# 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 Refractance Window™ (RW) drying method. The 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 puree is dried. In the energy study, water temperature, water circulation velocity, puree temperature, and puree moisture content were determined. In both pilot and commercial scale RW dryers with circulating water at 95C, drying of pumpkin puree from 80% to 5% moisture content (wb) was achieved in less than 5 min. 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 95C, 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.*

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## INTRODUCTION

Dehydrated vegetables, fruits and other food ingredients are widely used in prepared foods. Maintenance of quality attributes such as aroma, color, and nutrients is always 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 semiliquid 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 semiliquid 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 evaporate moisture from the product. In a previous quality study, RW drying resulted in very high retention of $\beta$-carotene in carrots and vitamin C in strawberries (Abonyi $et$ $al.$ 2002). However, as drying is often the most energy intensive unit operation in food processing operations, an in-depth analysis of energy consumption of this new drying system is needed especially because of its direct relation to the cost of dried product.
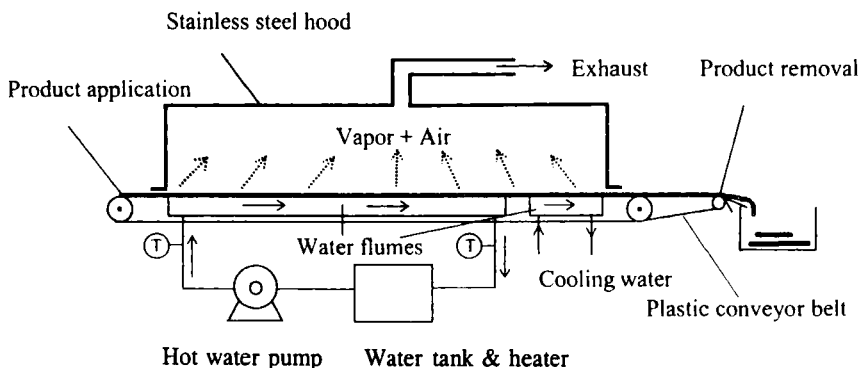


FIG. 1. SCHEMATIC OF A PILOT SCALE REFRACTANCE WINDOW™ DRYING SYSTEM
WITH ONE WATER CIRCULATION COMPARTMENT

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 about 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 may 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 tolerances 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 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 Purees 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 pumpkin purees 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 4C for about 24 h, after which 11% maltodextrin was added to act as a carrier by modifying the viscosity for easy application of puree onto the belt. The purees were then well mixed and allowed to condition at room temperature for 6 to 8 h before using in the energy study experiment.

For the microbial tests, thawed pumpkin purees were homogenized with a pulper (White Laboratory Pulper, Model No. 60 G, Jones Tool Co., Seattle, WA) and coarse particles and fibers removed by filtering. The purees prepared in this manner had initial moisture between 85.2 to 86.5% (wb). The temperatures of the thawed purees were initially about 1C, which rose to ~10 to 13C after homogenization. In both the energy and microbial tests, a spreader bar was used as the puree application mechanism to form a uniform product film on the belt. The gap between the spreader bar and the drying belt was adjusted using spacers to control 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. Purees for moisture determination were scraped off the belt at nine points located 0.33 m apart in the pilot-scale dryer. For the commercial dryer, the purees were taken initially, at 3, 5, 7, and 9 m along the belt and at the end of the belt (14.7 m). The moisture contents of collected purees 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 drying section enclosed with a stainless steel hood (Fig. 1), and at the exit point for the dry purees. A precalibrated Raynger ST™ infrared thermometer (Raytek, Santa Cruz, CA) was used for the temperature measurements. In the separate precalibration tests, the emissivity values were obtained by adjusting the infrared thermometer until the temperature reading matched with that of the thermocouple. Other measurements of puree temperature change over time were made using the 3 m × 0.6 m pilot scale RW dryer with the Mylar® belt in a stationary position. For this latter case, pumpkin puree was spread onto the belt to about 0.65 mm using a spreader bar, after which the flume underneath it was filled with hot water. Four precalibrated Type-J thermocouples were carefully secured at selected 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 (five times the length of the pilot scale dryer) has an endless Mylar® plastic belt measuring 1.41 m wide and approximately 0.2 mm in thickness. The effective heating section consists of four water circulation compartments covering a length of 12.9 m and a 1.8 m cooling section (Fig. 2). Before the heating section is a 0.5 m entry portion. At the puree application point, the belt moved at 2.98 m/min over a horizontal flat and rigid plate spanning the full width of the belt. A thin film of pumpkin puree approximately 0.4 to 0.6 mm 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
REFRACTANCE WINDOW DRYING PROCESS[1]

