Evaluation of Energy Efficiency and Quality Retention for the Refractance Window^{TM} Drying System

----- Research Report -----

Brendan I. Abonyi[1]
Juming Tang[1], Ph.D
Charles G. Edwards[2], Ph.D

[1]Department of Biological Systems Engineering
Washington State University, Pullman, WA

[2]Department of Food Science and Human Nutrition
Washington State University, Pullman, WA

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Brendan I. Abonyi

Ph. D. Student, Department of Biological Systems Engineering

Washington State University, Pullman, WA 99164-6120

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EXECUTIVE SUMMARY

This document contains the results of an eighteen-month project[a]. Energy efficiency, drying kinetics, beta carotene, total carotene, ascorbic acid (vitamin C), and color retention of selected materials[b] were studied using the Refractance Window™ pilot plant dryer in Tacoma, WA. The pilot scale drum, spray and freeze dryers were studied at Washington State University's food processing pilot plant in Pullman, WA for comparison.. The experiments were conducted with blanched carrot puree (CA) and with single strength strawberry puree with a) 70% maltodextrin additive-DE10 (SA) and b) without additive (SW). Chemical analyses were conducted at Washington State University.

The results are summarized as follows:

1. Energy efficiencies (27.9 - 47.6%) obtained for four different products or drying conditions for the Refractance Window™ system were comparable to or slightly higher than hot air drying methods (30-40%) reported in the literature.
2. Vitamin C retention in Refractance Window™ dried strawberry purees were comparable to or higher than purees freeze-dried to a similar moisture content.
3. Beta-, alpha- and total carotene retention of Refractance Window™ dried carrot purees were comparable to freeze-dried product and better than drum-dried products.
4. Color degradation in Refractance Window™ dried products was comparable to or slightly less than that of freeze-dried products.
5. Drying kinetics in the Refractance Window™ system for tested product generally followed the trend o[1]btained for similar products using other drying methods, with no apparent constant rate drying period (Feng et al., 1999).

The above results are based on only the selected materials conducted on pilot scale equipment. We expect deviation of test conditions for commercial processes, though deviations on quality will not be significant. We expect higher energy efficiency with commercial scale Refractance Window™ drying systems and see room for further improvement in energy efficiency. The relatively small throughputs and sometimes inconsistent product application of the system need to and can be improved.

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[1] [a]The project, titled "Studying Drying Characteristics of Foods in the Refractance Window™ System", was supported through the Focused Technology Initiatives Program of the Washington Technology Center and conducted between July 1998 to December 1999. [b]Selected materials include pureed carrots, strawberries and cooked corn.

1. INTRODUCTION

Refractance Window™ Technology is a novel drying system, developed by the owners of MCD Technologies, Inc. in Tacoma, Washington. It uses circulating water at atmospheric pressure as a means to carry thermal energy to material to be dehydrated. The products are spread on a transparent plastic conveyer belt and unused heat is recycled (Fig. 1). Products on the moving belt dry in a few minutes, contrary to hot air tray or tunnel dryers which take several hours, or freeze dryers which dry overnight. Refractance Window™ drying is believed to have a major advantage over drum drying or spray drying, in that foods and pharmaceutical ingredients are exposed to much milder temperatures and final products maintain good sensory qualities, such as color and aroma. The technology is relatively inexpensive and the equipment is simple to operate and maintain.

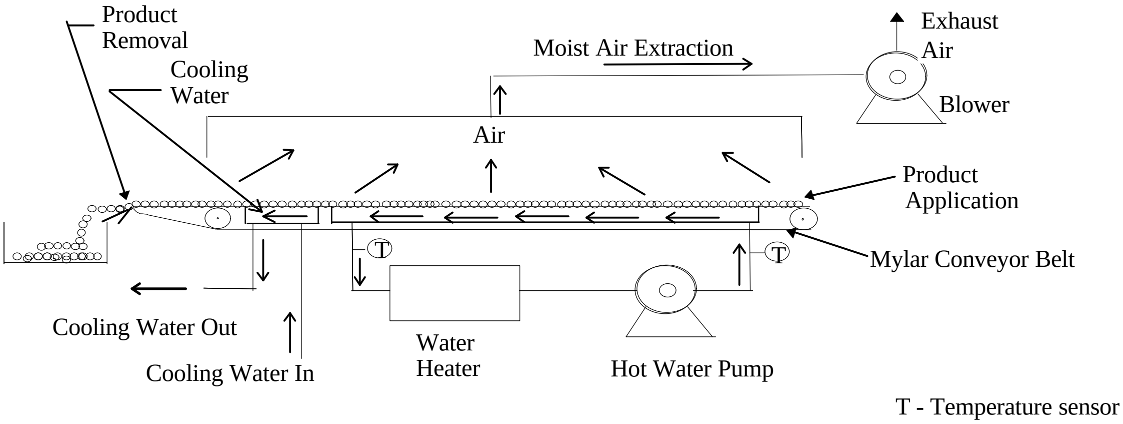


Fig. 1.1. The schematic diagram of the Refractrance Window™ Dryer.

Singh (1986).stated that the food industry in the US consumes 10^6 billion kJ of energy annually, 82% of which is spent on food processing, marketing and preparation The cost of energy was observed to be on the increase in the last two decades. For example, within said period the cost of electrical energy increased from $2.89 to $9.70 per 1.055 GJ (1 GJ = 10^6 kJ), while that of natural gas increased from $0.38 to $2.60 per 1.055 GJ (Singh, 1986). It is, therefore, imperative that major emphasis in the food industry should continue to be placed on energy conservation.

Drying represents one of the most energy intensive unit operations used in the food processing industry and energy constitutes a major portion of the operating costs. The energy efficiency of drying methods, which typically falls between 20 and 70% (32,000 -

11,500 kJ heat per kg water evaporated) is thus an important consideration in evaluating a drying system. With potential rising costs of energy and more stringent environmental requirements on fume emissions, highly energy efficient drying methods would have a competitive edge over those methods with low energy efficiency. It is, therefore, important to document the energy efficiency of the Refractance Window™ drying system.

The effect of drying on nutrient retention is another major criterion in evaluating and selecting a drying method, because heat is used. Beta-carotene (pro-vitamin A) and ascorbic acid (vitamin C) are among the most heat-sensitive nutrients that are often significantly reduced during conventional drying operations using hot air. Nutritional losses in dried foods are dependent upon the drying method used. Table E.2 in Appendix E summarizes typical ranges of nutritional losses by various drying methods. Losses of vitamin C and vitamin A are commonly studied, because of their sensitivity to heat and their nutritional importance.

1.1. Objectives

The objectives of this study were as follows:

1. Evaluate the effects of MCD drying system on product quality, particularly on the retention of color, texture, flavor, enzyme activity, and vitamin C.
2. Determine the energy efficiency of the drying method under various operating conditions.
3. Conduct experiments to study the fundamental principles that govern the uniqueness of Refractance Window™ drying method.

In summary, the objective of the study was to compare a new drying technology (Refractance Window™) with existing ones in terms of energy efficiency and food quality. We specifically looked into the effect of Refractance Window™ drying technology on retention of flavor, aroma, color, vitamin C, and beta-carotene. Carrots were chosen as a model food for evaluating the effect of drying on beta-carotene and color retention and strawberries for flavor, color and vitamin C analyses, both materials being important sources of those nutrients. Drying kinetics studies were conducted on the two tested products.

1.2. Project Activity Chart

Project activities are summarized in Table 1.1. A preliminary visit was made in September 1998 to MCD Technologies, Tacoma, WA, for familiarization with the system. Instruments were tested for field measurement and as a means to quantify (calibrate) operational settings for belt speed, air velocity, water tank volume, and spreader bar applicator clearance. Also studied was the possibility of using several products (pureed broccoli, blueberry, and pineapple) as model foods for system evaluation with emphasis on examination of how the samples could be applied to the belt. A preliminary energy and mass balance was carried out. Two more visits were carried out in March and June 1999 for further studies and experimentation with the pilot plant unit of the company in Tacoma, WA. The development of a laboratory system based on the same principle of Refractance Window™ technology, and studies on the energy efficiency of the Refractance Window™ system and its effect on quality losses were conducted at Washington State University (WSU). All analyses of field test results, dried product chemical analyses, and product drying using pilot plant scale conventional drying technology were conducted at WSU.

Table 1. 1. Activities during the one year project period.

