ENERGY UTILIZATION AND MICROBIAL REDUCTION IN A NEW FILM DRYING SYSTEM

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ABSTRACT

Experiments were conducted with pureed pumpkin to evaluate energy efficiency and microbial reduction effect of a new thin-film drying method, Refractance Window™ (RW) drying method. RW drying system was designed based on a novel concept that uses hot water circulating beneath and in contact with a transparent plastic conveyor belt on which a thin film of pureed product is dried. In the energy study, heating water temperature, water circulation velocity, product temperature, and product moisture content were measured. In both pilot and commercial scale RW dryers with circulation water at 95ºC drying of pumpkin puree from 80% to 5% moisture content (wet basis) was achieved in less than 5 minutes. The Refractance Window™ dryer demonstrated 52% to 70% energy efficiency. The pilot scale unit was used to evaluate the effect of RW drying on microbial reduction. At a circulating water temperature of 95°C, RW drying of inoculated pumpkin purees resulted in at least 4.6, 6.1, 6.0, and 5.5 log reductions of total aerobic plate counts (APC), coliforms, *Escherichia coli*, and *Listeria innocua,* respectively.

INTRODUCTION

Dehydrated vegetables, fruits and other food ingredients are widely used in prepared foods. Maintenance of quality attributes such as aroma, color, and nutrients has always been a challenge in drying heat sensitive fruits and vegetables. Consumer demand for high quality dehydrated foods continually stimulates efforts toward development of improved and innovative drying methods. A novel thin film drying technique called Refractance Window™ (RW) drying was recently developed by MCD Technologies, Inc. (Tacoma, WA) for producing dried products from liquid and semi-liquid foods (Bolland, 2000). This drying method is characterized by mild product temperature and short drying times. In the operation of a RW dryer, liquid or semi-liquid foods (e.g., eggs, and pureed fruits and vegetables) are applied in a thin film onto a plastic belt that moves over a hot water flume (Fig. 1). The thermal energy is transferred from the hot water through the belt to remove moisture in the product. In a previous quality study it was found that this drying method results in high retention of β-carotene in carrots and vitamin C in strawberries (Abonyi, et al., 2000). However, drying known to be the most energy intensive unit operation in food processing operations. Therefore an in-depth analysis of energy consumption of this new drying system is crucial especially because of its direct relation to the cost of dried product.

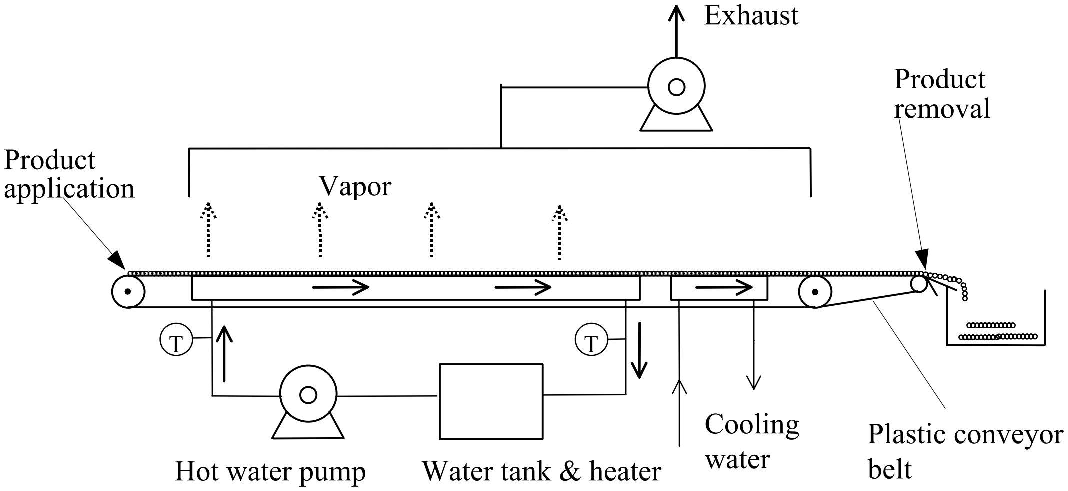


FIGURE 1: Schematic of a pilot scale Refractance Window™ drying system with one water circulation compartment

In the drying of heat sensitive foods including spices, tropical fruits, and liquid eggs, retention of characteristic quality attributes, such as flavor, pungency and functional properties, is also important. For this reason, some products are dried without prior heat treatments (e.g., blanching, precooking) to minimize exposure to heat (Vaughn, 1962; Sheneman, 1973). This raises concern over the safety of the dehydrated foods. For example, microbial counts in unblanched dehydrated vegetables could be 3 logs higher than that in the blanched counterparts, as reported by Vaughn (1951) in studies with beets, potatoes, and carrots. Previous studies also documented that food-spoilage organisms and foodborne pathogens could give rise to serious problems when dried ingredients are reconstituted by the end-user (Gibbs, 1986). To provide safe dehydrated foods to consumers, USDA imposed microbial count tolerance on soup mixes of less than 50,000 per gram for Aerobic Plate Count (APC) and less than 3 per gram for coliforms and *E. coli* (Anon., 1999).

The objectives of this study were to investigate 1) the energy efficiency of Refractance Window™ drying, and 2) the microbial reduction characteristics of RW drying technique by examining reduction of the total aerobic counts (APC), coliforms, *Escherichia coli*, and *Listeria innocua* in fresh and dried pumpkin purees.

MATERIALS AND METHODS

Preparation of Samples for Energy and Microbial Studies

Frozen pumpkin purees in 13.6 kg barrels were purchased from Stahlbush Island Farm, Inc. (Corvallis, OR). To reduce possible quality degradation, the samples for energy and microbial studies were transported to MCD Technologies (Tacoma, WA) via overnight delivery service. Pumpkin puree was used as a model food in these studies because of its good film forming ability. For the energy study, the frozen purees were thawed in cold storage at 4ºC for about 24 hours after which 11% maltodextrin was added. The samples were then well mixed and allowed to condition at room temperature for 6 to 8 hours before using in the experiment.