|  | 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/h) | 69.3 | 87.2 | 101.8 |
| Water removal rate (kg/h) | 54.3 | 68.6 | 80.4 |
| Water removal rate (kg/h. m$^2$) | 3.1 | 3.9 | 4.6 |

[1] Thickness of puree on the belt averaged between 0.4 ~ 0.6 mm.

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 the four compartments. The four water circulation compartments making up the heating section were in a rectangular enclosure with air filters on one side (Fig. 3a).
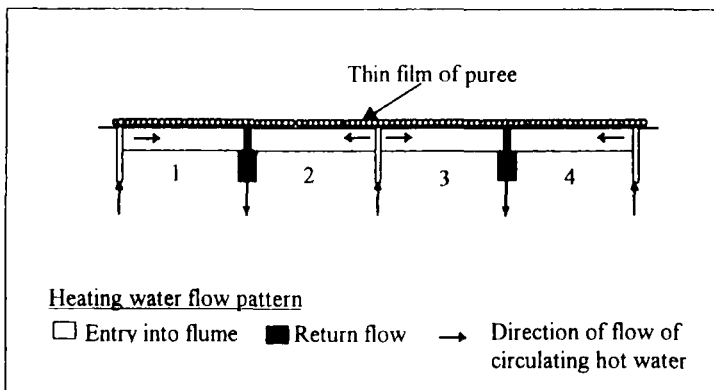


FIG. 2. SCHEMATIC OF WATER CIRCULATION PATTERN IN FOUR COMPARTMENTS
OF A COMMERCIAL RW DRYING SYSTEM

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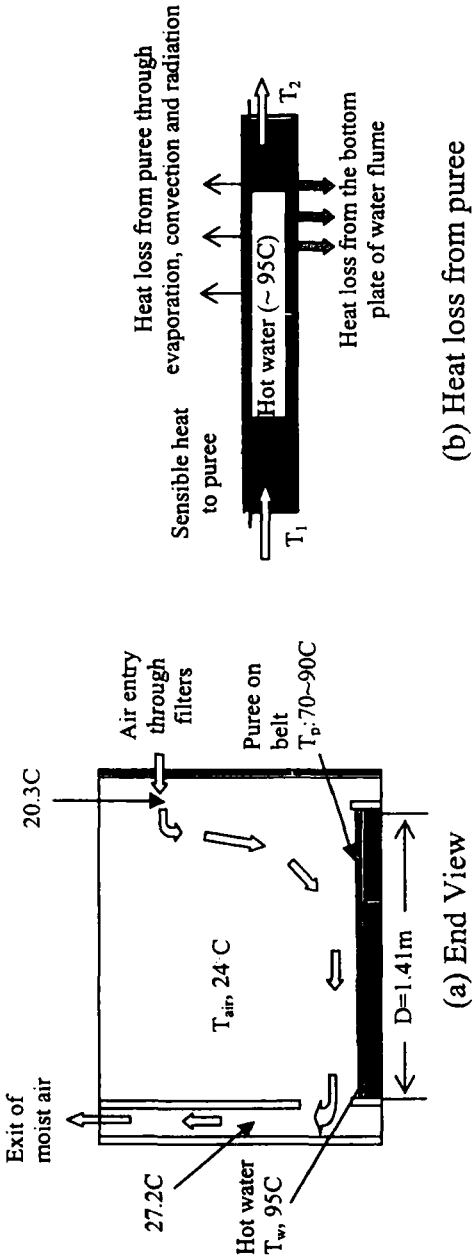
(b) Heat loss from puree