	Months											
Tasks	1	2	3	4	5	6	7	8	9	10	11	12
1. Preliminary tests on the MCD pilot scale unit at Tacoma	X											
2. Preliminary energy and mass balance calculations	X	X										
3. Development of a laboratory system based on the same principle of Refractance Window™ Technology		X	X	X	X	X	X					
4. Second tests on the MCD pilot scale unit at Tacoma							X					
5. Energy efficiency and vitamin C analysis on the selected test materials								X	X			
6. Third tests on the MCD pilot scale unit at Tacoma										X	X	
7. Energy efficiency , vitamin C, carotene, flavor, and color analysis on the selected materials											X	X
8. Comparative testing with freeze, drum, tray and spray dryers						X	X	X	X	X	X	

2. BACKGROUND LITERATURE

The technology of drying food as a method of food preservation dates back to early history of human existence. The principle of drying is to reduce microbial growth by removing free water from food products. Drying often leads to reduction of bulk volume and weight in the manufacturing of convenient foods. Dehydrated products have almost unlimited shelf life in proper packages, and substantially lower transportation, handling and storage costs compared to products of other preservation methods. Although several commercial drying methods have been developed, none can provide economical and high quality products. Each method has its own limitations in energy consumption, and on the quality of the finished products. Considerable equipment operation time and high capital investment are often further constraints in the choice of a dehydration method. Moreover, many fruit, vegetable, and pharmaceutical products are heat sensitive. Product color, texture, and nutrient retention, therefore, can be critical factors in selecting a drying method.

Commonly used dehydration techniques include sun drying, hot air tray or tunnel drying, spray drying, freeze-drying and drum drying. Sun drying and hot air drying cause significant loss of color which makes a product less appealing to consumers and also results in losses of vitamin C and rehydration ability (Jayaraman and Gupta,1995). Drum drying, developed for liquid products, causes severe quality loss in product due to exposure to high temperatures (120º - 170°C) (Van Arsdel and Copley 1964; Fellows, 1988). Although the drum may be enclosed in a vacuum chamber to reduce drying temperature, capital cost limits the use of this technique to only special applications (Fellows, 1988). Spray drying is often used for liquid foods, with major limitations of high capital costs and the requirement for relatively high feed moisture content to ensure that the feed can be pumped and atomized (Fellows, 1988). The atomization and high air temperature of 150 - 300°C (although the temperature of most particles may remain at the wet bulb temperature of the air) leads to high volatile losses (Fellows, 1988). High shear action during atomization may also make this technique unsuitable for products sensitive to mechanical damage. Moreover, spray-drying provides a very large surface area which enhances oxidation if the wall material is not thick or dense enough to provide a good oxygen barrier (Desobry et al., 1997). Freeze-drying is a commercial process that can produce high quality dehydrated products with good retention of shape, flavor, color, vitamin C and rehydration ability. The cost of producing freeze-dried product can be up to ten times the cost of using forced hot air drying.

Given all these processes, MCD Technologies, Inc. at Tacoma, Washington, developed the Refractance Window™ drying system to replace traditional methods for drying and processing heat-sensitive foods, enzymes, and pharmaceutical products. Industrial scale systems of five difference capacities were developed for commercial use. An in-house pilot scale system is used to test dry various products. However, MCD lacks the facilities and the expertise to thoroughly study drying characteristics of their system and to quantify its effects on quality.

Fruits and vegetables are the major sources of vitamin C (ascorbic acid) and provitamin A (beta-carotene) (Jayaraman and Gupta, 1995). Both vitamin C and carotenoids are, however, vulnerable to oxidation in spray-dried products (high specific surface) and in freeze-dried products (porous structure) (Chou and Breene, 1972). Strawberry (*Fragaria ananassa*) is a highly perishable fruit whose production has increased due to its popularity and relatively high return on investment (Venkatachalapathy and Raghavan, 1997). Strawberries are an important dietary source of ascorbic acid (vitamin C) in the human diet (Nunes et al., 1998). In adults the recommended dietary allowance (RDA) of vitamin C (60 mg/day) can be met with an average of 100g of strawberries per day (Food and Nutrition Board, 1989).

Dried strawberries may be stored for a long time and are used in the preparation of many products, such as jams and jellies, bakery products and cereals. Lin and Agalloco (1979), reported that the main factors responsible for rapid degradation of ascorbic acid include temperature, pH, oxygen concentration, light intensity, liquid in which the ascorbic acid is stored, presence of metal ions, and the initial ascorbic acid concentration. They reported that ascorbic acid degradation generally follows first-order reaction kinetics with rate coefficient being a complex function of several factors (Lin and Agalloco, 1979). Losses of vitamin C during commercial drying varies from 10% (freeze-drying) to 96% (sun drying). Table E.2 in Appendix E summarizes recorded effects of various drying processes on vitamin losses.

β-carotene is the name given to the orange and red pigments our bodies convert to vitamin A. Lack of this vitamin increases our susceptibility to contagious diseases and leads to night blindness and eye tissue damage and even blindness, particularly in young children. Vitamin A was reported to be the most common dietary deficiency in the world (Desobry et al., 1998). β-carotene theoretically possesses 100% vitamin A activity and provides 80% of vitamin A value of fruit and vegetable (Chou and Breene, 1972; Chen et al., 1995), while α-carotene possesses only 52% of vitamin A activity (Bushway and Wilson, 1982; Heinoven, 1990). Furthermore, the demand for β-carotene has been on the increase due its to reported anticancer activity and other health benefits (Sims et al., 1993). A concentration of 69.4 mg/ml of β-carotene and its cis isomers in raw carrot juice before processing has been observed (Chen et al., 1995). Simon (1987) reported that the average carrot in the grocery store has 70 to 80 parts of carotene per million while a new variety, β III, has 300 ppm and an even newer breeding stock contains 700 ppm. β-carotene content varies among carrot cultivars (Desobry et al., 1998; Simon and Wolff, 1987). Food processing has significant impact on α-carotene retention (Bushway and Wilson, 1982). While α-carotene contents of raw, canned and frozen carrots were 20-59, 32-48, 84-88 ppm respectively, β-carotene contents of raw, canned and frozen carrots were 46-125, 70-110, 260-281 ppm, respectively. Edwards and Lee (1986) observed an apparent increase in carotenoid content of canned carrots and attributed the increase to the loss of soluble solids into the brine during processing. Nichols and Baldwin (1983) reported on the energy and quality characteristics of carrots dehydrated by different home methods. Their results indicate that there were 18, 24 and 28% losses of carotene probably due to oxidation during dehydration using a food dehydrator, a convection oven and a microwave oven, respectively. In a related study, Arya et al. (1979) observed a rapid degradation of β-carotene during air drying of carrots. Rukimini et al. (1985) reported 82% and 72% losses of original amount of α- and β-carotene contents in sliced fresh carrots that were air dried at 60 to 70°C, milled and sieved to produce a carrot powder. Bao and Chang (1994) observed between 45% to 55% of carotene loss during freeze-drying of carrot. It is, therefore, important to pursue new technologies to retain important food nutrients.

3. MATERIALS AND EXPERIMENTS

3.1. Experimental Design

Table 3.1 summarizes the treatment conditions. Three drying treatments (Refractance Window™, freeze, and drum) were assigned in a complete randomized design to experimental unit (2.5 kg of carrot puree). Three experimental units were assigned to each treatment plus the control (fresh carrot puree). Duplicate analyses were done for each sample from the experimental unit for the carotene retention in parts per million on wet material basis. Similar treatment design was done on strawberry puree for ascorbic acid and flavor. Color retention for each treatment was repeated five times, each consisting of an average of five measurement. In the preliminary tests, it was found that strawberries could neither be drum-dried nor spray-dried without a carrier due to its high sugar content. Hence, following guidelines established by Hui (1992), enzyme converted maltodextrin with dextrose equivalent (DE = 10) was used as a carrier for strawberry samples during the spray drying experiments.

Dried samples were collected and stored in aluminum-coated polyethylene bags until chemical and moisture analyses.

Table 3.1. Operating conditions for different drying methods.

Drying method	Product			Operating conditions	Residence time
	Carrot	Strawberry	Strawberry + 70 % maltodextrin (DE10.)		
RW™ drying*	X	X	X	95^{o}C (water), 0.6 m/min (belt speed)	3-5 min
Drum drying	X			138 ^{o}C (steam), 414 kPa, 0.15 m drum diameter, 0.19 m length, 1mm nip., 0.3 rpm	3 min
Freeze drying	X	X	X	20 millitorr (vacuum), condenser temperature, -64^{o}C), plate 20 ^{o}C, freezer -20^{o}C	24 hrs
Spray drying			X	190^{o}C (air inlet), 95^{o}C (air outlet).	
Tray drying	X		X	95 ^{o}C, 1.48 m/s (air velocity).	4 hrs

*Refractance Window™ drying system.