For the microbial tests, thawed pumpkin purees were homogenized with a pulper (White Laboratory Pulper, Model No. 60 G, Jones Tool Company, Seattle, WA) and coarse particles and fibers removed by filtering. The purees prepared in this manner had initial moisture between 85.2−86.5% on the wet basis. The thawed purees had a temperature of about 1°C, which rose to 10~13°C after the homogenization. In both the energy and microbial tests, a spreader bar was used as the puree application mechanism to form the product film on the belt. The gap between the spreader bar and the drying belt was adjusted using spacers to control the film thickness.

Moisture Content and Temperature of Puree on Drying Belt

Changes in pumpkin puree moisture with time and along the belt from the application end to the exit point were determined for both the pilot-scale and the full-scale RW dryers. Samples for moisture determination were scrapped off the belt at nine points located 0.33 m apart in the pilot-scale dryer and at 0, 3, 5, 7, 9 and 14.7m in a commercial dryer. The 0m point refers to the puree application end. The moisture contents of collected samples were determined by the vacuum oven method (AOAC, 1990).

In the full scale dryer, the surface temperature of puree was measured at the application point, within the enclosed drying section, and for the dry product, at exit using a pre-calibrated Raynger ST™ infrared thermometer (Raytek, Santa Cruz, CA). Other measurements of puree temperature change over time were made using the 3m-long pilot scale RW dryer. For this latter case, pumpkin puree was thinly spread onto the belt while it was kept stationary and the flume underneath it filled with hot water. Four pre-calibrated Type-J thermocouples were carefully secured at different locations on the surface of the belt to measure the temperatures. The tips of the thermocouples were immersed in the thin-layer of puree throughout the drying period.

Drying Test for Energy Study

The energy study was conducted with a commercial Refractance Window™ dryer (Model 2, MCD Technologies Inc., Tacoma, WA). The full-scale dryer (5 times the length of the pilot scale dryer) has an endless Mylar® plastic belt measuring 1.41 m wide and approximately 0.2mm in thickness. The effective heating section consists of four water circulation compartments covering a length of 12.9m and a 1.8-meter cooling section (Fig.2). Before the heating section is a 0.5m entry portion. At the puree application point the belt moved over a horizontal flat and rigid plate spanning the full width of the belt. A thin film of pumpkin puree approximately 0.4mm thick was spread uniformly on the plastic belt. In total, 360 kg of puree with an average total solids content of 20.3% (including 11% maltodextrin) was used in three tests to evaluate the energy consumption of the full-scale RW dryer (Table 1).

TABLE 1: Puree input and drying rate data for energy study of RW drying process.*

	Exp. 1	Exp. 2	Exp. 3
Mass of pumpkin puree (kg):			
Before drying	73.9	141.0	145.9
After drying	16.0	30.2	30.6
Puree moisture content (% wb):			
Before drying	79.4	79.6	80.1
After drying	4.9	4.7	5.2
Total drying time, (min)	64	97	86
Effective belt surface area (m^2)	17.4	17.4	17.4
Puree input (kg/hr)	69.2	87.2	101.8
Water removal rate (kg/hr)	54.3	68.6	80.4
Water removal rate (kg/hr. m^2)	3.1	3.9	4.6

* Thickness of puree on the belt was about 0.4mm.

The effective heating section had four compartments with water flowing into each of two adjoining compartments from opposite directions and exiting through a gravity chute at their intersection (Fig. 2). The flow regime was designed in a way that prevents water from accumulating in the flumes, and therefore a uniform water level was maintained in all the four compartments. The four water circulation compartments making up the heating section was in a rectangular enclosure with air filters on one side (Fig. 3a).

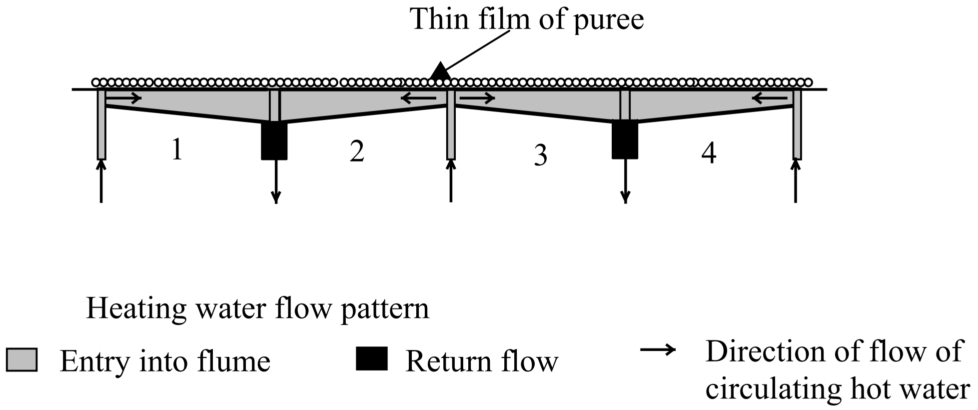


FIGURE 2: Schematic of water circulation pattern in four compartments of a commercial RW drying system

The circulating water was heated within two insulated 53-liter storage tanks by direct injection of steam from a 40-hp Clayton steam boiler (Clayton Industries, Clayton, CA). The natural gas consumption rating of this boiler at maximum steam output is 47m^3/hr, corresponding to a net heat output of 392 kW at a gauge pressure of 75 psig. At this operating condition the boiler requires 627 kg/hr of feed-water at 212ºF. The average gas consumption during the energy study experiments was 14.79 m^3/h, about 30 percent of the maximum rating. The gas burner for the boiler comes on when steam pressure is 55 psig and goes off at 75 psig, irrespective of load condition. The gas to steam conversion efficiency of the boiler is given as 80%.