FIG. 3. CONFIGURATION OF AIR FLOW, HEATING WATER AND HEAT LOSS FROM PUREE IN A
COMMERCIAL RW DRYING SYSTEM

The circulating water was heated within two insulated 760 L 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 47 $m^3$/h 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/h of feed water at 212F. The mean gas consumption during the energy study experiments was 14.79 $m^3$/h, about 30% 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 95C, the heat gained by the puree, the losses to the surroundings, and dryer efficiency are calculated using Eq. (1) to (8) that follow.

**Sensible Heating of Pumpkin Puree from about 21C to an End Point Product 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 mean specific heat of puree, taken as 3900 J/kg C (Rahman 1995) and $\Delta T$ is the mean increase of puree temperature.

**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 (Fig. 1 and 3a). The flow condition of the air over the puree during drying (whether laminar or turbulent) was established by calculating the Reynolds Number (Re):

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

Mean air velocity, $u_{air}$: 0.924 m/s; mean air temperature, $T_{air}$: 24C; mean temperature of the boundary air: 59.5C [(95 + 24)/2]; D is width of belt (m); and $v_{air}$, the kinematic viscosity of the air = 19.1 × 10$^{-6}$ m$^2$/s at the mean temperature of the boundary air. Therefore, Re = 68212. Since Re < 5 × 10$^5$, the air flow is laminar above the puree surface and Eq. (3) is applicable according to Incropera and DeWitt (1996). At 59.5C, the thermal conductivity ($k$) of air is 0.0287 W/mC, while the Prantl Number is 0.702. Therefore the convective heat transfer coefficient ($h_{air-1}$) between the air and the food may be obtained from the general laminar flow relationship:

$$Nu_T = \frac{h_{air-1}L}{k} = 0.664 Re^{1/2}Pr^{1/3} \quad \text{for } 0.6 \leq Pr \leq 10 \qquad (3a)$$

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

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

**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 Eq. (4a). By determining the Rayleigh Number $Ra_L$ (< 10$^{10}$ for natural convection), the heat transfer coefficient $h_{air-2}$ between the air and bottom plate of the water flume was calculated using Eq. (4a) and (4b) (Incropera and DeWitt 1996).

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

where,

$$Ra_L = \frac{g\beta(T_s-T_\infty)L^3}{v\alpha} \qquad (4b)$$

Where g is acceleration due to gravity (9.81 m/s$^2$), $\beta$ is the coefficient of volumetric thermal expansion of air (K$^{-1}$), L is characteristic length (m), $v$ is kinematic viscosity of air (m$^2$/s), $\alpha$ is thermal diffusivity of air (m$^2$/s), $T_s$ is dryer bottom surface temperature (368 K) while $T_\infty$ is the surrounding air

temperature (293 K). Therefore, $h_{air-2}$ = 1.22 W/m$^2$C; and the heat loss ($Q_{c2}$) below the bottom plate was obtained from:

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

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. The radiant heat loss is estimated using Eq. (5). Radiant heat losses were small because of the low surface temperatures involved. The endless plastic belt that moved close to the surface of bottom steel plate also minimized the heat losses.

$$Q_R = \varepsilon \sigma A_s \ F_{s-w} \ (T_s^4 - T_\infty^4) \qquad (5)$$

$\varepsilon$ is the surface emissivity (taken as 0.22 for steel and 0.95 for puree), $\sigma$ is Stefan-Boltzman constant (5.67 $\times$ 10$^{-8}$ W/m$^2$K$^4$), and A$_s$ is surface area (m$^2$). From the configuration and dimensions of drying section (12.9 m $\times$ 1.41 m $\times$ 0.9 m), which is completely enclosed, the belt surface to dryer wall view factor ($F_{s-w}$) is nearly 1.0 (Incropera and DeWitt 1996). Therefore, heat loss by radiation from the puree surface and from the bottom steel plate is very small.