Spray-drying. The samples were spray-dried in a pilot scale spray dryer (model Lab. S1, Anhydro Attleboro Falls Mass, Copenhagen, Denmark). The dryer was operated at an air inlet of 190 ± 5^{o}C and the outlet 95 ± 5^{o}C. The wet bulb temperature was 18^{o}C (air inlet = 70% RH), and air temperature was 22 ^{o}C.

Drum-drying. A pilot-scale double drum dryer was used. This dryer has two counter-rotating drums (19 cm diameter and rotated at 0.3 rpm, giving a residence time of 3 min). Carrot puree was fed to the surface of the drums between the rolls. The drum surface temperature was maintained at 138°C by pressurized steam.

Freeze-drying. The samples were frozen at -35°C. A freeze dryer (model Freezemobile 24-Unitop 600L, Virtis Company, Gardiner, NY) was operated at a pressure of 25 mtorr. The temperature of the plate was 20°C, while the condenser temperature was set at -64°C.

Tray-drying. The thawed samples were air-dried in a laboratory tray dryer (model UOP-8, Armfield Ltd., Hampshire, England) at 95°C air temperature. The air velocity was 1.48 m/s. The dry bulb temperature was 22°C (air inlet = 70% RH).

Refractance Window™. A pilot scale unit of the Refractance Window™ dryer was used. The dryer has an effective length and width of 1.83 × 0.60 meters: Air conditions were RH = 52%, ambient temperature = 20°C; Average air velocity across the bed = 0.7m/s. The water temperature was 95 °C while the belt speed was 0.58 m/s. Thickness of application was 1 mm (see Fig. 1).

Drying kinetics study. Drying kinetics study data were collected for the Refractance Window™ drying and the tray drying tests.

3.2. Materials

The strawberries (Totem cultivar) were grown in the Willamette Valley, OR and harvested in June, 1998. The strawberries were washed, inspected, pureed, pasteurized (74°C), cooled (3°C), filled, labeled, palletized and frozen (-20°C) until time of study. The process time was 20 minutes. Carrots (Navajo cultivar) grown in the Columbia Basin, WA and harvested in July of 1998 were used. The process for the carrots, included dumping, washing, scrubbing/peeling, washing again, inspecting, blanching, pureeing, pasteurizing (85°C), acidifying (using citric acid solution), cooling (2°C), filling, labeling, palletizing and freezing (-20°C) until time of experiment. The total time taken from washing to palletizing was 33 minutes. Each process was passed through a metal detector to insure there were no metal particles in the puree. The strawberries and carrots were each selected from the same lot to minimize variability. The choice of strawberries (fruit) and carrots (vegetable) in this study was due to their importance as sources of vitamin C and pro-vitamin A (β-carotene), respectively, in the diet of most people in America and the world over.

3.3. Experiments

In both locations, Tacoma and WSU, each frozen carrot and frozen strawberry sample, with sample material at each location originating from the same batch and handled in an identical manner, was first thawed overnight at 22^{o}C and then blended prior to drying. °Brix determination was conducted at 20^{o}C with Fisher Abbe Refractrometer (model 5565, Fisher Scientific Co., Pittsburgh, PA) to determine the concentration of sugar in the material before the experimentation. °Brix of 6.65 and 8.5 were recorded for each batch of the strawberry and carrot puree, respectively. All drying treatments were conducted within one week and performed immediately after thawing and blending to minimize variability in treatment conditions. The dried products were allowed to cool to room temperature, then packed in aluminum coated polyethylene bags (to exclude light), flushed with nitrogen (to exclude oxygen), heat sealed, and stored at -20^{o}C prior to analysis.

Tables 3.1 and 3.2 show the moisture content and energy measurements for the carrot puree (CA), strawberry puree single strength with 70% maltodextrin additive-DE10 (SA) and without additive (SW) samples. Details on the moisture and energy measurements are included as Appendix A and B, respectively.

The color of the samples was measured with a Minolta Chroma CR-200 color meter. Color was represented by the L*a*b* color notation. This is a 3-D color presentation method in which L* is the lightness of the color, and equals zero for black and 100 for white. The a* is the degree of redness (0 to 60) or greenness (0 to -60) while b* is the amount of yellowness (0 to 60) or blueness (0 to -60) (Mallikarjunan and Mittal, 1994). The samples were ground, rehydrated to the same moisture content as the wet material, poured into a 35 mm Petri dish and wrapped with a Saran Wrap transparent film (Dow Brands L. P., Indianapolis, IN). Five replicates, each consisting of an average of five measurements (with the Petri dish filled completely) were made to obtain an overall color for each treatment. Quantitative evaluations were made by examining the total color change, ΔE, defined by:

$$\Delta E = \sqrt{\left(L^*{}_o - L^*\right)^2 + \left(a^*{}_o - a^*\right)^2 + \left(b^*{}_o - b^*\right)^2}$$

where, subscript “o” denotes the color of fresh sample of carrot or strawberry puree immediately after thawing. The value of ΔE indicates color change of the dried sample from fresh and is represented by the distance in the CIE L*a*b* color space between the points that represent the dried sample and fresh. A darkness factor b*/a* was also used to quantify possible discoloration as well as redness(a*) and blueness(b*) factors. The hue angle, H*, was obtained as:

$$H^* = \tan^{-1}(b^*/a^*)$$

Hue is the characteristic associated with the conventional perceived color name. An angle of 90° represented a yellow hue. Objects with higher hue angles are more green while lower angles are more orange-red (Gnanasekharan et al., 1992)

Table 3.1. Some physical properties of materials before and after drying* using the Refractance Window™ pilot scale dryer (water temperature = 95°C).

Material	Weight g (lb)		Moisture content, wb (%)		Moisture removed g (lb)	Drying time (minutes)
	m_i [1]	m_f [2]	$m.c._i$ [3]	$m.c._f$ [4]	m_w	
Carrot puree (CA)	9508.4 (20.96)	1071.1 (2.36)	89.4	5.9	8437.3 (18.60)	75.0
Strawberry (SA)	7290.0 (16.07)	1350.0 (2.98)	82.5	5.5	5940.0 (13.10)	80.0
Strawberry (Sw)	8206.8 (18.09)	562.4 (1.24)	93.6	9.9	7644.4 (16.85)	60.3

[1]initial weight of sample, [2]final weight of sample, [3]initial moisture content on a wet basis, [4]final moisture content on a wet basis,* values in the table are an average of three replicates.

Table 3.2. Energy measurement at the Refractance Window™ pilot scale dryer.

Source of energy input	kW	Btu/s
Water pump	1.54	1.46
Belt drive	0.03	0.03
Fan	0.35	0.33
Water heater on-time: 32.00% (CA),	0.3200 * 34.92 = 11.170	10.60
28.67%(SA),	0.2867 *34.92 = 10.010	9.49
34.27% (SW)	0.3427 * 34.92 = 11.967	11.35
Total: CA	13.09	12.41
SA	11.93	11.31
SW	13.89	13.17

4. RESULTS AND DISCUSSION

4.1. Results

Tables 4.1, 4.2, 4.3 and 4.4 summarize evaporation rate, energy for evaporation, thermal and overall energy efficiency for the samples and the alternative approach for energy efficiency calculations.

Results of carotene and ascorbic acid analyses are shown in Appendix C and D, respectively.

Table 4.1 Evaporation Rate (Q) for different materials.

Material	Evaporation Rate, Q[1]
CA	8437.32 g/ 4500 s = $1.875 * 10^{-3}$ kg/s ($4.13 * 10^{-3}$ lb/s)
SA	5940 g/ (4800 s) = $1.238 * 10^{-3}$ kg/s ($2.728 * 10^{-3}$ lb/s)
SW	7644.36g/ (3618 s) = $2.113 * 10^{-3}$ kg/s ($4.658 * 10^{-3}$ lb/s)

[1] Q = moisture removed /time. See Appendix A, for the detailed calculation of amount of removed moisture.

Table 4.2 Energy for Evaporation (E_{ev}) for different materials.

