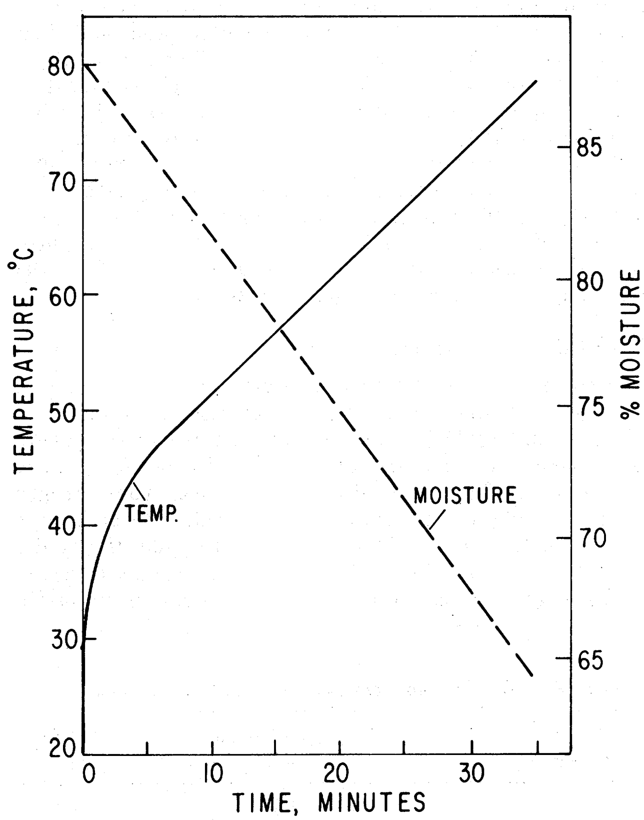

Fig. 3—Temperature and moisture of carrot dice during first stage drying.

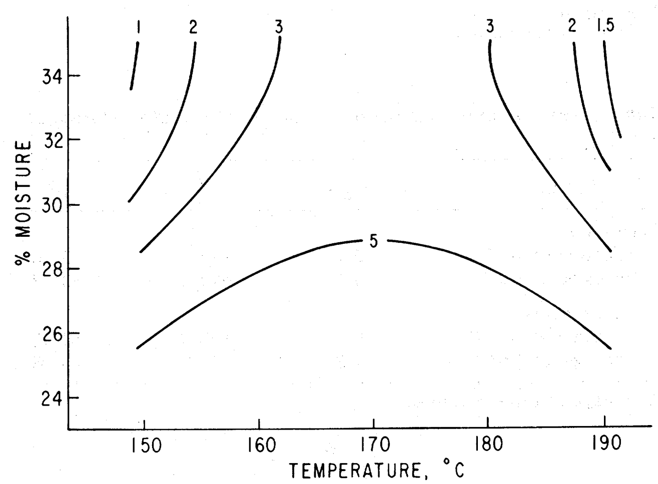

Fig. 4—Response surface of % disintegration at 131 kPa, % moisture vs temperature.

mal and recommended operating conditions at the highest moisture which could be selected with confidence.

A bias between lots was observed from the data after the two carrot lots were processed. There was a significant difference at 95% confidence limit. The individual ssudy of each lot gave excellent multiple correlation coefficients (R^2) for the dependent variables (Table 5). The evaluation when the lots were combined lowered the R^2 values (Table 3), but the coefficients remained well in the significant range.

Test of optimal conditions

The optimum was tested by processing partially dried carrot dice (31.4% wet basis) through CEPS at the specified pressure and temperature. These test conditions and their results are shown in Table 4. The predicted values and those obtained from the test run are reasonably close indicating the optimum point obtained from the model is valid.

Experimentally the feed moisture was low (31.4% instead of 34.8%). To compensate, the processing pressure should have been raised above the optimum suggested pressure (Fig. 7). With moisture and pressure low, the resultant dependent variables could be expected to differ slightly from the optimum. The explosion-puffed carrots, from the test, rehydreated to an excellent cooked product.

Informal storage evaluation

Total and β-carotene analyses were performed on the air packed explosion-puffed samples. The results are shown in Figure 8 and Table 6. Some of these carrots had been nitrogen packed for samples (stored at 0°C) and they were analyzed for β-carotene after 2-yr storage. The nitrogen packed sample had a higher β-carotene value. β-Carotene in air packed conventional dried carrots dropped off rapidly in a 6-mo period (Gee, 1979). Color difference measurements at two processing temperatures for explosion-puffed carrots measured at zero time and after 1½ yr of air storage at 3.3°C are shown in Table 7. Color difference values did not change with time.

Table 6—Explosion-puffed 1 cm dice carotene loss in storage

Sample	Total carotene µg/g	β-Carotene µg/g
Fresh	940	–
Blanched	1090	–
Zero time storage	930	670[x], 690[y]
1½ yr storage	690	440
2 yr storage	600	320
2 yr (N_2 pack) storage	780	440

[x] Estimated
[y] Obtained from literature

Table 7—Explosion-puffed carrots color difference after storage at 3.3°C

Sample	R_d[a]	a[a]	b[a]
Zero time			
Processed at 166°C	19.7	+21.5	+33.5
Processed at 188°C	17.1	+21.1	+31.7
After 1½ years			
Processed at 166°C	19.5	+23.6	+33.1
Processed at 188°C	17.3	+21.3	+31.6

[a] Average of three readings.

CONCLUSIONS

AN OPTIMUM POINT has been determined for the operation of CEPS, but if changes are desired, an optimum ridge offers a range of operating conditions which will produce desirable products with minimal losses.

An excellent dried carrot piece (4.0% moisture, a_w = 0.26) can be made by the explosion-puffing process. The carrots made by this process dry three times faster than those from the normal conventional hot air drying method. The product retains characteristic taste and texture and does not lose color or carotene rapidly.

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