Relationships for Estimating Heat Quantities in Refractance Window™ Dryer

To accurately audit the energy consumption for the full scale RW dryer, the natural gas supply to the steam boiler was monitored. After using the steam to heat the circulating water to about

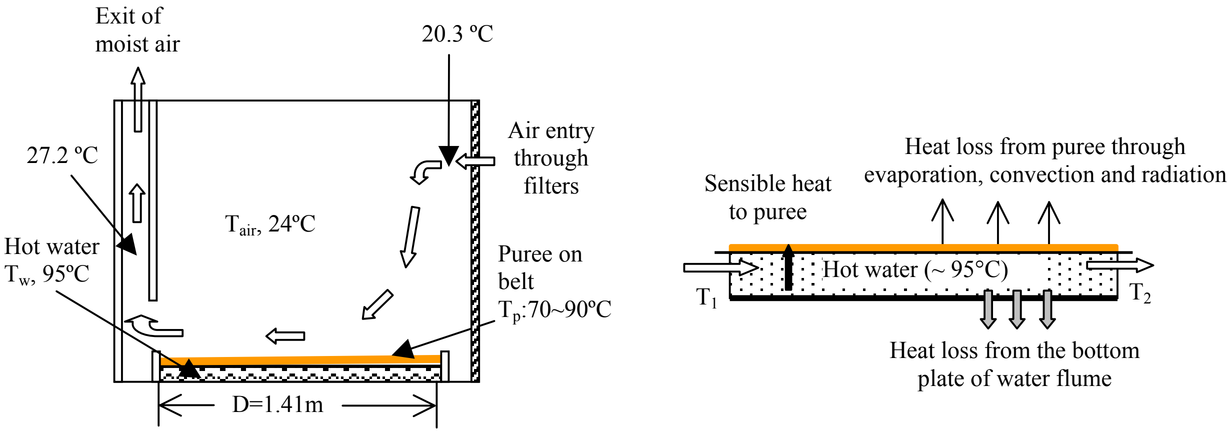
95ºC, the heat gained by the puree, the losses to the surroundings and dryer efficiency are calculated using equations (1) to (8) that follow.

1) Sensible heating of pumpkin puree from about 21° C to drying temperature

The energy Q_{sp} supplied for sensible heating of the puree was calculated from the expression:

$$Q_{sp} = m_p \times c_p \times \Delta T \tag{1}$$

where, m_p is the mass of puree processed per hour (kg/h), c_p is the average specific heat of puree, taken as 3900 J/kg ºC (Rahman, 1995) and ΔT is the average increase of puree temperature (ºC).



(a) End View (b) Heat loss from puree

FIGURE 3 Configuration of air flow, heating water and heat loss from puree in a commercial RW drying system

2) Heat lost by convection from the puree surface

A centrifugal fan located on the roof of the dryer building was used to exhaust the moisture-laden air from the dryer (Figs. 1&3a). The flow condition of the air over the puree during drying (whether laminar or turbulent) was established by calculating the Reynolds Number (Re):

$$\mathrm{Re} = \frac{u_{air} D}{\nu_{air}} \tag{2}$$

Average air velocity, u_{air}: 0.924m/s; average air temperature,T_{air}: 24ºC; mean temperature of boundary air: 59.5ºC [(95+24)/2]; and ν_{air}, the kinematic viscosity of the air = 19.1x10^{-6} (m^2/s) at the film temperature. Hence Re = 68212. Since Re<5x10^5, the air flow was laminar above the puree surface and equation (3) below is applicable according to Incropera and DeWitt (1996). At 59.4ºC, the thermal conductivity (k) of air is 0.0287 W/mºC, while the Prantl Number is 0.702. Therefore the convective heat transfer coefficient (h_{air-1}) between the air and the food was obtained from the general laminar flow relationship:

$$Nu_T = \frac{h_{air-1} L}{k} = 0.664\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3} \qquad \text{for} \quad 0.6 \le \mathrm{Pr} \le 10 \tag{3a}$$

where, Nu_T is Nusselt Number and L= 1.41m. Therefore, h_{air-1} = 3.14 W/m^{2o}C. Since effective heating surface area (A_p) is known, the heat loss from above the puree, Q_{c1} (W), was calculated as:

$$Q_{c1} = A_p h_{air-1}\left(T_p - T_{air}\right) \tag{3b}$$

3) Heat loss from the bottom plate of the water flume

Since no blower was used below the bottom plate of water flume, natural convection conditions prevailed as confirmed by calculations from equation (4a). By determining the Rayleigh Number Ra_L ($<10^{10}$ for natural convection), the heat transfer coefficient h_{air-2} between air and bottom plate of water flume was calculated using equations below (Incropera and DeWitt, 1996).

$$Nu_B = \frac{h_{air-2}L}{k} = 0.27 Ra_L^{1/4} \tag{4a}$$

$$\text{where, } Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} \tag{4b}$$

Also, g is acceleration due to gravity (9.81 m/s^2), β is the coefficient of volumetric thermal expansion of air (K^{-1}), L is characteristic length (m), ν is kinematic viscosity of air (m^2/s), α is thermal diffusivity of air (m^2/s), T_s is dryer bottom surface temperature while T_∞ is the surrounding air temperature (°K). Therefore, $h_{air-2} = 1.22$ W/m^2°C; and the heat loss (Q_{c2}) below the bottom plate was obtained from:

$$Q_{c2} = A_s h_{air-2}\left(T_s - T_\infty\right) \tag{4c}$$

Some thermal radiation losses arise from the heated dryer surfaces, especially the bottom steel surface and also from the surface of the puree being dried. Using equation (5), the radiant heat loss is estimated and these were small because of low surface temperatures involved. The endless plastic belt that moved close to the surface of bottom plate also minimized the heat losses.

$$Q_R = \varepsilon\sigma \mathrm{A}_s\left(T_s^{\ 4} - T_\infty^{\ 4}\right) \tag{5}$$

ε is the surface emissivity (taken as 0.95), σ is Stefan-Boltzman constant ($5.67\text{x}10^{-8}$ $\mathrm{W/m^2K^4}$), and $\mathrm{A_s}$ is surface area ($\mathrm{m^2}$).