Material	Energy for Evaporation (E_{ev}[1])
CA	$1.875 * 10^{-3}$ kg/s * 2257 kJ/kg = 4.232 kW ($4.130*10^{-3}$ lb/s* 970.98 Btu/lb = 4.01 Btu/s)
SA	$1.238 * 10^{-3}$ kg/s * 2257 kJ/kg = 2.794 kW ($2.728*10^{-3}$ lb/s* 970.98 Btu/lb = 2.65 Btu/s)
SW	$2.113 * 10^{-3}$ kg/s * 2257 kJ/kg = 4.769 kW ($4.658*10^{-3}$ lb/s* 970.98 Btu/lb = 4.52 Btu/s)

[1] $E_{ev} = Q * h_{fg}$

h_{fg} = latent heat of evaporation

Table 4.3. Thermal and overall energy efficiency for the samples

Material	Overall energy efficiency (%)	Thermal energy efficiency (%)
	EF[1] = E_{ev}/Total Energy input	EF = E_{ev}/Water heater energy input
CA	EF = (4.232 /13.088) * 100 = 32.3	EF = (4.232 /11.17) * 100 = 37.9
SA	EF = (2.794 /11.928) * 100 = 23.4	EF = (2.794 /10.01) * 100 = 27.9
SW	EF = (4.769 /13.888) * 100 = 34.3	EF = (4.769 /11.97) * 100 = 39.9

See Appendix B, for thermal energy input determination. [1] EF equals energy effeciency given by the equation below:

$$EF = \frac{EnergyUse\ for\ Evaporation\,(E_{ev})}{Energy\ Input}$$

Table 4.4. Alternative approach to the energy efficiency calculation

Thermal and overall energy efficiency	CA	SA	SW
Total thermal energy input per sec.(Btu/s)	10.6	9.5	11.4
Total thermal energy input (Btu)	47686.5	45552.0	41064.3
Total amount of water removed (lb)	18.6	13.1	16.9
Heat energy/lb water removed (Btu/lb H_2O)	2563.8	3477.3	2437.1
Overall energy input per sec (Btu/s)	12.4	11.3	13.2
Overall energy input (Btu)	55858.5	54302.4	4756.3

Thermal efficiency (%)	37.9	27.9	39.9
Overall energy efficiency (%)	32.3	23.4	34.3

Note: Latent heat of evaporation (imperial unit) = 970.98 Btu/ lb.

4.2. Discussion

4. 2. 1. Energy efficiency

Results of the analyses indicated a total energy efficiency of 32.3%, 23.4% and 34.3% and thermal energy efficiency of 37.9%, 27.9% and 39.9% for the carrot puree, strawberry puree with 70% maltodextrin (DE10) additive, and the strawberry puree without additive, respectively. In Table E.1 of Appendix E, the thermal energy efficiency of the Refractance Window™ dryer is compared to those of some conventional dryers. Energy efficiencies obtained for the tested products are comparable or in some cases slightly higher than hot air drying methods (30-40%) reported in the literature. The result with the Refractance Window™ system was very conservative due to some of the constraints on the pilot plant unit, which may not be present in commercial units. Efficiency results may have been adversely affected by the following factors:

1. On-again and off-again drying during the test because of the difficulty in spreading the material, leading to much longer than needed drying time.
2. Loss of energy due to evaporation of heating water especially at the water inlet end of the drying bed.
3. Heat losses in the trough and pipes.
4. Removal of heat by the moving air over the belt.

An oversized pump and air exhaust fans may also have contributed to slightly lower total overall energy efficiency.

4. 2. 2. Nutritional retention

β-, α- and total carotene retention of the carrot samples are shown in Table C.1 of Appendix C. Total carotene content for the control was 187.7 ppm while the content in the drum, freeze and Refractance Window™ dried samples were 82.3, 180.2 and 171.3 ppm, respectively, all on a wet basis. These values represent 56.1, 4.0 and 8.7% losses due to drum, freeze and Refractance Window™ drying, respectively. Alpha-carotene content for the control sample was 90.0 ppm whereas sample contents were 40.5, 87.9 and 83.4 ppm after drum, freeze and Refractance Window™ drying, respectively. These values represent 55.0, 2.4 and 7.4% losses due to drum, freeze and Refractance Window™ drying, respectively. Similarly, the beta-carotene content for the control sample was 97.6 ppm, whereas sample contents were 41.8, 92.3 and 88.0 ppm for the drum, freeze and Refractance Window™ dried samples, respectively. These values represent a 57.1, 5.4

and 9.9% losses due to drum, freeze and Refractance Window™ drying, respectively. The results suggest that Refractance Window™ dried product is comparable to freeze dried product, while that from drum drying yielded significantly higher percent losses of carotene due to drying.

Ascorbic acid (vitamin C) analysis is presented in appendix D. Table D.1 shows 6.4 and 6.0% loss of vitamin C due to freeze and Refractance Window™ drying of single strength strawberries, respectively. About the same percentage loss of vitamin C was recorded for the strawberry single strength dried by Refractance Window™ Technology compared to the freeze-dried product for a study conducted in March, 1999, on the same units. The ascorbic acid (vitamin C) result for the strawberry single strength with maltodextrin additive was not detectable due to inherent experimental errors for all the treatments, namely, Refractance Window™, spray, and freeze-dried strawberry samples.

4. 2. 3. Drying kinetics of the Refractance Window™ system

The results of the drying kinetics study for carrot puree and strawberries with 70% maltodextrin DE10 on a Refractance Window™ system are shown in Figs.4.1, 4.2, 4.3, and 4.4. All the data were collected at the hot water circulation zone of the dryer (see Fig. 1.1). There was apparently no constant rate drying period for either sample. All drying apparently took place in the falling rate period, with decreasing drying rates toward the end of drying, similar to the report on apples with medium to low moisture content dried in a microwave-spouted bed dryer (Feng et al.,1999). The lack of a constant rate drying period may be due to the thin layer of material that did not provide a constant supply of water for an appreciable period of time. Some resistance to water movement may exist due to possible shrinkage and the formation of a hard layer on the surface (case hardening) which reduced the drying rate considerably (Geankoplis, 1993). Case hardening is particularly common with foods that contain dissolved sugars and other solutes in high concentration (Potter, 1986). The falling rate may also be due to reduced heat transfer to the lower moisture product through the belt. A residence time of 2-3

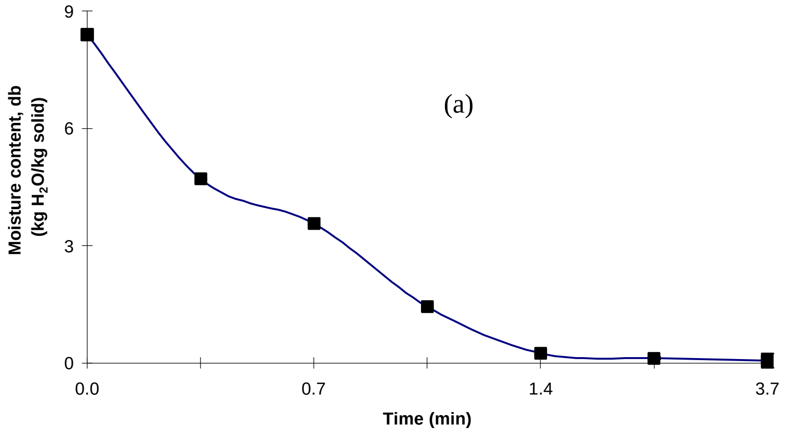
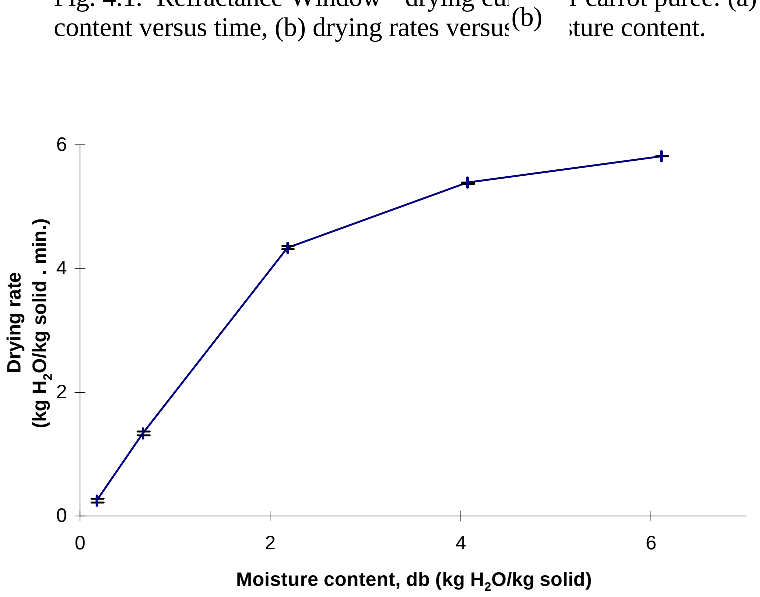
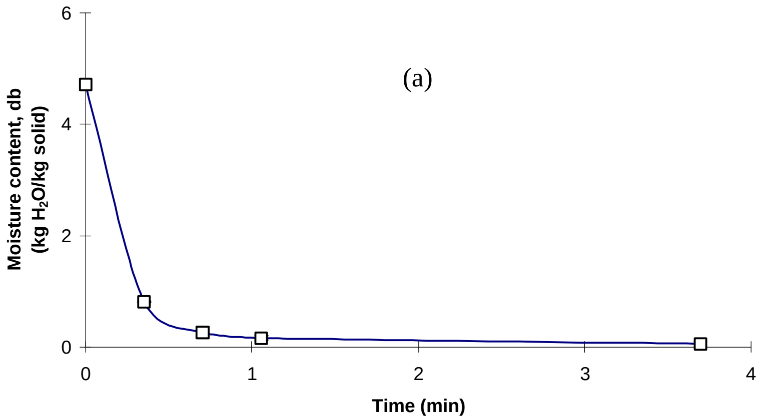


Fig. 4.1. Refractance Window™ drying curve for carrot puree: (a) moisture content versus time, (b) drying rates versus moisture content.



minutes seems adequate for both products as compared to 4 hours on the tray drier (Figs. 4.1, 4.2 and 4.5). The drying rate curves reveal that while it takes 6 minutes to remove 1 kg of water with the Refractance Window™ system, it takes about twenty times as much (120 minutes) to remove 1 kg of water in the tray drier (Fig 4.1b and 4.5b).