**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 95C 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 ($Q_{in-w}$) was estimated from Eq. (6a):

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

In addition, natural gas consumption for the dryer with and without raw material on the belt was recorded while maintaining the temperature of water circulating under the belt at 95C in both cases. 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 ($Q_{in-g}$) is given by:

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

where, $\eta_{sce}$ 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 ($\sim 1$C), use of Eq. (6b) instead of (6a) is preferred because it would give more accurate results. The estimated energy for moisture evaporation ($Q_{evl}$) was obtained from:

$$Q_{evl} = Q_{in-g} - (Q_{sp} + Convective\ and\ Radiation\ Losses) \quad (7a)$$

The energy used for moisture evaporation can also be calculated from the measured drying rate (kg H$_2$O/s) and the latent heat of vaporization of water, $\lambda_L$ (taken as 2336 kJ/kg at 95C), namely:

$$Q_{ev2} = \lambda_L \times Drying\ rate \quad (7b)$$

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

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

The net energy input for the drying is the difference in energy consumption with and without product on the plastic belt (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 95C and water circulation velocity of 0.037 m/s. Residence time on the drying belt for puree with 0.65 mm thickness was about 5 min. This ensured a dried pumpkin puree with a final moisture content less than 7.0% (wb). A 100 g and a 10 g sample were each collected for analysis before and after each test. Both the fresh purees and dried purees were sealed in Ziploc bags and stored at 2C 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 –20C until use. Each culture was propagated in Tryptic Soy Broth (TSB, Difco Laboratories, Detroit, MI) at 37C for 24 h. 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 purees. For each test, 6.8 kg of puree was mixed with the culture cocktail to reach about $10^6$ CFU/mL. The inoculated purees were then dried and subsequently rehydrated.
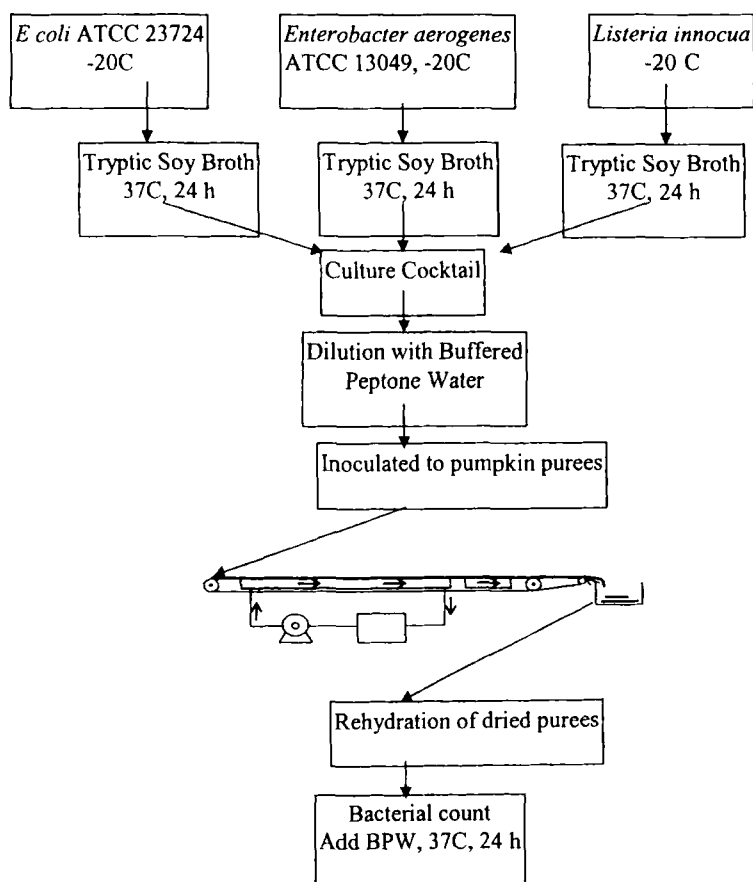