4) Measurement of water velocity, heat input from natural gas and the thermal efficiency

The water flow velocity in the flumes of the commercial scale dryer was determined by noting the time taken to fill each of the four linked sections of the dryer. The temperature of circulating water at the flume inlet was regulated at 95°C and monitored periodically using infrared thermometer with its field of view targeted on a black tape mounted on the stainless steel body. Temperature of the return flow was measured similarly at the discharge point. By measuring the hot water circulation rate and the inlet and the exit temperatures (Fig. 3b), the sensible heat given up by the hot water ($Q_{in\text{-}w}$) was estimated from equation (6a):

$$Q_{in-w} = mass\ \ flow\, rate\ \ (kg/h) \times sp.\,heat\left(kJ/kg^{\circ}C\right) \times temp.\,change\left({}^{\circ}C\right) \tag{6a}$$

In addition, natural gas consumption in the dryer with and without raw material spread on the belt was recorded. Since the circulating water was heated by direct steam injection, the difference between the two gas measurements was the total energy used for sensible heating of puree (Q_{sp}), moisture evaporation (Q_{ev}) plus thermal convection and radiation losses from the dryer. Therefore, energy input from gas consumption ($Q_{in\text{-}g}$) is given by:

$$Q_{in-g} = \eta_{sce} \times calorific\ value\left(kJ/m^3\right) \times gas\ consumption\left(m^3/h\right) \tag{6b}$$

where, η_{sce} is gas to steam conversion efficiency (given by steam boiler manufacturer as 80%) and calorific value of gas is 37.2MJ/m^3. Since the observed differences in water temperature between the flume inlet and outlet points were small (~1°C), use of equation (6b) instead of (6a) is preferred because it would give more accurate results. The estimated energy for moisture evaporation (Q_{ev1}) was obtained from:

$$Q_{ev1} = Q_{in-g} - \left(Q_{sp} + Losses\right) \tag{7a}$$

The energy used for moisture evaporation can also be calculated from the measured drying rate (kg H_2O/s) and the latent heat of vaporization of water, λ_L (taken as 2336kJ/kg at 95°C), namely:

$$Q_{ev2} = \lambda_L \times \text{Drying rate} \tag{7b}$$

The overall thermal efficiency (TE) for the dryer is therefore determined from the relationship:

$$TE = \frac{Q_{ev} + Q_{sp}}{\text{Net energy input for the drying}} \times 100\% \tag{8}$$

The net energy input for the drying is the difference in energy consumption with and without product on the plastic belt (See results in Table 2).

Drying Test for Microbial Study

To investigate the effect of RW drying process on microbial reduction, a pilot scale dryer was used. The dryer was operated with a circulating water temperature of 95°C and water circulation velocity of 0.037m/s. Residence time of the purees on the drying belt was about 5 min to ensure a dried product with final moisture content less than 7.0 % (wb). A 100 and a 10 g sample were each collected for analysis before and after each test, Both the fresh purees and dried samples were sealed in ziploc bags and stored at 2°C before using for microbial enumeration two days after the drying tests.

Procedure for Microbial Culture and Bacterial Count

Three different cultures (*Escherichia coli* ATCC 23724, *Enterobacter aerogenes* ATCC 13049 and *Listeria innocua* from WSU culture collection) were used in this study. All strains were maintained at –20°C until use. Each culture was propagated in Tryptic Soy Broth (TSB, Difco Laboratories, Detroit, MI) at 37°C for 24h. After the incubation, the strains were mixed to form a culture cocktail. The cocktail was serially diluted with buffered peptone water (BPW) and then inoculated to pumpkin samples. For each test, 6.8 kg of sample was mixed with the culture cocktail to reach about 10^6 CFU/ml. The inoculated samples were then dried and subsequently rehydrated.