Fig.4.3 shows the temperature profile for carrot puree in the Refractance Window™ System, as measured by a type T thermocouple (response time 0.8s) at pre-designated location along the drying bed and at a known belt speed. The temperature appears to decrease slightly with drying time over the drying zone of the dryer with average product temperature ranging between 60 - 70 ^{o}C. The decrease in temperature could be attributed to the evaporative and air cooling effect of blower air over the drying bed and the poor



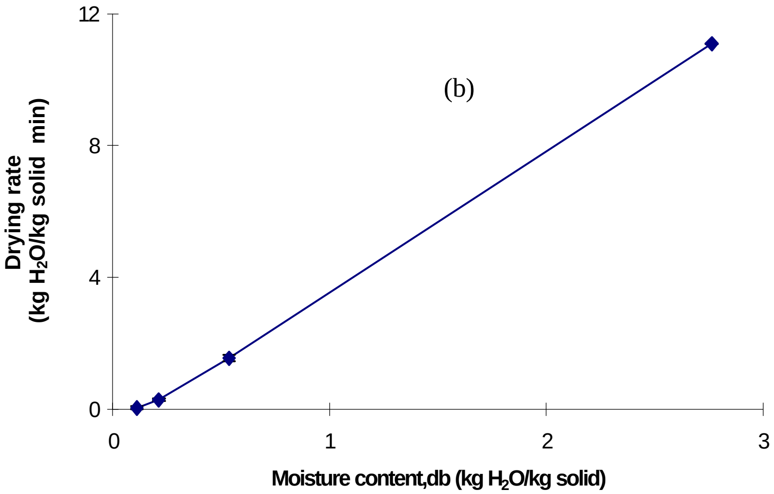


Fig. 4.2. Refractance Window™ drying curve for strawberries with maltodextrin DE10: (a) moisture content versus time, (b) drying rates versus moisture content.

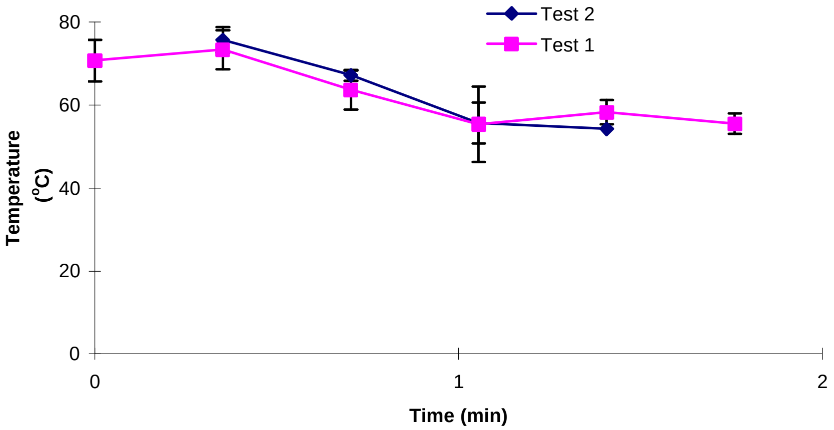


Fig. 4.3. Refractance Window™ temperature profile for carrot puree.

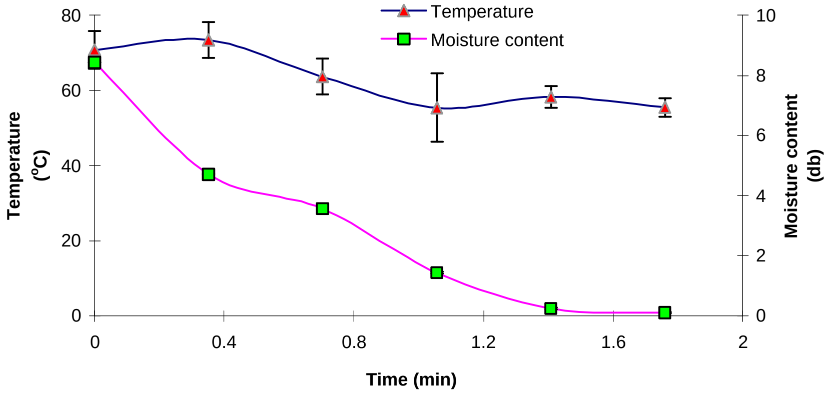


Fig. 4.4. Moisture-temperature profile plot for the carrot puree dried with the Refractance Window™ system.

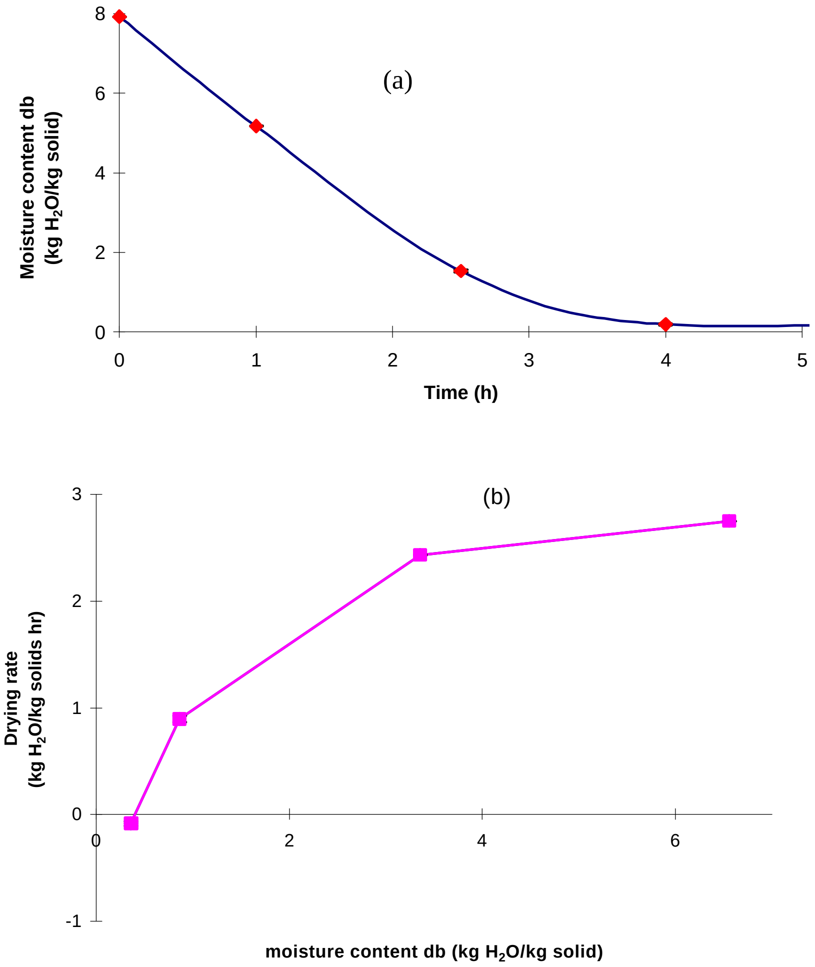


Fig. 4.5. Tray drying curve for carrot puree: (a) moisture content versus time, (b) drying rates versus moisture content.

heat conduction of the dried food material. This point was explained clearly in the case of a drum drier in which the product tends to crimp, roll up, and accumulate and stick to the doctor blade in a taffy-like mass in the absence of the cold zone (Potter, 1986). The moisture-temperature profile shows a decrease in moisture content with temperature (Fig 4.4). Mass and heat transfer for any drying system is affected by temperature, humidity, air velocity, surface area, and the food material properties (Jayaraman and Gupta,1995). A mathematical model may be developed to predict the Refractance Window™ drying system for different food products as affected by belt speed, water temperature, thickness of application by the spreader bar or nozzle, wet and dry bulb temperature, material properties, and dryer dimension.