FIG. 4. PROCEDURES FOR MICROBIAL CULTURE, PUREE COLLECTION,
DRYING TEST, AND BACTERIAL COUNT

In the control experiments, 100 g of puree was weighed 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 presents the pilot scale test results for 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 95C.
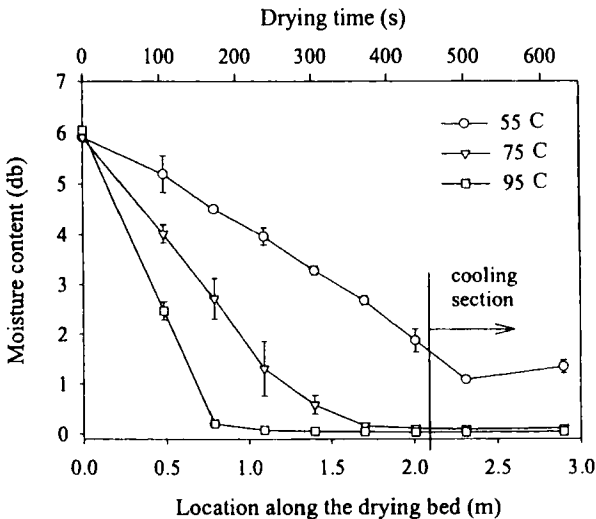


FIG. 5. DRYING CURVES OF PUMPKIN PUREES IN A PILOT SCALE RW DRYER WITH HEATING WATER TEMPERATURE AT 95, 75 AND 55C AND CIRCULATING WATER VELOCITY OF 0.037 m/s
Reported results are means of three replicates and error bar indicates one standard deviation.

When the circulating water temperature was 95C, the puree moisture reached about 16.6% (wb) within the first one third of the effective heating section, while at 75C circulating water temperature, the product traveled about 2/3 of the heating section to reach an equivalent moisture content. At 55C the moisture content of the puree remained as high as 57.3% (wb) when the puree reached the removal end of the drying bed. Increasing the water temperature can therefore reduce the drying time and improve the 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 radiation 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 95C and a belt speed of 2.98 m/min, a similar trend was observed (Fig. 6).
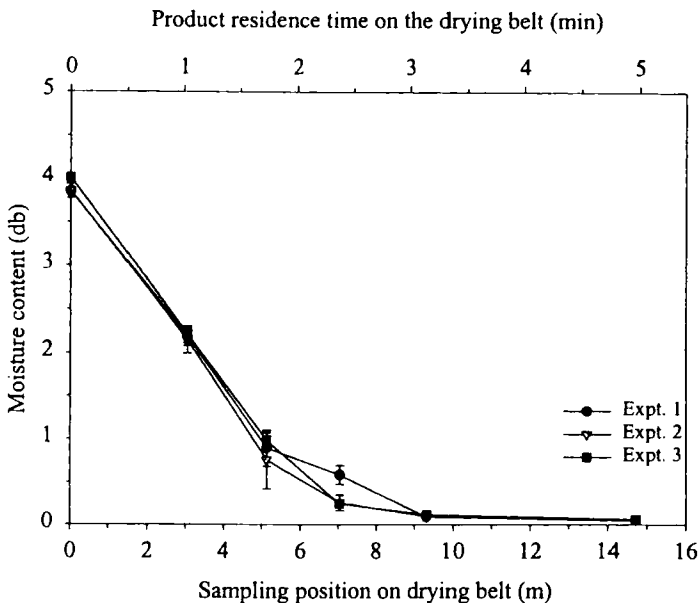
Product residence time on the drying belt (min)