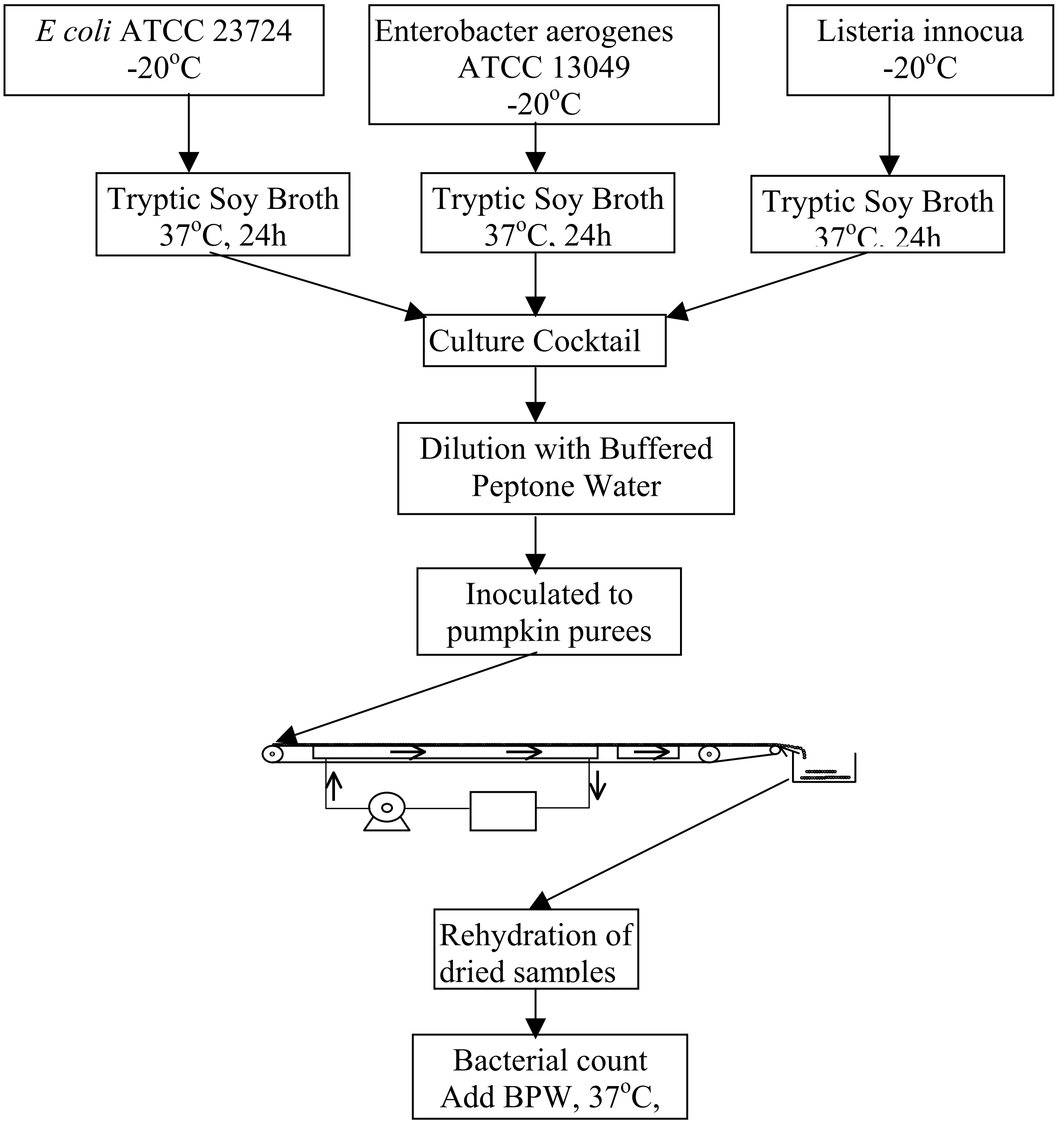


FIGURE 4: Procedures for microbial culture, sample preparation, drying test, and bacterial count

In the control experiment, 100 g of puree was measured and mixed with BPW for dilution. After serial dilution, the diluents were plated on VRBA (Violet Red Bile Agar, Difco), EMB (Eosin Methylene Blue, Difco), and OX (Oxford agar medium, Difco) for isolation and enumeration of coliforms, *E. coli*, and *L. innocua*, respectively. Three replications were done for the tests. The whole procedure for microbial culture and bacterial enumeration is summarized in Fig. 4.

RESULTS AND DISCUSSION

Effect of Circulating Water Temperature

Figure 5 shows the pilot scale test results of changes of moisture content in purees during drying. The belt was moving at a fixed speed of 0.27 m/min. At the end of the 2.9 m long drying belt, the moisture contents of the product was reduced to 57.3, 10.7, and 3.8% (wet basis), respectively, when the circulating water was 55, 75, or 95°C.

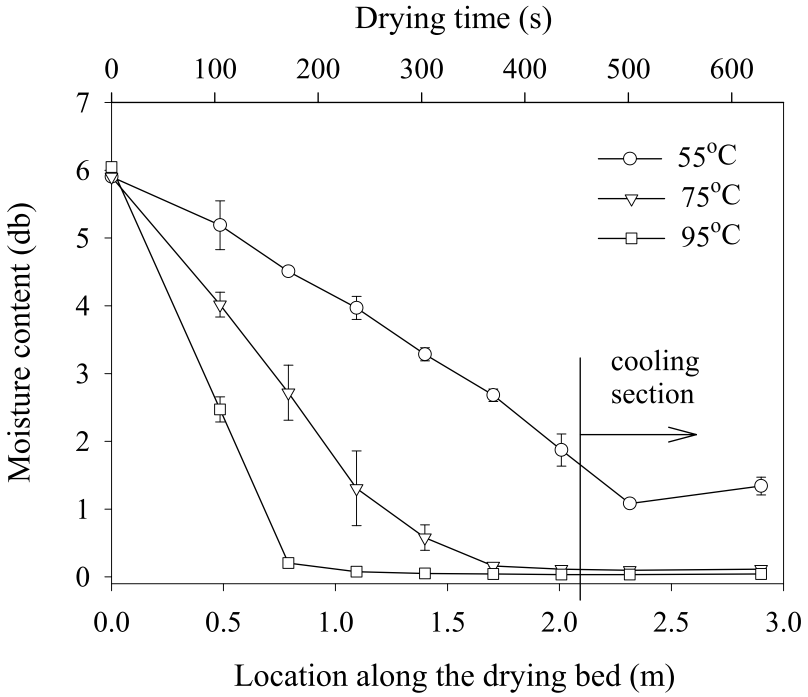


FIGURE 5: Drying curves of pumpkin purees in a pilot scale RW dryer with heating water temperature at 95, 75 and 55ºC and circulating water velocity of 0.037 m/s. Reported results are means of three replicates and error bar indicates one standard deviation.

When the circulating water temperature was 95°C, the puree moisture reached about 16.6% (wb) within the first one third of the effective heating section, while at 75°C circulating water temperature, the product traveled about 2/3 of the heating section to reach the same moisture content. At 55°C the moisture content of the puree remained as high as 57.3% (wb) when the product reached the removal end of the drying bed. Increasing the water temperature can therefore reduce the drying time and hence improve throughput capacity of the dryer. The drying rate can be improved further by increasing the temperature of heating medium (adding glycol or other similar chemicals) while at the same time suppressing the boiling point. Boiling tends to create bubbles that interfere with radiative and convective heat transfer from the hot water to plastic belt. When the experiment was repeated using the commercial scale dryer with heating water at 95°C and a belt speed of 2.98m/min, a similar trend was observed (Fig 6).