4. 2. 4. Color comparison studies

The color changes in carrot samples as affected by different drying methods is shown in Table 4.3 and illustrated in Fig 4.6. The freeze dried sample shows the least pronounced color degradation (being very close to the fresh sample as shown by in Fig. 4.6 and the hue angle in Table 4.3). The Refractance Window™ dried samples showed less hue angle than the fresh sample. This suggest more orange-red color and probably concentration of the carotenoids content in the sample. The drum dried carrot sample showed the most pronounced color degradation. The higher hue angle suggested more yellow color and probably more oxidative loss of the carotenoids. Carotenoids are susceptible to oxidative changes during dehydration due to the high degree of unsaturation in their chemical structure (Jayaraman and Gupta, 1995)

Tables 4.4 and 4.5 present the results of color measurements for strawberry with maltodextrin and strawberry puree without additive samples. The total color change, ΔE, and darkness factor, b*/a*, characterized the overall color quality of the strawberry samples. The spray dried strawberries with maltodextrin had the most pronounced color degradation and the Refractance Window™ the least pronounced color degradation (Table 4.4 and Fig. 4.7). However, Refractance Window™ dried strawberries without additive showed relatively slight color degradation, with product exhibiting slightly less degradation than freeze dried (Table 4.5 and Fig. 4.8). The darkness of the freeze dried sample of strawberry with maltodextrin, indicated by a lower b*/a* value, increased slightly more than that of spray and Refractance Window™ dried samples (Table 4.4). The darkness of the Refractance Window™ dried strawberries without maltodextrin increased slightly more than that of the freeze dried samples (Table 4.5). The darkness of carrots and strawberries can be attributed to non-enzymatic browning (NEB) in the presence of glucose, fructose, and malic acid. The NEB rates, generally increase as water is removed during a drying process and reach a maximum at intermediate moisture contents (18% to 25%, dry basis) (Copley and Van Arsdel, 1964).

Table 4.3. Color measurement results (L*a*b*), darkness factor b*/a*, and total color difference ΔE for carrot puree

Treatment	L*	a*	b*	b*/a*	ΔE	H*
fresh	54.3±0.8	28.7±0.2	44.0±1.0	1.53	0	56.8
drum dried	67.5±0.6	20.8±0.4	39.4±1.7	1.89	17.5	62.1
RW dried	72.0±0.3	34.1±0.5	45.1±0.8	1.32	19.7	52.8
Freeze dried	77.6±0.4	27.1±1.2	44.1±0.4	1.63	24.5	58.5

L^* – lightness, a^* - redness, b^* - blueness, ΔE – difference between the color of fresh and dried products.
H*-Hue angle = $\tan^{-1}(b^*/a^*)$

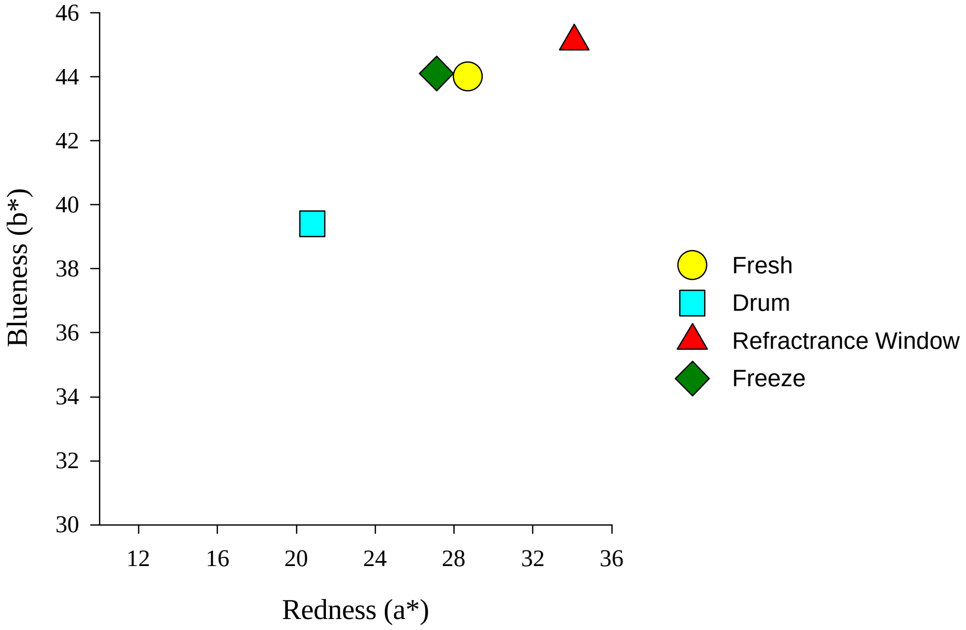


Fig. 4.6. Redness (a*) and blueness (b*) color comparison for carrot puree.

Table 4.4. Color measurement results (L*a*b*), darkness factor b*/a*, and total color difference ΔE for strawberry + maltodextrin DE10.

Treatment	L*	a*	b*	b*/a*	ΔE
Fresh	45.3±1.6	27.0±1.7	22.0±1.9	0.81	0
Spray dried	77.8±0.7	23.9±0.6	16.8±0.5	0.70	34.4
RW dried	63.2±0.5	29.3±0.6	20.2±0.5	0.70	19.3
Freeze dried	71.5±0.5	25.6±0.8	16.6±0.6	0.65	28.1

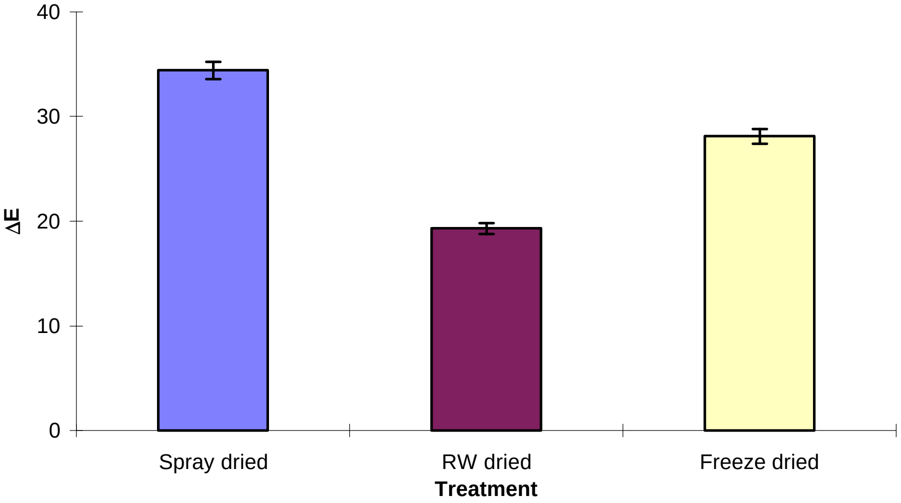


Fig. 4.7. Total color difference ΔE for strawberry + maltodextrin DE10.

Table 4.5. Color measurement results (L*a*b*), darkness factor b*/a*, and total color difference ΔE for strawberry puree.

Treatment	L*	a*	b*	b*/a*	ΔE
Fresh	36.1±1.0	25.6±0.6	19.8±0.9	0.77	0
RW dried	53.8±0.3	27.9±0.3	16.9±0.3	0.60	18.50
Freeze dried	53.8±0.5	30.0±0.4	18.8±0.4	0.63	18.70

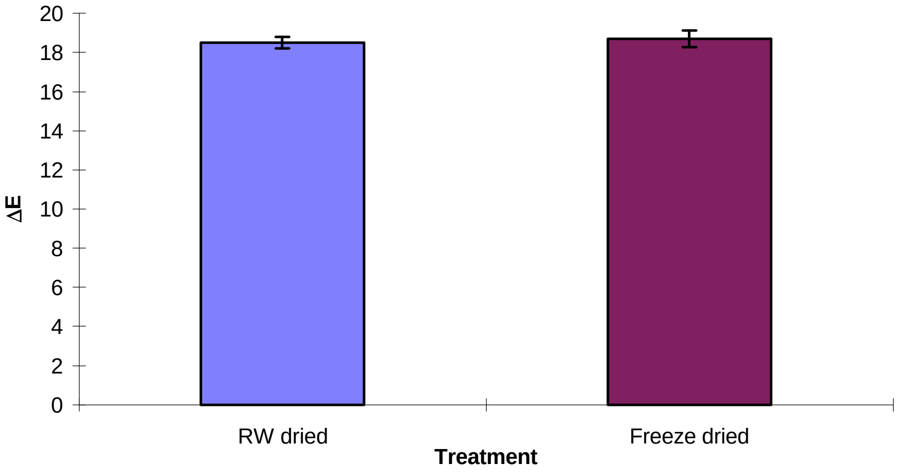


Fig. 4.8. Total color difference ΔE for strawberry puree.