FIG. 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 puree temperature-time history, the profile presented in Fig. 7 was established. The readings were taken with the belt stationary to ensure good contact between puree and thermocouples. The mean circulating water temperature was 90C. The measurement was made beyond 300 s (5 min) to evaluate puree temperature changes over an extended drying period. There was a rapid increase in puree temperature at the beginning of the drying after which it remained nearly constant at about 19C below that of the circulating water temperature. Towards the end of the drying, puree temperature increased again to approach the circulating water temperature. It is likely that during the initial heating period immediately after the puree was applied to the drying belt, the large temperature difference between the puree and drying belt resulted in a rapid rise in puree temperature. After the puree reached an appropriate temperature, a thermal balance was established between the heat transfer from the circulating water to the puree 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 (5 min) of drying (Fig. 5), the evaporative cooling was reduced significantly due to much slowed moisture migration, and as a result, the puree 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 puree temperature after the initial rapid increase was less apparent.
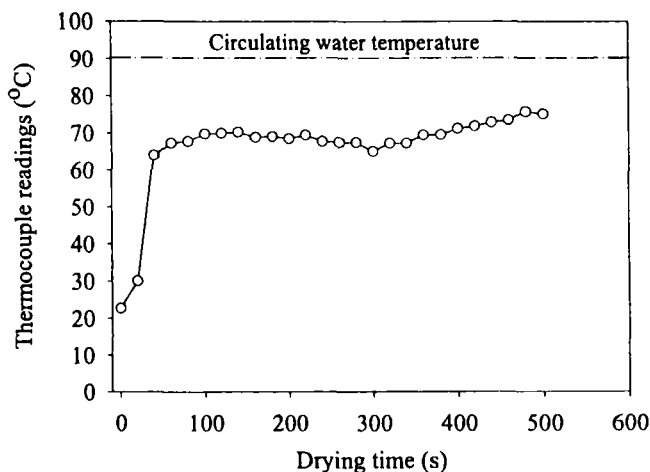


FIG. 7. TYPICAL PUREE TEMPERATURE DURING DRYING (CIRCULATING
WATER VELOCITY 0.037 m/s AND PUREE THICKNESS OF 0.65 mm)

## 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 m³/h of natural gas consumption [gas calorific value = 37.2 MJ/m³; See Eq. 6b]. A sizable percentage of energy supplied by gas is utilized in maintaining the system in equilibrium (Table 2). Additional insulation of the thermal well and other exposed parts of the steam supply system may be necessary for improving the overall efficiency. Rapid flow of circulating hot water within relatively short flume lengths (2.94 m) in each compartment (Fig. 2) resulted in 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, approximately 33.3 to 53.2% of the net heat energy from gas (greater than 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, $Q_{in-g}$ | 28.7 | 33.0 | 34.8 |
| Heat transfer components (as % $Q_{in-g}$) |  |  |  |
| 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, $Q_{ev1}$ (as % $Q_{in-g}$) | 33.3 | 51.8 | 53.2 |
| - Experimental, $Q_{ev2}$ (as % of $Q_{in-g}$) | 34.8 | 33.9 | 38.7 |
| Thermal efficiency, TE (%) | 52.2 (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 21C to its drying temperature.

When Eq. (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, $Q_{in-g}$ (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 the puree, in addition to contact heating from the belt, combined to create rapid drying. From the results obtained, the RW drying system is comparatively more efficient (between 52 to 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 THERMAL EFFICIENCY OF REFRACTANCE
WINDOW DRYING SYSTEMS AND OTHER SELECTED DRYERS[1]

| Dryer Type | Typical Capacity (kg H$_2$O/h) per m$^3$ or m$^2$ | Typical Product Temperature (C) | Thermal Efficiency |
|---|---|---|---|
| Rotary dryer | 30 ~ 80 m$^{-3}$ | ~ 175[2] | 50 ~ 25 |
| Spray dryer | 1 ~ 30 m$^{-3}$ | 80 ~ 120 | 51 ~ 20% |
| Drum dryer (for pastes) | 6 ~ 20 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% |

[1]Mujumdar and Menon (1995)
[2]Barr and Baker (1997)