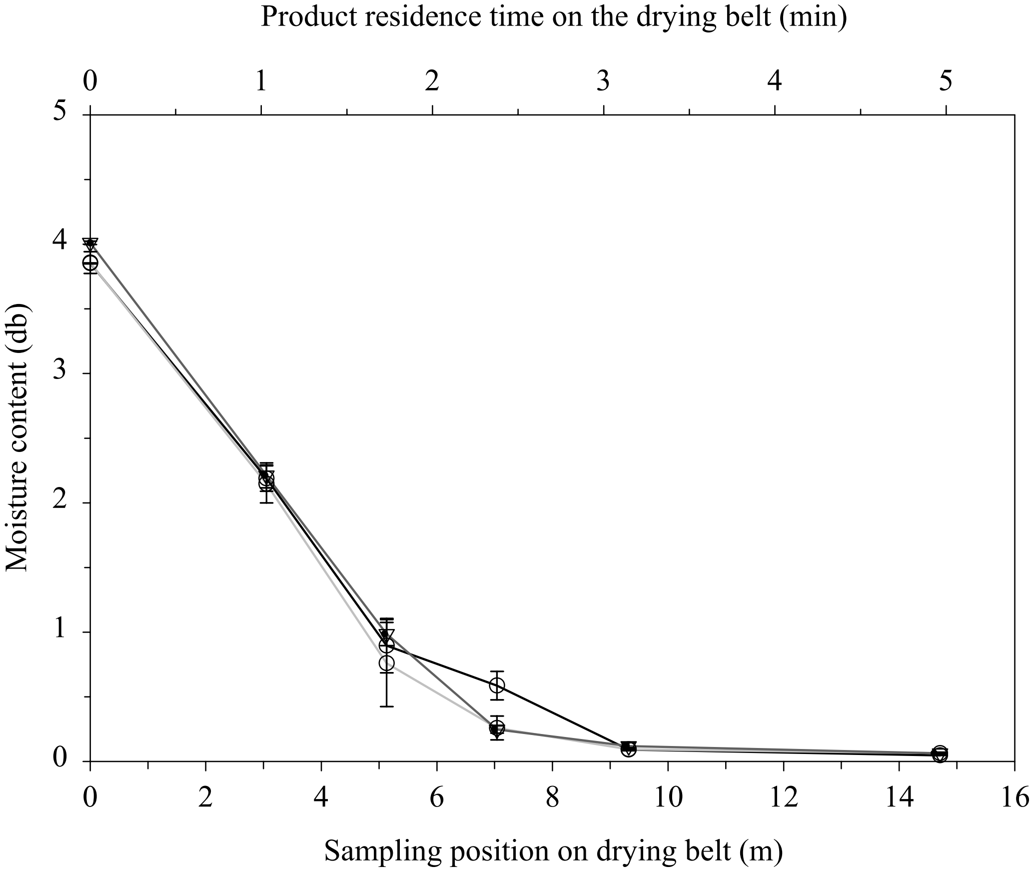


FIGURE 6: Change of puree moisture content for full-scale Refractance Window™ dryer. Results are means of three replicates and error bars are for one standard deviation.

Temperature of Puree during Drying

When the pilot scale dryer was used to study the product temperature-time history, the profile presented in Figure 7 was established. The readings were taken with the belt stationary to ensure good contact between puree sample and thermocouples. The average circulating water temperature was 90^{o}C. The measurement was made beyond 300 seconds (5min) to evaluate product temperature changes over an extended drying period. There was a rapid increase in product temperature at the beginning of the drying after which it remained nearly constant at about 19^{o}C below that of the circulating water temperature. Towards the end of the drying, product temperature increased again to approach the circulating water temperature. It is likely that during the initial heating period immediately after the product was applied to the drying belt, the large temperature difference between the product and drying belt resulted in a rapid rise in product temperature. After the product reached an appropriate temperature, a thermal balance was established between the heat transfer from the circulating water to the product surface and the removal of thermal energy due to surface moisture evaporation. This scenario created evaporative cooling. After most of the moisture was removed at about 300 s (5min) of drying (refer to Fig. 5), the evaporative cooling was reduced significantly due to much slowed moisture migration, and as a result, the product temperature started to increase again (Fig. 7). For the full scale dryer in which both the belt and hot water were in constant motion, this rise in product temperature after the initial rapid increase was less apparent.

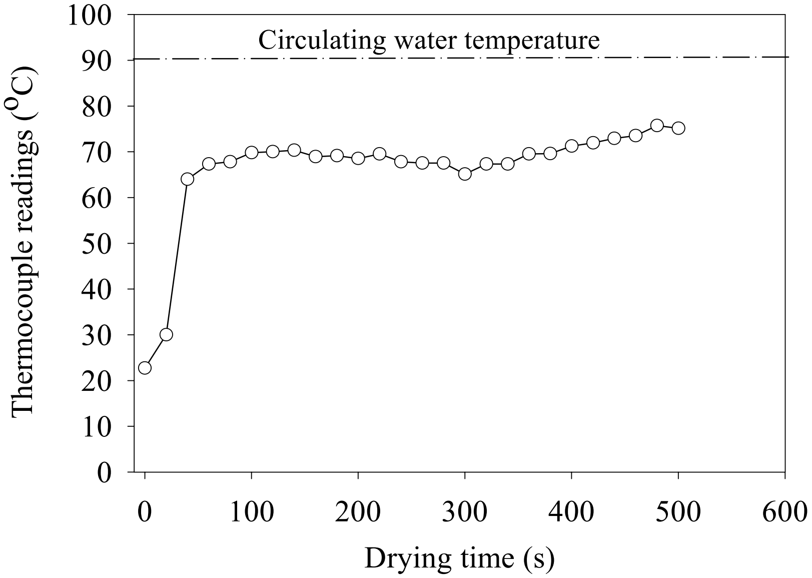


FIGURE 7: Typical puree temperature during drying (circulating water velocity 0.037 m/s and puree thickness of 0.65mm)