5. SUMMARY AND FUTURE STUDIES

5.1. Summary

The results of the study so far are as follows:

1. Energy efficiencies (47.6, 37.9, 27.9, 39.9 %, for four different products or drying conditions, respectively) obtained from tested products are comparable or slightly higher than hot-air drying methods (30-40%).
2. Vitamin C retention of the tested product (strawberry) after drying with the Refractance Window™ system was comparable, and sometimes higher than when freeze-dried to a similar moisture content.
3. Beta-, alpha- and total carotene retention of the tested product (carrot) after drying with the Refractance Window™ system were comparable with the freeze-dried samples and much higher than the drum-dried ones.
4. The color degradation obtained for tested products are comparable or slightly less than freeze-dried products.
5. The drying kinetics of Refractance Window™ system for test product generally follow the trend obtained for similar product using other drying methods, with no apparent constant rate drying period (Feng et al., 1999).

Observations made to date in this study are as follows:

1. The Refractance Window™ system has a unique potential for the dehydration of fruits with high sugar content, even without the addition of a carrier. The retention of heat liable nutrient is very impressive and is comparable to the retention for freeze dried products.
2. It has the potential for improved energy efficiency when the constraints highlighted in this document is removed.

5.2. Future Studies

Future work will be based on how to overcome the following constraints:

1. On-again and off-again drying during the test because of the difficulty in spreading the material, leading to much longer than needed drying time.
2. Loss of energy due to evaporation of heating water especially at the water inlet end of the drying bed.
3. Heat losses in the trough and pipes.
4. Removal of heat by excessive moving air over the belt.

In all, optimization of the Refractance Window™ drying system will focus on increased energy efficiency while maintaining product quality as high as possible.

APPENDIX A. MOISTURE DETERMINATION

A.1. Method for moisture determination No. 934.06, AOAC (1996)

The moisture content of both the wet pureed products as well as the dried product were determined using a vacuum oven method (70^{o}C and 37.3 kPa) recommended by the Association of Official Analytical Chemists for dehydrated fruits and vegetables. Three replicates of each sample were used for determining the moisture content. Data from the moisture content determination is included here in Appendix A. (Data collected on power input from the heater, pump, fan and belt are listed in Table 3.2 while detailed calculation of the the thermal energy input is located in Appendix B.) The precision of the moisture content analysis was verified by determining the moisture content in three replicates each of four randomly selected samples from the treatments. The results of the moisture determination compared favorably (less than 2.9% difference) with those obtained using Karl-Fisher Coulomatic Titrimeter Model 447 (Fisher Scientific, Kent, WA) which is used as a standard to calibrate oven methods. The moisture analysis of the kinetics study was determined using the moisture/volatiles tester, C. W. Brabender model SAS 1071 (S. Hackensack, NJ). The results obtained showed less than 3.3% difference from the vacuum oven results for three replicates of the tested treatment samples.

A. 2. Calculation of amount of moisture removed

A. 2.1. Use of mass balance to derive initial weight from moisture content and final weight

It was difficult to determine the weight of wet material used for drying due to losses in handling and applications. This weight was, therefore, estimated based on the final weight of the product and the final and initial moisture contents. Product initial and final moisture content were as listed in Table 3.1

Table A.1. Amount of material and water in the tested product

Weight of material and/or moisture	CA g (lb)	SA g (lb)	SW g (lb)
Total weight of dried product, m_d	1071.08 (2.36)	1350 (2.98)	562.4 (1.24)
Moisture inside dried product, $= m.c_f * m_d$	63.20 (0.14)	74.25 (0.16)	55.64 (0.12)
Dry matter of product, DM $= m_d - m.c_f * m_d$	1007.89 (2.22)	1275.75 (2.81)	508.82 (1.12)
Total amount of water in the material, w_w	8500.50 (18.74)	6014.25 (13.26)	7698 (16.97)
Total amount of wet material, m_T $= DM + w_w$	9508.4 (20.96)	7290 (16.07)	8206.82 (18.09)
Weight of evaporated water, m_w $= m_T - m_d$	8437.3 (18.6)	5940 (13.1)	7644.36 (16.85)

APPENDIX B. DATA FROM POWER MEASUREMENTS

Table B. Water heater energy data

	CA	SA	SW
Run Time, s	4500	4800	3618
On Time, s	1447	1376	1240
Duty cycle, %	32.0	28.7	34.3
Phase voltage, volts	480	480	480
Line current , amperes	42	42	42
Total power, kW (Btu/s)[1]	34.92 (33.12)	34.92 (33.12)	34.92 (33.12)
Thermal energy used, kW (Btu/s)	11.17 (10.60)	10.01 (9.49)	11.97 (11.35)

[1] Total power = $\sqrt{3}$ *480 * 42 watts (Nilsson, 1986)

APPENDIX C. DETERMINATION OF CAROTENE CONTENT IN CARROT SAMPLES

C.1. Preparation of the dried carrot samples

Samples (2.5kg) were collected from Refractance Window^{TM}, drum and freeze dryers, with each treatment replicated three times. Samples were flushed with nitrogen to minimize oxidative loss and packaged in aluminum coated polyethylene bags (to exclude light) and stored at -20 °C until ready for analyses.

C. 2. Wet control sample extraction and saponification; modified AOAC method No. 941.15, (1996)

Upon thawing overnight at 22°C, 5 g was placed in Sorvall Omni-Mixer (Ivan Sorvall Inc., Newtown, CT). Forty (40) ml acetone, 60 ml hexane, and 0.1 g $MgCO_3$ was added to the sample and blended for 5 min. The sample was filtered by suction. The filtration was carried out through a 5.8 cm diameter Buchner funnel containing Whatman #4 filter aid (Celite 545, Fisher Co. PA). The residue was washed with two 25 ml portions acetone, then with 25 ml hexane. The extracts were combined and transferred into 250 or 500 ml separation funnel covered with aluminum foil and kept in the dark for 1 hour. Two phases were obtained, the lower phase was released into a flat bottom flask. The upper phase was saponified by adding 40% methanolic KOH (5 ml). This saponification step was conducted in the dark for 16 h at 22° C. The extract was washed of acetone with five 100 ml portions H_2O. The upper layer was transferred to a 100 ml flask and diluted to volume with hexane.

C. 3. Dried sample extraction and saponification; No. 970.64, AOAC (1996)

Sample was ground to pass No.40 sieve. A freshly ground and sieved sample (1 g) was extracted with 30 ml extractant (hexane-acetone-ethanol-toluene, 10:7:6:7, v/v/v/v) in a 100 ml Flask. The resulting slurry was saponified (cold saponification) by adding 40% methanolic KOH (2 ml) and left to stand in the dark for 16h at 22° C. Hexane (30 ml) was then added to the flask and swirled gently for 1 min. After diluting to volume with 10% Na_2SO_4 and shaking vigorously for 1 min, the flask was allowed to stand in the dark for 1 h until two layers were formed and before chromatography.

C. 4. Instrumentation.

The samples were analyzed using the Waters HPLC System (Waters, Milford, MA). It consisted of the Waters 2690 separation module pump and the Waters 996 photodiode array detector. The samples were eluted through a 3 μm particle size Microsorb-MV^{TM}, reverse phase column (100 × 4.6 mm i.d.) (Varian, Walnut Creek, CA). The mobile phase consisted of a mixture of (acetonitrite-dichloromethane-methanol, : 85:10:5,v/v/v) plus 0.05 % ammonium acetate. The flow rate was 1 ml/min.