## Microbial Reduction

The results of microbial tests are summarized in Table 4. The microbial counts after RW drying were greatly reduced for the four microorganisms. The initial total aerobic count (APC) in noninoculated 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 may be attributed to high counts of soil or water-borne 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 may survive because of greater resistance to heat (Skovgaard 1968). Prescott *et al.* (1922) isolated molds in dehydrated vegetables but reported no yeasts. We speculate 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[1]

| | 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 | |

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

For the inoculated purees, 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 foodborne pathogen (Alpa *et al.* 2000), and often a target pathogen in developing mild heat processes (Anderson *et al.* 1991). In certain circumstances, *L. innocua* is 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 results with *L. innocua* that the RW drying system can achieve significant inactivation in *L. monocytogenes* during drying of pumpkin puree. The inactivation of coliforms and *E. coli* was also substantial during RW drying procedures. Coliforms and *E. coli* were chosen as indicator organisms because they are often selected to identify sanitation critical control points (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 pumpkin puree with reduced pathogen counts.

Sullivan and Egoville (1986) studied 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 on oyster mushrooms dried with sun drying, fluidized bed drying, and thin layer drying methods following blanching, and soaking in potassium metabisulphite at concentrations of 0.5, 1.0, and 1.5%. They examined the total bacteria count, coliforms, yeast, and fungi in fresh and dried oyster mushrooms. For blanched samples, they achieved less than 2 log reductions for blanched mushrooms after the three selected drying methods. Compared with the microbial studies reported in the drying literature

and based on results in Table 4, RW drying is effective in reducing microbial counts.

A typical temperature-time history in pumpkin puree and microbial reduction during drying is presented in Fig. 8. The log reduction of *L. monocytogenes* exposed to equivalent drying temperatures (calculated from $D_{70}$ = 0.2 min and z = 6C for *L. monocytogenes)*, is also plotted in Fig. 8. The estimated thermal reduction for *L. monocytogenes* at the end of drying is 20 logs, though this estimation may be too high because microorganisms become more heat resistant as moisture content decreases (Archer *et al.* 1998). Only 5.5 log reduction in *L. innocua* counts were observed because the initial inoculation limits the number of observed microorganisms (CFU/mL). Furthermore, zero counts were observed in the dried pumpkin purees. The reductions observed during drying experiments therefore, does not contradict the predicted reduction.
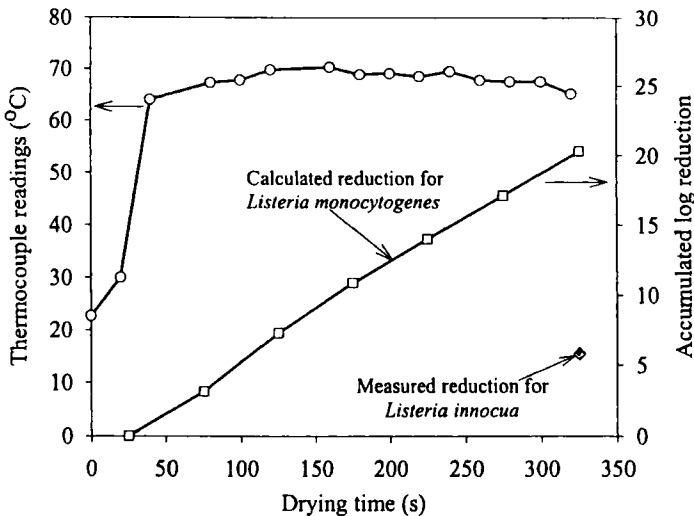


FIG. 8. PUREE TEMPERATURE AND ACCUMULATED LOG REDUCTION IN
POPULATION OF *LISTERIA MONOCYTOGENES* AS A FUNCTION OF DRYING TIME
The accumulated decimal reduction was calculated from the temperature profile and the
$D_{70}$ value of 0.2 min.

## CONCLUSIONS

Studies conducted with both the pilot scale and full scale RW dryer demonstrated that with a circulating water temperature of 95C, complete drying of pumpkin puree was achieved in less than 5 min. With the steam boiler operating at 30% of its design gas consumption capacity, between 28.7 and

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 and 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 purees. The results obtained demonstrate that the RW system is energy efficient and provides adequate microbial reduction during the drying of pumpkin purees.

## ACKNOWLEDGMENTS

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