Thermal Efficiency of Refractance Window™ Dryer

Table 2 summarizes the magnitude of thermal energy quantities used during full-scale operation of a RW dryer. The 100% energy input (with the product on the belt) is equivalent to 12.2, 15.8, 16.3 m^3/hr of natural gas consumption [gas calorific value = 37.2MJ/m^3; See equation (6b)]. From Table 2 it can be seen that a sizable percentage of energy supplied by gas is utilized in maintaining the system in equilibrium. Additional insulation of the thermal well and other exposed parts of the steam supply system may be necessary for improving the overall efficiency. Fast flows of circulating hot water within relatively short flume lengths (2.94m) in each compartment (Fig. 2) resulted in very small changes in circulating water temperature between the flume inlet and exit points. For the system studied, the capacity of the steam boiler was greater than the load requirement for drying, even at 30% gas consumption. Still, when the dryer was operated under these conditions, 33.2~53.2% of the net heat energy from gas (above that needed for creating thermal equilibrium) was used directly for moisture evaporation.

TABLE 2: Energy balance results for Refractance Window™ drying of pumpkin purees

	Exp. 1	Exp. 2	Exp. 3
Energy input from natural gas (%)			
(a) With puree on belt (Q_{total})	100.0	100.0	100.0
(b) Without puree on belt	71.3	67.0	65.2
(c) Net heat input from gas, $Q_{in\text{-}g}$	28.7	33.0	34.8
Heat transfer components in (c) above (%)			
Convection over puree, Q_{co}	13.4	9.0	8.3
Radiation from puree, Q_R	34.4	23.2	21.3
Sensible heating of puree, Q_{sp}	18.9	16.0	17.2
Heat for moisture evaporation (%)			
- Calculated, Q_{ev1}	33.3	51.8	53.2
- Experimental, Q_{ev2} [as % of Q_{total}]	34.8	33.9	38.7
Thermal efficiency, TE (%)	52.1 (33.3)*	67.8 (51.8)*	70.4 (53.2)*

*The figures in brackets refer to the percentage of heat energy used for moisture evaporation alone, excluding that expended in sensible heating of the puree from 21°C to its drying temperature.

When equation (7b) is used to calculate the energy for moisture evaporation Q_{ev2}, the absolute values obtained are higher but closer to the net energy input from natural gas, $Q_{in\text{-}g}$ (Table 2). This discrepancy may be the result of errors from many sources, including 1) use of gas to steam conversion of 80%, 2) measurement of puree moisture content, 3) flow rate of circulating water and, 4) losses from steam heating. The radiant heat transfer from the circulating hot water through the belt into puree, in addition to contact heating from the belt, all combined to create very fast drying. From the results obtained, the RW drying system is comparatively more efficient (between 52-70%) when compared with other dryers existing in the market (Table 3). In addition, its use of mild heating temperatures means better retention of desirable volatiles for heat sensitive products.

TABLE 3: Comparison of capacities and energy consumption of RW systems and other selected dryers

Dryer Type	Typical capacity (kg H_2O/h) per m^3 or m^2	Typical product temperature (˚C)	Thermal Efficiency
Rotary dryer*	30~80 m^{-3}	~175	50 ~ 25
Spray dryer	1 ~ 30 m^{-3}	80 ~ 120	51 ~ 20%
Drum dryer (for pastes)	10 ~ 80 m^{-2}	120 ~ 130	78 ~ 35%
Refractance Window™			
- pilot scale dryer	10 m^{-2}	70 – 90	48 ~ 28%
- full-scale dryer	4.6 m^{-2}	90~95	70 ~ 52%

* Barr and Baker (1997)

Microbial Reduction

The results of microbial tests are summarized in Table 4. It can be seen that the microbial count after RW drying was greatly reduced for all four microorganisms. The initial total aerobic count (APC) in non-inoculated pumpkin puree was 7.17-log CFU/ml and after drying the APC was reduced to 2.54-log CFU/ml, a 4.6-log reduction. The high initial CFU in pumpkin puree might have been due to high counts of soil-borne or waterborne microorganisms because pumpkins grow in direct contact with the soil (Vaughn, 1951). During drying, the gram negative rods were mostly inactivated while the gram positive flora might have survived because of their higher resistance to heat (Skovgaard, 1968). Prescott and his associates (1922) isolated molds in dehydrated vegetables but found no yeasts. It is likely that the residual microbes in dehydrated pumpkin puree were mainly molds and some gram positive bacteria.

TABLE 4: Microbial counts in log CFU/ml as affected by Refractance Window™ drying[*]

	APC		Coliforms		*Escherichia coli*		*Listeria innocua*	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Control	7.17	0.12	6.78	0.09	6.73	0.14	6.14	0.11
Treated	2.54	0.26	< 0.69	NA	< 0.69	NA	< 0.69	NA
Log reduction	4.63		6.09		6.04		5.45	

[*] Circulating water temperature was 95°C and the reported data are means of three replicated tests for each group of microorganism.