Table C.1. Carotene[a] losses from carrot puree dried by drum, freeze and Refractance Window^{TM} drying techniques

Sample	Total carotene		alpha carotene		beta carotene	
	ppm[1]	loss (%)	ppm	loss (%)	ppm	loss (%)
Control	187.7 ± 9.2		90.0 ± 3.8		97.6 ± 5.5	
Drum dried	82.3 ± 2.3	56.1 ± 1.2	40.5 ± 1.0	55.0 ± 1.1	41.8 ± 1.2	57.1 ± 1.3
Freeze dried	180.2 ± 6.7	4.0 ± 3.6	87.9 ± 3.3	2.4 ± 3.7	92.3 ± 3.4	5.4 ± 3.5
RW^{TM}* dried	171.3 ± 3.8	8.7 ± 2.0	83.4 ± 3.3	7.4 ± 2.2	88.0 ± 1.8	9.9 ± 1.8

*Refractance Window.[1]ppm wet basis. [a] In ppm, fresh-weight basis, average of three replicates

Table C.2. Comparison of carotene losses in carrot due to RW^{TM} drying with other methods

Treatment	Alpha-carotene loss (%)	Beta-carotene loss (%)	Total carotene loss (%)
RW^{TM} dried*	7	10	9
freeze dried*	2	5	4
drum dried*	55	57	56
convection oven			24
Food dehydrator			18
microwave oven			28, 63
freeze dried		24	45-55
air dried	82	72	
explosive puff dried		36	
air dried		48	

* indicate our own results, other data were from Bao and Chang (1994), Park (1987) , Arya et al.(1979) , Rukmini et al. (1985), and Jayaraman and Gupta (1995).

APPENDIX D. DETERMINATION OF ASCORBIC ACID (VITAMIN C) CONTENT IN STRAWBERRY SAMPLES

D. 1. Procedure

Extraction of raw samples was adapted from (NCARL, 1968). Wet samples of the puree (20 g) were weighed into a Waring blender and 100ml of 3 % metaphosphoric acid was added and blended for 10 seconds. The blended mixture was centrifuged in a CRU-500, centrifuge IEC, Beckman J2-HS, speed 2000 rpm, temperature 4^{o}C, for 10 minutes. Aliquots of the filtrate (5ml) were transferred to 50 ml Erlenmeyer flasks, and titrated rapidly with 2,6-dichlorophenolindophenol solution. The volume used to reach a permanent pink color was (determined from a standard curve).

Table D.1. Comparison of Vitamin C content of Refractance Window^{TM} and Freeze Dried Products.

Sample	Sample mass (g)	Vit. C[1] in 100g sample (mg)	Vit. C loss (%)	M.C[2] wb (%)
Strawberry (single strength) without Additives				
wet sample	20	11.5		93.6±0.2
Refractance Window^{TM} dried	5	152.4	6.0±1.3	9.9±0.6
Freeze dried	5	148.1	6.4±1.6	12.1±0.5

[1] Ascorbic acid (Vitamin C), [2] moisture content on a wet basis , average of three replicates

Table D.2. Comparison of Vitamin C content of Refractance Window™ and Freeze Dried Products.

Sample	Sample mass (g)	Vit. C[1]in 100g sample (mg)	Vit. C loss (%)	M.C[2] wb (%)
Strawberry (commercial conc.)				
wet sample	20	81.1		73.0±2.7
Refractance Window™ dried	5	246.8	8.3	10.4±0.1
Freeze dried	5	231.5	10.4±1.0	14.0±1.1
Strawberry (single strength)				
wet sample	20	31.2		92.6±0.4
Refractance Window™ dried	5	375.6	2.6±0.2	8.7±0.4
Freeze dried	5	345.0	10.4±0.4	11.6±0.1
Strawberry (RW™ conc.)				
wet sample	20	9.4		83.5±0.7
Refractance Window™ dried	5	109.2	ND*	13.0±1.3
Freeze dried	5	48.0	2.2±0.3	13.4±1.2
Pineapple				
wet sample	20	8.1		88.6±0.3
Refractance Window™ dried	5	98.3	ND	7.4±0.6
Freeze dried	5	61.2	6.0±0.1	8.5±0.2
Cooked carrot (commercial)				
wet sample	20	3.1		90.0±0.3
Refractance Window™ dried	5	6.6	77.0±0.1	7.9±0.7
Freeze dried	5	5.5	81.7±0.04	4.9±0.3
Cooked corn (commercial)				
wet sample	20	1.3		85.7±0.1
Refractance Window™ dried	5	3.3	59.2±0.03	8.3±0.2
Freeze dried	5	2.2	74.4±0.05	2.5±0.1

[1] Ascorbic acid (Vitamin C), [2] moisture content on a wet basis

* ND - not detectable due to inherent experimental errors.

Table D.3. Comparison of ascorbic acid (Vitamin C) losses due to RW^{TM} drying with other methods

Food (drying method)	% Losses in ascorbic acid
Cooked carrots (Refractance Window^{TM} dried)	77*
Cooked carrots (Freeze dried)	82*, 60
Cooked corn (RW^{TM} dried)	59*
Cooked corn (Freeze dried)	74*
Strawberry (RW^{TM} dried from single strength)	3 - 6*
Strawberry (Freeze dried from single strength)	6 - 10*
Strawberry (RW^{TM} dried from concentrate)	8*
Strawberry (Freeze dried from concentrate)	10*
Apricots (unsulfited and sun dried)	96
Apricots (sulfited and sun dried)	74
Apricots (sulfited and air dried)	76
Apricots puree (unsulfited and drum dried)	82
Cauliflower (salt & sugar short soak + air drying)	83
Cauliflower (salt & sugar long soak + air drying)	61
Blueberry (freeze dried)	11
Blueberry (air dried)	56
Blueberry (vacuum dried)	89
carrots (freeze dried)	60
carrots (air dried)	81

* indicate our own results, other data were from literature (see Table E.2, Appendix E)

APPENDIX E. ENERGY, ASCORBIC ACID AND BETA-CAROTENE COMPARISON

Table E.1. Capacity and Energy Consumption for Selected Dryers.*

Dryer type	Typical evaporation capacity (kg H_2O/h.m^2 or kg H_2O/h.m^3)	Typical energy consumption kJ/kg of H_2O	Thermal efficiency
Tunnel dryer	-	5500 - 6000	42 - 38%
Band dryer	-	4000 - 6000	58 - 38%
Impingement dryer	50 m^{-2}	5000 - 7000	46 - 32.9%
Rotary dryer	30 - 80 m^{-2}	4600 - 9200	50 -- 25%
Fluid bed dryer		4000 - 6000	58 - 38%
Flash dryer	5 - 100 m^{-3}(depends on particle size)	4500 - 9000	51 - 26%
Spray dryer	1 - 30 m^{-3}	4500 - 11,500	51 - 20%
Drum dryer(for pastes)	6 - 20 m^{-3}	3200 - 6500	78 - 35%
RW^{TM} ** dryer	6 m^{-2}	4743	47.6%
		5957	37.9%
		8086	27.9%
		5664	39.9%

*adapted from Mujumdar and Menon (1995). **Refractance Window

Table E.2. Vitamin losses in selected foods during drying.*

	Loss (%)						
Food	Vitamin A	Thiamin	Vitamin B_2	Niacin	Vitamin C	Folic Acid	Biotin
Fruits**	6[b]	55[b]	0[b]	10[b]	56[b]		
Apricots (unsulfited, sun dried)	14[d]				96[d]		
Apricots (sulfited, sun dried)	13[d]				74[d]		
Apricots (sulfited, air dried)	0[d]				76[d]		
Apricots puree (sulfited, drum dried)	22[d]				82[d]		
Cauliflower (salt & sugar short soak + air drying)					83[c]		
Cauliflower (salt & sugar long soak + air drying)					61[c]		
Blueberry (freeze dried)	19[a]			46[a]	11[a]		
Blueberry (air dried)	52[a]			50[a]	56[a]		
Blueberry (vacuum dried)	50[a]			47[a]	89[a]		
Blueberry (microwave + air dried)	42[a]			40[a]	83[a]		
Fig (sun-dried)		48[b]	42[b]	37[b]			
Milk (spray dried)					15[b]	10[b]	10[b]
Milk (drum dried)					30[b]	10[b]	10[b]
Chicken (freeze dried)		5-6[e]	4-8[e]				
Pork (freeze dried)		5-30[b]					
Pork (air dried)		50-70[b]					
Selected veg.*** (air dried)	5[b]	5-9[b]	<10[b]	<10[e]			
Carrots (freeze dried)					60[d]		
Carrots (air dried)		29[e]					
Potato (air dried)		25[e]					
Carrots (Pasteurized, RW™ dried)					77		
Corn (Pasteurized, freeze dried)					74		
Corn (Pasteurized, RW™ dried)					59		
Strawberry(freeze dried)					10		
Strawberry (RW™ dried)					3		

*adapted from a) Yang and Atallah (1985), b) Fellows (1988), c) Jayaraman et al., (1990), d) Jayaraman and Gupta (1995),and e) Sokhansanj and Jayas (1995).

** mean loss from fresh apple, apricot, peach and prune

*** include peas, corn, cabbage and beans

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