For the inoculated samples, the test microorganisms were reduced to the minimum detection limit of <5 CFU/ml, which corresponds to a microbial reduction of at least 6.1-, 6.0-, and 5.5-log CFU/ml for coliforms, *Escherichia coli*, and *Listeria innocua*, respectively. *Listeria monocytogenes* is an important heat-tolerant food borne pathogen (Alpa et al., 2000). It is often a target pathogen in developing mild heat processes (Anderson et al., 1991). In certain circumstances, *L. innocua* has been widely used as a surrogate microorganism for *L. monocytogenes* because of the similarity in thermal resistance between the two species (Carminati et al., 2000). It is, therefore, expected from the result of *L. innocua* that the RW drying system can achieve a significant destruction in *L. monocytogenes* population. In the case of coliforms and *E. coli*, the numbers were strongly inhibited by RW drying procedures. The main reason to use these microorganisms is that coliforms and *E. coli* are usually used as indicator microorganisms for food safety and hygiene (Edberg et al., 1991; Jayaraman and Das Gupta, 1995). The reduction of inoculated populations (10^6 CFU/ml) of coliforms and *E. coli* to an undetectable level indicates that RW drying can produce products with much reduced counts of pathogens.

Sullivan and Jo Egoville (1986) studied the microbial reduction during explosion puff drying of unblanched mushrooms and observed a 5.2- log CFU/ml reduction in total microbial count. A study conducted by Gothandapani et al. (1997) investigated the microbial reduction of oyster mushroom dried with sun drying method, fluidized bed drying, and thin layer drying, after blanching, treatment with potassium metabisulphite and soaking at concentrations of 0.5, 1.0, and 1.5%. They examined the total bacteria count, coliforms, yeast, and fungi in fresh and dried samples. For blanched samples, they achieved less than 2-log reductions for all three drying methods in all the four indicators examined. Compared with the microbial studies reported in the drying literature and based on results in Table 4, it is seen that RW drying is very effective in reducing microbial counts.

A typical temperature-time history in pumpkin puree and microbial reduction during drying is shown in Fig. 8. The log reduction of *L. monocytogenes* when exposed to the same drying temperatures (calculated from D_{70}= 0.2 min and z = 6ºC for *L. monocytogenes)*, is also plotted in the same figure. The estimated thermal reduction for *L. monocytogenes* at the end of drying is 20-log. We recorded only 5.5-log reduction in *L. innocua* counts because the level of initial inoculation limits the number. Furthermore, we detected zero count in the dried samples. The recorded reduction from experiments, therefore, does not contradict the predicted reduction.

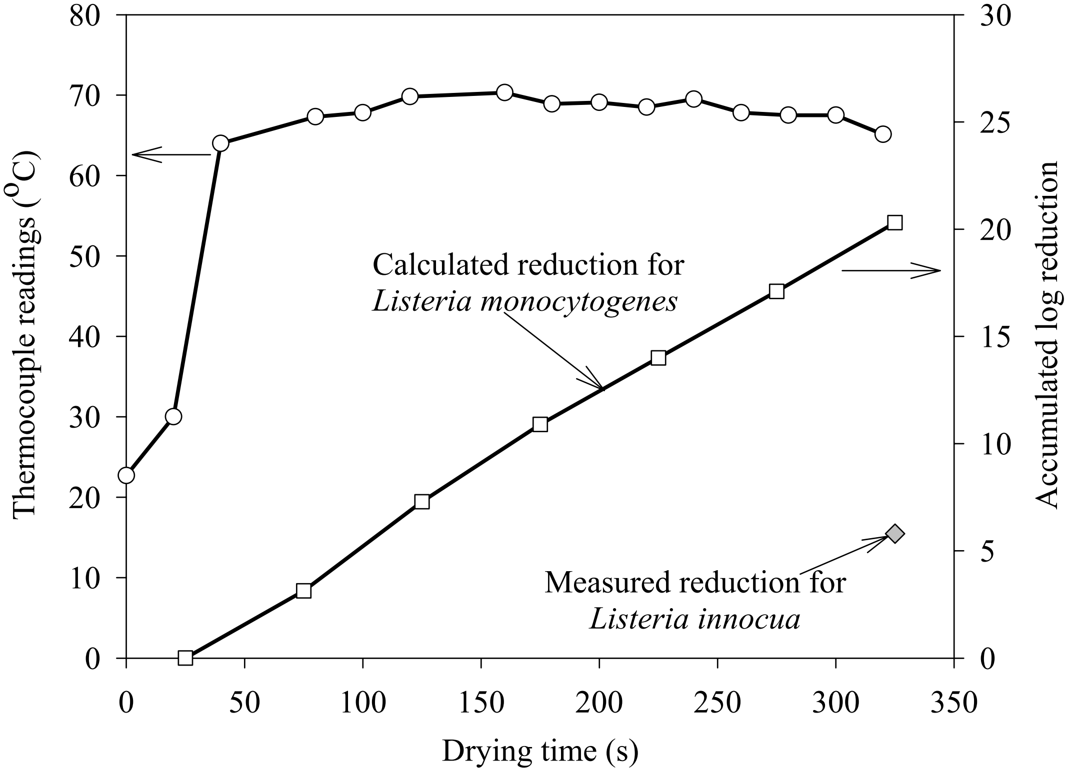


FIGURE 8: Puree temperature and accumulated log reduction in population of *Listeria monocytogenes* as a function of drying time. The accumulated decimal reduction was calculated from the temperature profile and the D_{70} value of 0.2 min.

CONCLUSION

Studies conducted with both the pilot scale and full scale RW dryer showed that with a circulating water temperature of 95ºC, complete drying of pumpkin puree was achieved in less than 5 minutes. With the steam boiler operating at 30% of its design gas consumption capacity, between 28.7~34.8% of the energy was used in the RW dryer. When energy expended in sensible heating of puree is lumped with that for moisture evaporation, then the overall thermal efficiency of the full scale RW dryer is between 52~70%. In the microbial tests, at least 4.6-, 6.1-, 6.0-, and 5.5 log reductions were achieved for APC, coliforms, *E. coli*, and *L. innocua,* respectively. The coliforms, *E. coli*, and *L. innocua* counts were reduced to undetectable levels in the RW dried samples. The results obtained show that the RW system is energy efficient and has good microbial reduction ability.

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